CDM Sport develops and distributes rehabilitation and fitness products to the health care, wellness and sports medicine markets. You can find us in the training rooms of most professional sports organizations, Division I athletic programs and the trailers that support professional golf tours. We’re in over 2500 spine and physical therapy clinics in the US and Canada.

Change your body. Change your game.

- LightForce™ by LiteCure®
- OTIS
- DS2 Platform
- MR Cube
- MR Squat
- RNT Tubing
- Instant Replay
- Back System 3

DEEP TISSUE LASER THERAPY™

Know No Boundaries
- Achieve the very best outcomes
- Treat your most challenging conditions
- Drug free, pain free, surgery free

LightForce Therapy Lasers
- Protocols based on science
- Patented massage ball application
- Easy-to-use graphic interface
- Manufactured in the USA
- Industry leaders in support

Stop by Booth # 27-28 to FEEL THE DIFFERENCE

LightForceLasers.com // 302.709.0408
EDITORIAL STAFF & BOARD

Phil Page, PT, PhD, ATC, CSCS
The Hygenic Corporation
Akron, Ohio – USA

Mark Paterno, PT, PhD, MBA, SCS, ATC
Cincinnati Children's Hospital Medical Center
Cincinnati, Ohio – USA

Charles E. Rainey, PT, DSc, DPT, MS, OCS, SCS, CSCS, FAAOMPT
United States Public Health Service
Springfield, Missouri - USA

Michael P. Reiman, PT, DPT, OCS, SCS, ATC, FAAOMPT, CSCS
Duke University School of Medicine
Durham, North Carolina – USA

Mark F. Reinking, PT, PhD, SCS, ATC
Saint Louis University
St. Louis, Missouri – USA

Jill Robertson, PT, MSc (PT), Dip Manip PT
Beaverbank Orthopaedic and Sport Physiotherapy
Halifax, Nova Scotia – Canada

Kevin Robinson, PT, DSc, OCS
Belmont University
Nashville, Tennessee – USA

Barbara Sanders, PT, PhD, SCS, FAPTA
Texas State University-San Marcos
San Marcos, Texas – USA

Teresa L. Schuemann, PT, DPT, SCS, ATC, CSCS
Colorado Physical Therapy Specialists
Fort Collins, Colorado – USA

Brandon Schmitt, PT, DPT, ATC
PRO Sports Physical Therapy of Westchester
Scarsdale, New York - USA

Patrick Sells, DA, ES
Belmont University
Nashville, Tennessee – USA

Laurie Stickler, MSPT, OCS
Grand Valley State University
Grand Rapids, Michigan – USA

Steven R. Tippett, PT, PhD, SCS, ATC
Bradley University
Peoria, Illinois – USA

Timothy F. Tyler, PT, ATC
NISMAT Lenox Hill Hospital
New York, New York – USA

Timothy Uhl, PT, PhD, ATC
University of Kentucky
Lexington, Kentucky – USA

Mark D. Weber, PT, PhD, SCS, ATC
University of Mississippi Medical Center
Jackson, Mississippi – USA

Kevin Wilk, PT, DPT
Champion Sports Medicine
Birmingham, Alabama – USA

Erik Witvrouw, PT, PhD
Ghent University
Ghent – Belgium
Executive Committee
Walter L. Jenkins, PT, DHS, LATC, ATC
President
Blaise Williams, PT, PhD
Vice President
Mitchell Rauh, PT, PhD, MPH, FACSM
Secretary
Bryan Heiderscheit, PT, PhD
Treasurer
Stacey J. Pagorek, PT, DPT, SCS, ATC
Representative-At-Large

Administration
Mark S. De Carlo, PT, DPT, MHA, SCS, ATC
Executive Director
Mary Wilkinson
Director of Marketing/Webmaster
Managing Editor, Publications

Contact Information
P.O. Box 431
Zionsville, Indiana 46077
877.732.5009 Toll Free
317.669.8276 Fax
www.spts.org

IJSPT is a bimonthly publication, with release dates in February, April, June, August, October and December.

ISSN 2159-2896
# TABLE OF CONTENTS
## VOLUME 11, NUMBER 6

<table>
<thead>
<tr>
<th>Page Number</th>
<th>Article Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>820</td>
<td>THE PATELLOFEMORAL JOINT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biomechanics and Pathomechanics of the Patellofemoral Joint</td>
<td>Author: Loudon JK</td>
</tr>
<tr>
<td>831</td>
<td>Examination of the Patellofemoral Joint</td>
<td>Authors: Manske RC, Davies GJ</td>
</tr>
<tr>
<td>854</td>
<td>Current Concepts in the Treatment of Patellar Tendinopathy</td>
<td>Authors: Reinking MF</td>
</tr>
<tr>
<td>867</td>
<td>Current Concepts in the Treatment of Gross Patellofemoral Instability</td>
<td>Author: Buchanan G, Torres A, Czarkowski B, Giangarra CE</td>
</tr>
<tr>
<td>877</td>
<td>Current Concepts in Biomechanical Interventions for Patellofemoral Pain</td>
<td>Authors: Willy RW, Meira EP</td>
</tr>
<tr>
<td>891</td>
<td>Current Concepts and Treatment of Patellofemoral Compressive Issues</td>
<td>Authors: Mullaney MJ, Fakarowana T</td>
</tr>
</tbody>
</table>

## ORIGINAL RESEARCH
<table>
<thead>
<tr>
<th>Page Number</th>
<th>Article Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>936</td>
<td>The Nine Test Screening Battery - Normative Values on a Group of Recreational Athletes</td>
<td>Authors: Flodstrom F, Haepke A, Bitt ME, Frohm A</td>
</tr>
<tr>
<td>945</td>
<td>Functional Hop Tests and Tuck Jump Assessment Scores Between Female Division I Collegiate Athletes</td>
<td>Authors: Hoog P, Warren M, Smith CA, Chimera NJ</td>
</tr>
<tr>
<td>954</td>
<td>Pre-season Jump and Hop Measures in Male Collegiate Basketball Players: An Epidemiologic Report</td>
<td>Authors: Brumitt J, Engidis A, Isaak D, Briggs A, Mattocks A</td>
</tr>
</tbody>
</table>

## CASE REPORT / SERIES
<table>
<thead>
<tr>
<th>Page Number</th>
<th>Article Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>962</td>
<td>Functional Outcomes After Distal Biceps Brachii Repair: A Case Series</td>
<td>Authors: Redmond CL, Morris T, Otto C, Zerella T, Semmler JG, Human T, Phadnis J, Rain GI</td>
</tr>
<tr>
<td>980</td>
<td>Cervical Contribution to Functional Shoulder Impingement: Two Case Reports</td>
<td>Authors: Pheasant SD</td>
</tr>
</tbody>
</table>

## CLINICAL COMMENTARY / LITERATURE REVIEWS
<table>
<thead>
<tr>
<th>Page Number</th>
<th>Article Title</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>992</td>
<td>Midfoot and Forefoot Involvement in Lateral Ankle Sprains and Chronic Ankle Instability. Part 1: Anatomy and Biomechanics.</td>
<td>Authors: Fraser JJ, Figer MA, Hertel J</td>
</tr>
</tbody>
</table>

## LETTER TO THE EDITOR AND RESPONSE
Join us in exciting Las Vegas at the beautiful Planet Hollywood Resort and Casino for Team Concept Conference 2016!

This year’s conference will be a special one as we partner with the International Federation of Sports Physical Therapy (IFSPT) to bring you not only the biggest and brightest names in sports medicine in the US, but the world!

This intensive three-day course will feature a golf medicine symposium on day one, followed by an education session and welcome reception sponsored by Theraband®.

Day two brings hands-on labs, themed sessions and a keynote speech by Richard Parks, famed extreme environment athlete from Wales. Day three focuses on more sessions and labs, including a return to play session presented by IFSPT members.

The full agenda and more information may be found at www.spts.org/education/conferences

Reserve your spot now!

Remember...exhibitor space is also available by contacting mwilkinson@spts.org.
ABSTRACT

The patellofemoral joint is a joint that can be an area of concern for athletes of various sports and ages. The joint is somewhat complex with multiple contact points and numerous tissues that attach to the patella. Joint forces are variable and depend on the degree of knee flexion and whether the foot is in contact with the ground. The sports medicine specialist must have a good working knowledge of the anatomy and biomechanics of the patellofemoral joint in order to treat it effectively.

Key Words: Anatomy, biomechanics, patella
INTRODUCTION
Patellofemoral joint pain (PFP) is one of the most common conditions presented to the sports physical therapist.¹ Disorders of this articulation are found in a variety of active individuals including runners,² tennis players,³ and military personnel.⁴ Females tend to report more patellofemoral pain due to numerous speculations for this reason.⁵⁻⁸

One of the most common contributory factors causing PFP is biomechanical dysfunction.⁹ The patella and trochlea articulation is variable and for some individuals the patella does not fit well.⁹ Also, the patellofemoral joint requires an intricate balance of the soft tissue structures that surround the joint. Unequal pull from one set of structures can cause increased force distribution between the patella and femur leading to pain.¹⁰⁻¹² To treat PFP effectively, it is imperative that the clinician understand the anatomy and biomechanics of this joint.¹³ The purpose of this clinical commentary is to provide the reader with a thorough understanding of anatomy and biomechanics of the patellofemoral joint.

FUNCTIONAL ANATOMY
Osseous Structure/cartilage
The patellofemoral joint is a diarthrodial plane joint that consists of the posterior surface of the patella and the trochlear surface of the distal anterior femur. The patella is the largest sesamoid bone in the body. Geometrically, the patella is shaped like an upside-down triangle that sits distal to the muscle bulk of the quadriceps that forms the patellar tendon. The superior surface is referred to as the base and the inferior patella is the apex (Figure 1). The peak dimensions of the average patella are 4 - 4.5 centimeters in length, 5 - 5.5 centimeters in width and 2 - 2.5 centimeters thick.¹⁴,¹⁵

The patella is composed of a thin cortical shell with a trabecular core. The anterior surface of the patella is convex in both anterior-posterior, and medial-lateral planes. The posterior surface of the patella is divided into a variety of facets (Figure 2). A major vertical ridge divides this surface into a medial and lateral half. The two halves can be further divided into seven facets, three horizontal pairs: proximal, middle, and distally and an odd facet that is located on the far medial, posterior aspect of patella. The patellar facets are convex in shape in order to accommodate the concave femoral surface with the lateral side wider to help maintain patellar position. The majority of the articulating surface of the patella is covered with a thick layer of articular cartilage, up to seven millimeters.¹⁶ This thick cartilage is thought
would indicate trochlear dysplasia (less depth of the
trochlea) and a tendency for patellar subluxation.

Soft tissue
Due to the shallow and incongruent fit between
the patella and the trochlea, the stability of the patello-
femoral joint is dependent on the static and dynamic
soft tissue structures.\textsuperscript{15} Static stability is offered
by the patellar tendon, joint capsule, and ligamentous
structures. The medial structures become important
in minimizing lateral translation and the primary
structure to lateral restraint is the medial patello-
femoral ligament (MPFL) This ligament runs from
the adductor tubercle to the medial border of patella.
Desio et al. describe the MPFL as providing 60% total
restraint at 20 degrees of knee flexion.\textsuperscript{15,17} A second-
ary restraint includes the medial meniscopatellar
ligament which originates from the anterior aspect
of the menisci and inserts into the inferior 1/3 of
patella and the medial retinaculum with superficial
fibers that interdigitate with the medial collateral
ligament and the medial patellar tendon.\textsuperscript{17}

On the lateral side of the patellofemoral joint, the
following structures aide in stability: lateral patello-
femoral ligament, joint capsule, iliotibial band (ITB),
and lateral retinaculum. The lateral retinaculum
consists of a thinner superficial layer that extends
from the ITB to the patella and quadriceps expan-
sion and a thicker deep layer that interdigitates with
the vastus lateralis, patellofemoral ligament, and
patellotibial ligament.\textsuperscript{18} The joint must rely on the
medial and lateral retinaculum and joint capsule
at angles less than 20-30 degrees of flexion because
there is minimal to no bony stability.

Dynamically, the contractile structure of the quad-
riceps, pes anserine muscle group, and biceps femo-
ris muscle help to maintain patellar alignment. The
importance of the vastus medialis oblique (VMO)
has been discussed extensively in the literature.\textsuperscript{18–20}
The VMO attaches to the mid-portion of patella,
the MPFL and adductor magnus tendon. Its more
oblique alignment (as compared to the vastus medi-
alis longus) provides mechanical advantage to pro-
mote medial stabilizing force to the patella.\textsuperscript{21,22} The
rectus femoris inserts on the anterior portion of
superior aspect of patella\textsuperscript{22}. The vastus intermedius
inserts posteriorly at the base of patella. The vastus
KINESIOLOGY/BIOMECHANICS

Function

The function of the patella is multifaceted. Its primary purpose is to serve as a mechanical pulley for the quadriceps as the patella changes the direction of the extension force throughout knee range of motion. Its contribution increases with progressive extension. According to Huberti and Hayes the patella is critical in the last 30 degrees of knee extension.24 At full knee extension the patella provides 31% of total knee extension torque, while between 90 and 120 degrees of flexion it provides only 13%. Additionally, the patella acts as a bony shield for the anterior trochlea and due to its interposed position between the quadriceps tendon and femur it prevents excessive friction between the quadriceps tendon and the femoral condyles.25,26

Static Alignment

The static alignment of patella is related to the depth of the femoral sulcus, height of the lateral femoral condyle wall, and the shape of patella. Typically, gross alignment is assessed with the patient in a supine position. McConnell27 has established assessment criteria; however the inter-reliability of this method has been questioned28. For the clinician, observational analysis of obvious abnormalities remains clinically useful but is subjective and cannot be easily quantified.

When observing in the frontal plane with the knee in full extension the patella typically sits midway between the two condyles, although some sources suggest a slight lateral deviation.12 In this position, the patella is superior to the trochlea and minimal contact exists between the patella and femur, thus, in this position the patella is most mobile. Clinically, the Q-angle is commonly used to identify alignment of the quadriceps muscle pull. The Q-angle is the angle between the line of pull of the quadriceps (anterior superior iliac spine to mid-patella) and a line connecting the center of patella with tibial tuberosity (Figure 5). Normal Q-angle for males is 10-13 degrees and 15-17 degrees for females. An increased Q-angle is thought to create excessive lateral forces on the patella through a bowstring effect.10,16 Recently, studies have shown no association between the static Q-angle and patellofemoral kinematics or pain.29,30 Therefore the best way to assess Q-angle is during dynamic active function using video analysis.31

In the sagittal plane with the knee in slight flexion, the apex of the patella rest just at or slightly proximal to the joint line. A more sophisticated method to measure sagittal plane patellar position is the Insall-Salvati ratio.32 This measurement is the ratio of the patellar tendon length compared to the patellar height with the knee bent to around 30 degrees. A ratio of around 1.0 is considered normal. A ratio less than 0.80 is indicative of an inferior patella or “patellar baja” that may be due to a shortened patellar tendon. A ratio greater than 1.2 is termed “patella alta”
In this more superior position it takes longer for the patella to reach the bony constraint of the femoral trochlea, thus the patella is at a greater risk for subluxation.

Additionally, the patella should be lined up so that the superior and inferior borders are equidistant from the femur. If any surface of the patella deviates either anterior or posterior this is termed “tilt”. In the sagittal plane, these motions are described by the location of the inferior pole of the patella in either a depressed (inferior tilt) or elevated (superior tilt) position (Figure 7). An inferiorly tilted patella can be problematic as it may pinch or irritate the patellar fat pad that lay underneath the patellar tendon.

In the transverse plane, the patella should lie horizontally such that the medial and lateral borders are equidistant from the femur. A lateral tilt, when the medial border is higher than the lateral border, can lead to lateral patellofemoral compression syndrome (Figure 8).

Rotation of the patella occurs around an anterior–posterior axis and is described by the direction of the inferior pole of the patella. A lateral rotation occurs when the inferior pole is directed toward the lateral side of the knee, while a medial rotation occurs when the inferior pole is directed medially (Figure 9). This rotational position may indicate underlying torsion of the tibia such as lateral tibial torsion.

**DYNAMIC MOVEMENT/KINEMATICS**

More important than assessing static alignment is for the clinician to understand the dynamic movement of the patella, commonly referred to as patellar tracking. Movement of the patella during tibiofemoral motion is dependent upon the active contraction of the quadriceps, the extensibility of the connective tissue about the patella, and the geometry of the patella and trochlear groove. As a gliding joint, the patella has movement in multiple planes. These motions include superior/inferior glide, medial and lateral glide, medial and lateral tilt, and medial and lateral rotation. Superior glide is also termed patellar extension and this motion occurs during tibiofemoral extension when the quadriceps contract creating a superior pull on the patella. An inferior glide is patellar flexion and occurs in conjunction with tibiofemoral flexion. Lateral and medial glide occur as translations in the frontal plane that correspond with tibiofemoral motion. During lateral glide the lateral edge of the patella moves closer to the lateral side of the knee (Figure 10), and during medial glide the medial side moves toward the medial edge of the
knee. Tilt occurs about a longitudinal axis. Tilts are described by which direction the reference facet is moving. In a medial tilt, the medial posterior facet moves closer to the medial femoral condyle, while a lateral tilt is movement of the lateral posterior patellar facet moving closer toward the lateral femoral condyle.

**Open chain**

During open chain knee motion, the patella follows the path of the tibia due to the distal insertion of the patellar tendon to the tibial tubercle. The patella glides inferiorly with knee flexion and superiorly with knee extension (Figure 11). With a quadriceps set the patella should migrate approximately 10 mm superiorly.32

As the knee flexes, the articulating surface of the patella changes throughout the range of knee motion.

**Figure 7.** Inferior tilted patella (Figure 14.14 in Loudon – Clinical Mechanics and Kinesiology) © Human Kinetics

**Figure 8.** Lateral tilted patella (Figure 14.14 in Loudon – Clinical Mechanics and Kinesiology) © Human Kinetics

**Figure 9.** Lateral and medial rotation of the patella (Figure 14.14 in Loudon – Clinical Mechanics and Kinesiology) © Human Kinetics

The contact point moves proximally along the patella and inferior-posterior along the femoral condyles (Figure 12). The overall pattern of patellar contact area increases with increasing knee flexion, which
60 degrees of knee flexion, the superior half of the patella contacts part of the femoral groove slightly inferior to the contact area at 30 degrees. The contact area gradually increases as the joint becomes more congruent. The contact area continues to increase as the knee flexes to 90 degrees and is estimated to be 6.0 cm². At this point, the superior portion of the patella is contacting an area of the femoral groove just above the notch.

Figure 11. Open chain patellar motion with knee extension (superior glide) and knee flexion (inferior glide) (Figure 14.13 in Loudon – Clinical Mechanics and Kinesiology) © Human Kinetics

Figure 12. Patellar contact points during knee motion. (Figure 14.16 in Loudon – Clinical Mechanics and Kinesiology) © Human Kinetics

serves to distribute joint forces over a greater surface area. In those with normally aligned patellofemoral joints, this distribution of force allows the knee to resist the deleterious effects that could occur from routine exposure to high compressive forces.

Several references report that in full knee extension, the patella lies just proximal to the trochlea of the femur, resting on the suprapatellar fat pad and suprapatellar synovium.15,16,23,26 Contrary results by Powers et al. indicate that there is contact of the patella and the trochlea at full knee extension.33 Nevertheless, the trochlear groove is shallow at this point resulting in compromised stability of the patella and there is a greater potential for instability at this position.

As the knee begins to flex, the inferior aspect of the patella contacts the uppermost portion of the femoral condyles. This contact begins between the lateral femoral condyle and the lateral facet of the patella, but by 30 degrees the contact is evenly distributed on both sides of the condyles and the total contact area has been estimated to be approximately 2.0 cm². The contact area initially is small and gradually increases as the joint become more congruent. At

After 90 degrees and until 120 degrees of knee flexion the superior aspect of the patella contacts the area of the femoral groove immediately surrounding the intercondylar notch. In deep flexion the patella actually bridges the span of the intercondylar notch and there is only contact on the far medial and lateral edges of the patella.34 At full flexion, the odd facet is the only articulating contact between the patella and the lateral surface of medial femoral condyle.

Besides the superior and inferior motion of the patella, it also tracks lateral-medial-lateral during tibiofemoral extension to flexion.16 In the normal knee little excessive medial or lateral motion occurs during flexion as the patella remains relatively centered on the trochlea. It is important to note that in full knee extension the patella sits slightly lateral because of the external rotation of the tibia. The estimated amount of medial and lateral displacement is about 3 mm in each direction. As the knee flexes, the patella glides medially and centers itself within the trochlear groove. During knee extension from 45 degrees to 0 the patella tilts medially 5–7 degrees
Patellofemoral joint reaction force (PFJRF) is the resultant compression force acting on the joint and is dependent on knee joint angle and muscle tension (Figure 13). The actual stress placed on the patellofemoral joint is the PFJRF divided by the patellofemoral joint contact area and referred to as joint stress measured as force per unit area. The greater the contact area between the patellar surface and femur the less stress is placed on the articular tissue. A high PFJRF combined with a small contact area results in high patellofemoral joint stress and may be harmful to the joint cartilage. This stress can be amplified with poor patellar positioning which will be discussed in the next section.

As the contact point changes between the patella and trochlea throughout the range of motion; accordingly, the joint forces change too due to a change in the lever system. In non-weightbearing, the contact area between patella and trochlea increases as the knee flexes from 0-90 degrees and therefore less patellofemoral stress occurs as knee flexion increases. It has been commonly accepted to minimize patellofemoral joint stress open chain exercises should occur from 90 to 30 of knee flexion. When the foot is fixed, the PFJRF increases from 90 to 45 degrees, then decreases as the knee approaches full extension. PFJRF and patellofemoral joint stress can be tremendous during even the simplest of activities of daily living, not to mention with sports and recreational activities. Studies have demonstrated forces of 1.3 times body weight (BW) during level ambulation, 3.3 times BW during stair ambulation, 5.6 times BW during running, and up to 7.8 times BW during a deep knee bend or squat.

CLINICAL APPLICATION

Excessive patellofemoral joint stress appears to be the cause of PFP. The joint stress can be caused by abnormal anatomy or alignment, abnormal patellar tracking, lower kinetic chain factors, and general overuse. The goal of the evaluation is to identify the likely cause of symptoms.

Wiberg has suggested that the shape of the patella as an influencing factor in the development of patellar

![Image: Patellofemoral joint reaction force](Figure 13. Patellofemoral joint reaction force (Figure 14.17 in Loudon – Clinical Mechanics and Kinesiology) © Human Kinetics)
have reported the development of PFPS in subjects who exhibited lack of pronation during gait.\textsuperscript{46,47} Other distal factors that may influence the kinematics at the knee are limited dorsiflexion and excessive midfoot mobility.

**CONCLUSIONS**

Excellent comprehension of the structures and forces that influence patellofemoral function is paramount to understanding the wide variety of clinical problems found at the patellofemoral joint. This information may be applied when examining and assessing athletes, as well as when prescribing rehabilitation interventions so that exercises are performed in ranges of motion that place minimal strain on damaged or vulnerable structures.

**REFERENCES**


38. Reilly DJ, Martens M. Experimental analysis of the quadriceps muscle force and patello-femoral joint...


44. Willson JD, Davis IS. Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands. *Clin Biomech Bristol Avon.* 2008;23(2):203-211.


ABSTRACT

Patellofemoral pain is one of the leading causes of knee pain in athletes. The many causes of patellofemoral pain make diagnosis unpredictable and examination and treatment difficult. This clinical commentary discusses a detailed physical examination routine for the patient with patellofemoral pain. Critically listening and obtaining a detailed medical history followed by a clearly structured physical examination will allow the physical therapist to diagnose most forms of patellofemoral pain. This clinical commentary goes one step further by suggesting an examination scheme and order in which it should be performed during the examination process. This step-by-step guide will be helpful for the student or novice therapist and serve as review for those that are already well versed in patellofemoral examination.

Keywords: Patellofemoral assessment and Clinical reasoning, evaluation

CORRESPONDING AUTHOR

Robert C. Manske, PT, DPT, SCS, ATC, CSCS
Professor and Chair - Department of Physical Therapy
Wichita State University
Sports Physical Therapist - Via Christi Health
Wichita, KS
E-mail: Robert.manske@wichita.edu

1 Wichita State University, Wichita, KS, USA
2 Via Christi Health, Wichita, KS, USA
3 Armstrong State University, Savannah, GA, USA
4 Coastal Therapy, Savannah, GA, USA
5 Gundersen Health Systems, LaCrosse, WI, USA
INTRODUCTION
Patellofemoral pain syndrome (PFPS) is considered to be one of the most common medical diagnoses made in outpatient orthopedics in patients complaining of knee pain. PFPS has an incidence between 15-25%. Additionally, PFPS accounts for up to 25% of sports related knee injuries. Recent consensus statements have elucidated the importance of this sometimes perplexing condition. The seemingly simple design of the patellofemoral joint, is, in reality, a very complex articulation with contributing factors that are both intrinsic and extrinsic in nature, noncontractile and contractile, some of which include substantial interplay from other more distant sources, such as the hip or foot. In order to determine what form of intervention is needed in a patient with knee pain, the clinician must initially perform an accurate, comprehensive, yet concise physical examination. Examination findings are not always consistent, nor directly related to symptoms. Additionally, there is no single definitive clinical test used to diagnose patellofemoral pain syndrome. At times important clues and findings regarding PFPS may be very subtle. Clinical experience examining and treating many patients with knee conditions is helpful in making a correct diagnosis. Following an examination scheme consistently will provide the clinician with a good foundation to decipher what findings may be considered normal and abnormal. This systematic, complete, and detailed approach to examination will allow the clinician to identify all contributing factors, ultimately leading to optimal treatment approaches by addressing all potential causative factors, which should result in a more compliant patient and better outcomes.

HISTORY
The cornerstone of any examination is the medical history. If the clinician listens closely enough, and asks the appropriate questions during any medical history the patient will often describe what their diagnosis is. Knowledge about the symptoms' onset, mechanism of injury, location, character or description, severity under different conditions, and any aggravating or alleviating factors will help with the diagnosis. Classical red or yellow flag symptoms such as weight loss, lack of appetite, erythema, and unusual lumps should clearly be ruled out prior to assuming this condition is localized to the patellofemoral joint. A systems review should be performed to identify any potential medical problems (red flags) that may be causing or contributing to the patient's symptoms. If indicated, it is important to understand that it is always prudent to refer back to the original referral source or to another medical provider in order to rule out any suspicious symptoms that are out of the ordinary or may not be attributable to musculoskeletal factors.

PFPS is in many instances a nonspecific complaint that can be traced to or associated with multiple conditions. These include compressive issues, instability, biomechanical dysfunction, direct patellar trauma, soft tissue lesions, overuse syndromes, osteochondritis dissecans, and neurologic disorders. Compressive issues usually are characterized by aching symptoms that worsen when the knee is positioned in flexion for long periods of time. Going to a movie, sitting in a car or plane during long trips often aggravate the symptoms. Deep squats and stairs are also commonly symptomatic. In more severe conditions both ascending and descending steps will cause or increase the pain. In less acute conditions ascending stairs, which requires a concentric contraction of the quadriceps muscle, may not create symptoms. However, because descending steps (Figure 1) requires an eccentric contraction, it may create pain due to the increased compressive loads placed upon the articular cartilage of the posterior patellar facets during eccentric loading.

The patient with patellar instability will usually describe symptoms such as though the knee is slipping, giving way or giving out. Instability does not have to be the result of a macrotraumatic patellar dislocation or injury and is oftentimes subtle and microtraumatic in nature.

Biomechanical issues such as increased knee valgus, increased hip adduction and tibial abduction or foot pronation are generally reported as vague
starts, stops and jumping sports. A common apophyseal injury in teenagers during times of rapid growth that directly involves the patella is Sindig-Larsen-Johannsen’s Syndrome.

Overuse injuries occur when training type, frequency, duration or intensity exceeds the body’s ability to repair itself. These types of conditions are more common in athletes such as runners, or someone starting an overzealous exercise program. At times overuse of the anterior knee can also occur as a result of vocational activities, especially those that require repetitive squatting, stair climbing or walking. It must be remembered though that overuse injuries can present as an acute re-exacerbation of a condition; consequently an acute on chronic condition is not uncommon with PFPS.

Osteochondritis dissecans (OCD) can create PFPS symptoms that are deep in the knee often described as behind the patella. Patellar chondral OCDs are less common than those at the lateral portion of the medial femoral condyle.10 Patellar dislocations frequently result in an OCD lesion. However because these lesions both lie directly behind the patella they are often very symptomatic and seem to be patellar in nature. Intermittent knee effusions and painful weight bearing would indicated a need for special imaging to rule this condition out.11

Lastly, complex regional pain syndrome or reflex sympathetic dystrophy can cause anterior knee pain. This condition is usually trauma or surgically induced. An exaggerated pain response due to sympathetically maintained pain would be the presentation of this condition.

In most instances a patient with PFPS will simply complain of anterior knee pain, oftentimes with bilateral complaints. This pain may be localized in a small area or it may be a large, vague general pain complaint that is not easily isolated. Grelsamer and McConnell10 report that the location of pain may indicate specific tissues involved. Table 1 presents information that may assist with differential diagnosis by listing location and possible causes. Lastly, it is important to know if the patient has had any past surgeries. Knowing the exact procedure and what the complaints were prior to that surgery are both important.
PHYSICAL EXAMINATION OVERVIEW
The patient’s knees, and ideally the entire lower extremity, should be exposed for the examination. The uninvolved knee should be evaluated first to establish a baseline “normal” for the patient before the involved extremity is examined.

Observation/Posture
Following the medical history and subjective examination, the clinician should begin the observation portion of the examination. The clinician begins by looking for obvious signs of deformity, discoloration, swelling or scars. Abnormal protuberances, ecchymosis, joint effusion or edema should be noted in or around the knee. Scars may be from history of trauma or surgery. The examination will progress from standing, to seated, to supine.

Standing Examination
General standing examination should be evaluated in the three basic cardinal planes. Each plane has certain unique aspects that should be examined to ensure the clinician has a good understanding of structural or functional adaptations or compensations that may be a source of PFPS symptoms.

Postural Anterior/Posterior View for Frontal Plane Alignment
A varus or valgus knee posture can usually be seen clearly in the anterior sagittal plane view (Figure 2). A reduction of the normal 125-degree inclination of the femoral neck and femoral shaft (coxa vara) will create a genu valgus at the knee, while an increase in the normal angle (coxa valga) will create genu varus at the knee. The clinician should ensure that femoral rotation and foot pronation are not contributing to the varus or valgus angulation at the knee. The patella position should also be assessed for a bayonet sign or excessive external tibial torsion. The tibial alignment for tibia varum should also be assessed realizing that some distal tibia varum is normal. The foot should be evaluated from the anterior view to check for a forefoot dysfunction,
Anterior View for Transverse Plane Alignment

Transverse plane views are best to observe femoral rotation. Excessive femoral anteversion will create increased medial rotation of the patella position, while excessive femoral anteverision will create increased lateral rotation of the patella position. Much like viewing the sagittal plane, the clinician must ensure that the rotation component they are viewing is not coming distally from foot pronation. General alignment of the hips and pelvis will give the indication of either a short or long leg or pelvic rotation. Palpation of the iliac crest, anterior superior iliac spine (ASIS), anterior inferior iliac spine (AIIS) and posterior superior iliac spine (PSIS) is done by kneeling in front of or behind the athlete. These are generally palpated bilaterally with use of the dominant eye to gauge for symmetry. Asymmetry may be due to pelvic obliquity, hip abnormalities, or leg length differences. While viewing anteriorly the clinician will usually be able to note atrophy of the quadriceps. Atrophy can occur anywhere around the knee or calf therefore the clinician should view both above and below the knee joint.

Figure 3. Posterior view can be used to assess valgus/varus angulation of the knee, and to assess forefoot, mid-tarsal, and subtalar joint position.

Figure 4. Lateral view can be used to assess for genu recurvatum, knee flexion contracture, and patella alta or baja.

Postural Lateral View for Sagittal Plane Alignment

The lateral view (Figure 4) is best to observe for either genu recurvatum or a flexion contracture. Excessive genu recurvatum can create a Hoffa's syndrome due to impingement of the infrapatellar fat pad and the inferior pole of the patella. Quadriceps weakness due to either strength loss or inhibition may present as knee hyperextension. A flexion contracture is the result of loss of knee extension range of motion. This can be caused from motion limitations post-surgery, trauma, injury, or excessive hamstring tightness. This posture will cause overuse of the quadriceps muscle due to inability to achieve end range extension. This view also allows for a clinical assessment of a patella alta or infera (baja). Additionally, this view permits assessment of a camel sign of the knee which may be normal or be a contributing factor to a Hoffa's syndrome.

Anterior View for Transverse Plane Alignment

Transverse plane views are best to observe femoral rotation. Excessive femoral anteversion will create increased medial rotation of the patella position, while excessive femoral anteverision will create increased lateral rotation of the patella position. Much like viewing the sagittal plane, the clinician must ensure that the rotation component they are viewing is not coming distally from foot pronation. General alignment of the hips and pelvis will give the indication of either a short or long leg or pelvic rotation. Palpation of the iliac crest, anterior superior iliac spine (ASIS), anterior inferior iliac spine (AIIS) and posterior superior iliac spine (PSIS) is done by kneeling in front of or behind the athlete. These are generally palpated bilaterally with use of the dominant eye to gauge for symmetry. Asymmetry may be due to pelvic obliquity, hip abnormalities, or leg length differences. While viewing anteriorly the clinician will usually be able to note atrophy of the quadriceps. Atrophy can occur anywhere around the knee or calf therefore the clinician should view both above and below the knee joint.
Q-Angle
The “law of valgus” describes the natural tendency for the patella to track laterally during dynamic movements.11 This valgus angulation occurs due to the quadriceps attachments to the femur. Q-angle is a measurement of the angle formed by the intersection of a line drawn from the anterosuperior iliac spine to the midpoint of the patella and the proximal extension of a line drawn from the tibial tubercle to the midpoint of the patella.12 A larger Q-angle may create a larger lateral vector and potentially a greater predisposition to lateral patellar tracking when compared to a smaller Q-angle.13 A greater Q-angle in women (15-18 degrees) compared to men (12 degrees) may partly explain higher incidences of patellofemoral pain in women due to a larger lateral valgus vector, although complaints of pain are usually multifactorial.14 Due to the variability of measurement techniques performed in supine, standing, with quadriceps contracted, with quadriceps relaxed, etc; the clinical utility of measuring Q-angle cannot be supported.15 Based on a meta-analysis examining the Q-angle, it was determined that this measurement by itself is not a risk factor for development of patellofemoral pain.1 Additionally, the relationship between Q-angle and signs and symptoms has not always been consistent.16 It is possible that an excessive Q-angle may only be problematic in a subpopulation of those with PFPS pain. Other factors that are unrelated to Q-angle may be more predominant in certain patellofemoral patients. Clinicians have to remember that in most measurement methods, Q-angle is a static measurement that is hypothetically measuring a dynamic function of the quadriceps.

Leg Length Measurements
Leg length differences alter gait symmetry and joint mechanics during weight bearing, potentially contributing to atypical compressive and tensile stresses on the joint structures of the lower limb.17

The clinician can palpate several bony landmarks to see if the pelvis and hips are in normal alignment. Palpation of the iliac crests bilaterally (unshod) will determine pelvis height or level (Figure 5). The clinician should ensure that the patient’s feet are both in neutral position. A higher iliac crest could indicate a long leg, while a lower iliac crest could indicate a short leg. The body will normally try to equalize this length through compensations to restore homeostasis. Anterior knee pain could result from either a long or short leg. The long leg may require compensation by pronating at the foot and subtalar joint, while the shorter foot may compensate by having to supinate in an attempt to equalize the leg length. Additionally, in standing the clinician can measure with a flexible tape measure the distance from the anterior superior iliac spine (ASIS) to the medial malleolus (Figure 6). A difference more than 1.5 cm may be

Figure 5. Palpation of the iliac crest to examine for pelvis height. Higher iliac crest could indicate a longer leg, while a lower iliac crest could indicate a shorter leg.

Figure 6. Measurement of standing leg length measurement taken with flexible tape measure from anterior superior iliac spine to medial malleolus. A difference in length of limbs greater than 1.5 cm is thought to be pathologic.
considered pathologic. The authors encourage clinicians to take leg length measurements in weight bearing positions so they do not miss any potential compensatory patterns. As an example, if a patient has unilateral recurvatum or unilateral pronation, those conditions will not show up in a non-weight bearing leg length measurement position.

The clinician can also measure leg lengths with the patient supine. The patient should lie with the legs at right angle to the two ASIS. With a flexible tape measure the clinician measures as they did in standing from the ASIS to the medial malleolus. A difference of as much as 1.0 to 1.5 cm is considered normal. A follow up test to see where the discrepancy lies is to measure from the iliac crest to the greater trochanter (for coxa vara, and from the greater trochanter to the lateral knee joint line (for femoral shaft length), and from the medial knee joint line to the medial malleolus (for tibial length). Tibial length can also be examined in prone. The clinician flexes the patient's knee to 90 degrees while they are lying prone. The relative heights of the heels are noted. Another way to view femur length is to simply compare the heights of knees while the patient is lying supine with hips flexed 45 degrees. A longer distal femur (knee) would indicate a longer femur.

The Weber-Barstow maneuver is also used in supine to measure leg length differences. To begin the patient lies supine with hips flexed 45 degrees. While the clinician holds the patient’s feet while the patient lifts their hips off the supportive surface, and then returns them to resting position. The clinician then passively extends the knees and hips and compares bilaterally the position (length) of the medial malleoli. This measurement can be taken in supine (Figure 7a) or in long sitting (Figure 7b). A difference would present as either a shorter or longer leg.

**Foot Posture**

While standing, foot posture can be assessed. Excessive pronation can be seen usually in relaxed standing (Figure 8) and during normal walking or running. Flat-foot, or a flattened medial longitudinal arch, or a valgus hindfoot could indicate excessive pronation. Examination of heel position for pronation has been performed for some time and has demonstrated good intertester and intratester ICC’s ranging from .68 to .91. 

![Figure 7](image7.png) Weber-Barstow measurement comparing position of malleoli in supine (a) and long sitting (b).

![Figure 8](image8.png) Excessive pronation seen as medial arch collapse in relaxed standing.
called the navicular drop and is used to quantify mid-foot mobility. If the navicular drop is 10 mm or less, it is considered to be within normal limits (WNL). Feiss line and the medial longitudinal arch angle are other methods that have been described to identify a static pronated foot.20-22

DYNAMIC MOVEMENT ASSESSMENTS

Because in many instances cardinal plane deviations may not be seen in relaxed standing or during general gait assessment an activity with greater demand placed upon the knees is needed to be a part of the examination process. The step down test or the single leg squat is a method of examination that can be used.

Step-Down Test

A step-down test can be performed to assess hip and leg strength and endurance. The patient is asked to stand on a 20 cm box with leg to be tested. Patient should stand with arms folded across chest and be instructed to squat down on one lower extremity (Figure 10) 5-10 times consecutively, in a slow and

Figure 9. Assessment of subtalar joint in weight bearing functional position. Clinician will palpate the head of the talus on the dorsal medial aspect of the right foot with the finger and the talar dome on the lateral foot with the thumb.

Figure 10. The step-down test is performed to test hip and leg strength and endurance. Patient stands with arms folded across chest as they lower themselves in a slow and controlled manner until heel touches the floor.
heel to the ground, then return to the starting position. Patient should be rated on the criterion listed in Table 3. Rabin scored participants with patellofemoral pain as good (score, 0-1) or moderate (score 2 or greater). Participants in their study with moderate scores exhibited dorsiflexion range of motion limitations and less hip external rotation and knee extensor muscle strength.

Single-Leg Squat
Nunes at al report that the best available test for PFP is anterior knee pain elicited during a squatting maneuver. PFP is evident in 80% of people who are positive in this test. Consequently the single leg squat is a test of dynamic hip and quadriceps strength in the examination (Figure 11). This maneuver imposes higher mechanical demands, than a bilateral squat, that may induce compensatory movements such as knee valgus. This may partially be due to the smaller base of support and increased amounts of dynamic control that are needed in all planes during the single limb squat.

Table 2. Step Down Test Alterations

<table>
<thead>
<tr>
<th>Overall Impression</th>
<th>Trunk</th>
<th>Pelvis</th>
<th>Hip</th>
<th>Knee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintain balance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perturbation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth of movement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed of movement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral deviation/interior</td>
<td>Lateral rotation</td>
<td>Lateral flexion</td>
<td>Forward flexion</td>
<td></td>
</tr>
<tr>
<td>Rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lateral flexion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forward flexion</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Scoring for Lateral Step-Down Test

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Interpretation</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm strategy</td>
<td>Removes hands from waist</td>
<td>1</td>
</tr>
<tr>
<td>Trunk alignment</td>
<td>Leaning in any direction</td>
<td>1</td>
</tr>
<tr>
<td>Pelvic plane</td>
<td>Loss of horizontal plane</td>
<td>1</td>
</tr>
<tr>
<td>Knee posture Steady</td>
<td>Tibial tuberosity medial to 2nd toe</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Tibial tuberosity medial to medial border of foot</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Stepping down on non-tested limb, or wavering from side to side</td>
<td>1</td>
</tr>
</tbody>
</table>

Nakagawa reports that compared to controls, males and females with patellofemoral pain showed increased ipsilateral trunk lean (Figure 12), contralateral pelvic drop (Figure 13), hip adduction and knee abduction (Figure 14) during a single-leg squat.
Figure 11. Single-leg squat with proper form and good control.

Figure 12. Single-leg squat with compensatory increased ipsilateral trunk lean.

Figure 13. Single-leg squat with compensatory increased contralateral pelvic drop.

Figure 14. Single-leg squat with compensatory hip adduction and knee abduction.
These altered kinematics were associated with decreased strength of the hip abductors and external rotators as measured eccentrically on an isokinetic dynamometer.

The patella can also be palpated for grating or crepitus, in both closed kinetic and open kinetic chain movements, which may be an indication of articular cartilage damage. If the crepitus correlates with patient’s symptoms at a particular point in the range of motion (ROM), then it assists in clinical reasoning and forming guidelines for designing the therapeutic exercise program. Likewise, palpating the peripatellar soft tissue in a weight-bearing position may also produce symptoms, which are not present in a non-weight bearing position.

Gait
Qualitative gait evaluation begins as soon as the patient enters the clinic, even with informally observing gait when moving into the clinic. The formal gait evaluation needs to be performed with appropriate shoes (if in sports, then those shoes should be used; if specified work shoes like OSHA hard soled, steel toe shoes are required, then the gait evaluation should be performed in those shoes) If the patient wears orthotics themselves should also be evaluated to see if they are still functionally and structurally sound. With shoes on, it is difficult to actually see some of actual food mechanics. Ideally, the gait evaluation is also performed bare footed so the actual mechanics of the foot can also be assessed. The observation should be performed from anterior, posterior and lateral views. Because the patient is in one place by walking on a treadmill, this allows for consistent observation of the foot and lower extremity mechanics. However, if performing a qualitative gait analysis with the patient walking in the clinic, because they are moving toward or away from the clinician with the anterior or posterior views, each step and observational perspective of the patient is different because of the varying distances from the examiner.

If the patient is a runner, then they also need to be evaluated under various running conditions. Additionally, with cell phones so common and numerous biomechanical apps available (Dartfish, SloPro, CMV, Coach’s Eye, Hudl, SkyCoach, etc.), it is easy to video the patients gait using their own phone so that they can see the mechanics of their walking, running, etc.

Examination for systemic hypermobility (Beighton Index)
To examine for overall widespread joint hypermobility throughout the body the clinician can utilize the Beighton scale of hypermobility. The test criterion is presented in Table 4. Although no studies have clearly described positive findings of hypermobility, most sources state that a score of 4 or more points indicates generalized hypermobility.26-28

Sendur and colleagues29 assessed knees and compared Q-angle in those with normal mobility compared to those with joint hypermobility. They placed subjects in three groups of 20 based on presence of Beighton scale score. The mean Q angle values for healthy hypermobile patients was significantly higher than those that were non-hypermobile. In their population they found the frequency of joint hypermobility, (Beighton scale of 4 or more) to be 29.25%. Quatman et al30 found that in contrast to males, females may have greater generalized joint laxity following onset of puberty, while pre-pubertal males and females were similar. Due to these findings it would seem important to perform generalized laxity testing on those with larger Q angles or on females at any time in their growth period to determine if hypermobility may be contributory factor to patellofemoral pain.

**SEATED EXAMINATION**

**Tibial tubercle sulcus angle**
The tibial tubercle sulcus angle is measured with the patient sitting on the edge of the treatment table...
with knee flexed to 90 degrees. To determine this measurement the clinician observes the position of the tibial tubercle relative to the patellar center. A vertical line is drawn from the center of the patella to the center of the tibial tubercle. A second horizontal line is drawn through the femoral epicondyle. The patella should be completely captured within the femoral trochlea when flexed to 90 degrees. Measurement in this degree of flexion would indicate the amount of lateral displacement of the tubercle with reference to the femoral sulcus. Controversy exists as to what a normal angle is. Hughston\textsuperscript{31} reports a normal angle to be 0 degrees, while Kolowich\textsuperscript{32} considers upper limits of normal to be 10 degrees.

**Passive and active patellar tracking**

Passive and active patellar tracking is performed in the seated position. The patient is asked to sit back in the tripod position with arms extended behind for balance and to hold onto table and to decrease the tension on the hamstrings. This position also allows the pelvis to posteriorly rotate to put slack onto the hamstrings which may limit knee extension motion if sitting in more upright position. To begin with the clinician asks the patient to relax as the clinician passively extends the patients knee from 90 degrees' flexion to full extension (Figure 15a). Normal patellar motion is for the patella to move slightly medial and then slightly laterally back to the original neutral position upon terminal knee extension or to track in a relatively straight line. As normal slight variations exist between individuals and sometimes between individuals' two knees, small differences should not be cause for concern. Larger degrees of changes may be more indicative of pathology. Because this test is performed passively, it assesses the osseous and non-contractile tissues. If there is excessive gliding, it usually indicates tightness of the superficial retinacular fibers, whereas, if the patella has excessive tilting, then it implicates the deep retinacular fibers. Understanding this difference is important for determining how to treat the dysfunction. This test is then performed with the patient actively extending the knee from flexion to extension (Figure 15b). Careful attention should be paid to the range between 20-30 degrees of flexion to full extension as this is the location that most subluxation events occur. A lateral J-sign, or abrupt lateral deviation near terminal extension during an active quadriceps contraction may be indicative of a dysfunctional vastus medialis obliquus muscle lacking dynamic medial stabilization. The results of the passive and active tracking tests will contribute to the clinical reasoning for selection of appropriate interventions based on the cause of the dysfunction.

**Strength Testing (Hip Flexion, Knee Extension, Hip External Rotation, Hip Internal Rotation)**

Strength testing for a patient with patellofemoral pain is performed in both sitting and laying supine, side lying, and prone. Nicholas et al.\textsuperscript{33} was the first to demonstrate the concept of regional interdependency and total leg strength (TLS). Forty years ago, Nicholas suggested the inter-relationships between knee conditions and hip weaknesses. A subpopulation of patellofemoral pain patients that demonstrate proximal hip weakness may exist. Therefore, both

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure15.png}
\caption{Passive (a) and active (b) patellar tracking.}
\end{figure}
knee and hip strength should be routinely tested. In normal individuals these groups are all very strong and rarely exhibit weakness. Testing of these groups are substantiated by the fact that Pappas and Wong-Tom found that using pooled data, decreased strength of knee flexion and hip abduction is associated with those who have patellofemoral pain. Boling et al. found that decreased knee extension isometric strength was a predictor for patellofemoral pain syndrome, which is supported further by systematic reviews from Kooiker et al. and Lankhorst and colleagues.

SUPINE EXAMINATION
Related/Referral Joints (Some of these tests may also be performed in the standing position)

All joints proximal and distal to the knee that can refer or influence functioning at the knee should be assessed. There are various techniques used to perform “clearing” tests. The lumbar spine, sacro-iliac joint, hip joint, proximal tibio-fibular joint, ankle and subtalar joints should be checked. Various methods to clear the joints can be used such as active range of motion (AROM), passive range of motion (PROM), resistive range of motion (RROM), or special tests of the respective areas.

<table>
<thead>
<tr>
<th>Bony and Soft Tissue Knee Palpation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bony</strong></td>
</tr>
<tr>
<td>Patella</td>
</tr>
<tr>
<td>Inferior pole</td>
</tr>
<tr>
<td>Superior pole</td>
</tr>
<tr>
<td>Tibial tubercle</td>
</tr>
<tr>
<td>Adductor tubercle</td>
</tr>
<tr>
<td>Medial femoral condyle</td>
</tr>
<tr>
<td>Medial tibial plateau</td>
</tr>
<tr>
<td>Lateral femoral condyle</td>
</tr>
<tr>
<td>Lateral trochlear ridge</td>
</tr>
<tr>
<td>Lateral tibial plateau</td>
</tr>
<tr>
<td>Patellar facets</td>
</tr>
<tr>
<td>Tibiofemoral joint line</td>
</tr>
<tr>
<td>Fibular head</td>
</tr>
<tr>
<td>Gerdy’s tubercle</td>
</tr>
</tbody>
</table>

Table 5. Selected Bony and soft tissue areas of knee palpation

Palpation
Although palpation does not always correlate exactly to the location of pathology in general musculoskeletal conditions, it does appear to be more sensitive in the patient with anterior knee pain than in those without. In their study following examination and palpation, the physicians were blinded from the patient pain diagram. The physicians filled out a pain diagram to see if their perception from physical examination was similar to the patient self-reported diagram. Eighty-five percent of all patient complaint zones were included in the physician’s diagram. Additionally, Nunes et al. indicate tenderness on palpation of the patellar edges is evident in 71-75% of people with patellofemoral pain syndrome.
the hip and ankle and STJ measurements distally need to also be taken because limitations in these joints can contribute to problems at the patello-femoral joint due to the regional interdependency interaction.

Passive ROM of Knee
Goniometric measurements should also be performed during PROM. One can always obtain more PROM compared to AROM. Assessing the qualitative aspects of the end feels often provides guidelines for treatment interventions.

Flexibility Tests
There are numerous flexibility tests (length tests of the musculo-tendinous unit) for musculature around the knee that are important because of the regional interdependence model and biarticular nature of several muscles around the hip and knee. Flexibility deficits may influence the function of the muscles affecting the patellofemoral joint and/or the tracking of the patella. Specific length tests that should be performed in the supine position include: hamstring 90/90 test, Thomas test, rectus femoris test, gastrocnemius, soleus, hip adductors, and gracilis tests.

Hamstring flexibility can be tested in several different methods. The 90/90 active straight leg raise test is performed in supine by flexing both hips to 90 degrees (Figure 17). The patient grasps behind the knee with both hands to keep the thigh vertical. The patient actively extends the knee as much as possible. Normal flexibility should be around 160 degrees (or 20 degrees from 0) of popliteal angle. The sitting hamstring flexibility test can be done with both knees extended (Figure 18) or one knee flexed against the chest and the other extended. The patient will flex at the trunk and attempt to touch the toes of the extended test limb. The test can be repeated to both sides. An inability to touch the toes indicates tight hamstring muscles.

Hip flexors are tested in supine using the Thomas test. The examiner flexes the opposite knee until the lower back is flattened and lordosis is decreased, and the contralateral hip is held in 120 of hip flexion. When this position is reached the examiner holds it there. In this position the clinician examines the opposite limb. If there is tightness in the hip flexors, the hip

Figure 16. Standing stork test for static balance deficits

Neurological Examination
A screening neurological examination including sensation in dermatomes, reflexes, balance and/or proprioceptive testing should be performed. Some form of balance testing, whether it be a simple stork stand test (Figure 16), or completed using various testing instruments, should be performed because many patients with knee problems exhibit balance deficits. Proprioceptive testing in both open kinetic chain and closed kinetic chain positions can be accomplished using angular joint replication testing.

Active ROM of Knee, Hip, Ankle and STJ
Goniometric measurements should be performed with functional AROM. The typical documentation for the knee motion is: 10-0-135 degrees beginning with hyperextension, moving through neutral (0) and into flexion. Proximal ROM measurements at
of a tight iliotibial band. This test can be performed at the end of the table with the mid-thigh at end of table the clinician can also assess for rectus femoris tightness. If a contracture of the rectus is present, the knee extends slightly. The clinician can attempt to passively flex the knee to see whether it remains at 90 degrees on its own. If during passive flexion of the knee, the thigh flexes it is indicative of tightness.

Gastrocnemius/soleus flexibility is tested in supine. The gastrocnemius is a two joint muscle as it crosses the knee proximally and the ankle distally. To test the gastrocnemius the patient is asked to dorsiflex the ankle with the knee fully extended. The angle of the ankle at that point is the degree of flexibility. Because the soleus does not cross the knee proximally the patient is asked to flex the knee and dorsiflex the ankle. This angle is flexibility of the soleus.

**Special Tests**

When the patellofemoral joint is involved, it often creates a sero-sanginous synovitis response. Therefore, the first tests to be performed are effusion (intra-articular) vs edema, bursitis, hematoma, etc. (extra-articular) tests. There are several tests that can be performed, including milking tests, sweeping, and ballotment tests.

Both superficial and deep patellar retinacula need to be assessed in supine. Passive patellar glides are performed to assess the superficial lateral retinaculum and are performed with the knee in 30 degrees of flexion. Others report that testing should be done in full extension. Testing in full extension examines peripatellar soft tissue passive mobility solely. The authors preferred position is to test mobility in 30 degrees of knee flexion as the patella has started to enter the trochlea and provides a functionally stable position. In this position of slight flexion the clinician cannot only feel resistance from soft tissues, but also from the bony engagement of the patella into the trochlea. Most commonly patellar dislocations occur in this range, therefore it seems to be a functional position of testing.

To perform the test of passive patellar glide the patients relaxed knee is placed in 30 degrees of flexion over a bolster or towel roll. Patient relaxation is critical to obtain accurate results with this test. Even
slight amounts of guarding will decrease the amount of patellar mobility. The clinician, on the lateral side of the knee, will use their thumbs to passively glide the patella in the medial direction (Figure 19). The clinician then moves their hands to the medial side and repeats the same technique to assess lateral mobility. The lateral glide is also known as the Fairbank’s sign or apprehensive test. Therefore, it should be performed after the medial glide testing. The amount of patellar tilt must be kept constant during testing, as altering this factor will change the soft tissue mechanics. When tilt is not controlled the patella may rotate more giving the appearance of translation that is actually rotation. The clinician will estimate the amount of translation by dividing the patella into longitudinal quadrants and estimating the degree of number of quadrants worth of translation that can be induced during examination.43 Kolowich32 tested passive mobility in 20-30 degrees of flexion and reports that if the medial glide is less than one quadrant there is less than adequate medial mobility, while a medial glide of three to four quadrants suggests excessive hypermobility. Two quadrants of passive mobility are considered normal. Additional patellar glides can be performed to assess superior and inferior motion (Figure 20 and 21).

The moving patellar apprehension test is performed with the patient supine with the thigh on the examining table and the clinician holding the leg in full extension off the table.44 The clinician then translates

the patella laterally using their thumb (Figure 22), holding the patella laterally as the clinician flexes the knee to 90 degrees and then returns the knee to full extension. If there are symptoms while performing this movement the test is considered positive for lateral instability. To confirm this test, the clinician uses their thumbs to translate the patella medially while performing the same maneuver. If there are no symptoms on the second portion of this test, lateral instability is thought to be present. Again, the purpose of the testing is to assist in the clinical decision making to select appropriate interventions. So a positive finding may indicate the patient may
will report that the patella shifts laterally, invoking the clinician to assume that lateral subluxation is the pathology. However what the patient is actually feeling is the medial subluxed patella dramatically shifting laterally into the trochlea during early knee flexion. The key finding with medial patellar instability is a reproduction of the patient’s symptoms with the medial patella subluxation test. This is done with starting the test in full knee extension. The clinician applies a medial translational force to the lateral side of the patella. As the knee is flexed somewhere in the first 30 degrees the patient will report symptomatic pain, instability as the patella snaps laterally back into the trochlear groove.

The opposite of excessive laxity is patellar hypomobility. Lateral deep retinacular tightness is a condition that is very common in those with anterior knee pain. The lateral retinacular structures also include contributions from the IT band and the lateral patellofemoral and patellotibial ligaments. The force vector of these tissues is more posterior than lateral, which is why when tight they create more of a tilt than a lateral glide. The patellar tilt test assesses the deep retinacular fibers. This test is performed with the knee in full extension. With the patellar entered into the trochlea, even at 30-40 degrees of flexion create such a tightness of the deep retinacular fibers that no tilt would be possible. While the clinician is on the lateral side of the knee to be tested, they will push posteriorly on the medial anterior border while pushing anterior with the thumbs under the lateral border to assess whether the patella corrects its tilt to at least neutral (Figure 23). If the patient's patella is unable to tilt back to neutral it is indicative of excessive lateral tightness and the potential to have excessive lateral pressure syndrome. Comparisons to the opposite noninvolved side is extremely important as wide ranges of variation of tightness are the norm. The patella should tilt 15 degrees with both medial and lateral tilts.

Excessive lateral subluxation that is symptomatic is also known as the apprehension sign. Lax medial retinaculum or medial patellofemoral ligaments cause apprehension from repetitive subluxation events or from a previous dislocation, or from a congenital condition. Most patellar subluxations and dislocations occur toward the lateral side of the knee joint. This abnormal amount of lateral passive mobility is due to tearing of the medial patellofemoral ligament and the medial patellomeniscal ligament that contribute 23-80% and 22% of the lateral static restraint, respectively.

Another much less common problem is that of the reverse apprehension that occurs with excessive passive patellar mobility in the medial direction. One must be very astute to pick out this pathology as it is rare and may be seen following patellar malalignment surgical procedures used to help resolve lateral translation pathology. The patient may have had an overzealous tibial tubercle transfer or had their vastus lateralis transected at the time of a lateral release, and an overly tight and/or malpositioned medial patella femoral ligament graft. Underlying hyperlaxity, trochlear dysplasia, and deficient vastus lateralis musculature may also play a role in the development of medial patellofemoral subluxation. The patients with medial subluxation...
test and 0 and 30 degrees; and the varus stress test at 0 and 30 degrees.

**Screening for Meniscus**

Although not commonly associated with patellofemoral symptoms, using the McMurray's and dynamic McMurray's test to screen for potential meniscus involvement should be performed to rule out any co-morbidities.

**SIDE LYING EXAMINATION**

**Flexibility Testing**

Iliotibial band and TFL flexibility is assessed with the Ober's test and modified Ober's test. The patient is positioned in side-lying with the affected side up. The bottom leg is passively flexed slightly for stability. The tested extremity is passively abducted and extended with either the knee straight or flexed. The clinician slowly lowers the leg toward the table. If a contrac- ture is present, the thigh will remain elevated past horizontal. Testing with the knee flexed was the original description of this test, however the iliotibial band passes over the greater trochanter and has a greater stretch placed on it when the knee is fully extended.

**Strength Testing (Hip Abductors, Adductors)**

Strength testing of the hip abductors is performed in side lying. With the bottom leg slightly flexed for stability, the top hip is brought into slight abduction. Resistance is given toward the table with the clinician's hand on distal thigh near the knee joint. Replication of same placement of resistance is important for reassessment at a later date to ensure same moment arm is placed on the extremity. With the top leg in front of the bottom, the patient is asked to adduct the hip to be tested. Pressure is given on distal thigh in direction of table.

**PRONE EXAMINATION**

**Flexibility Testing**

Flexibility of the quadriceps is tested in the prone position. Because the rectus femoris crosses both the hip and the knee joint it can easily become passively insufficient. Ely's test is performed prone by placing the hip in neutral or extension (Figure 24), which places the rectus femoris on stretch proximally at the hip and again distally as the knee is further flexed. Clarkes “patellar grind” test has been described as a confirmatory test for patellar chondromalacia. In this test the patella is compressed against the trochlea manually while the clinician asks the patient to contract their quadriceps. A positive test is indicated by an exacerbation of the patient's symptoms. Nunes et al² and Doberstein et al⁵² have demonstrated that the patellar grinding and apprehension test (eg, Clarkes Test) have low sensitivity and limited diagnostic accuracy for patellofemoral pain syndrome. Furthermore, from a clinical perspective, performing the test creates a lot of false positive findings and can exacerbate the patient's condition, therefore should not be used.

**Screening for Knee Ligaments (Rule-Out Instability)**

Testing of the four major knee ligaments can be performed in supine and is imperative to rule out major ligament instability that could create anterior knee pain. There is a philosophy that NO ONE TEST IS THE BEST TEST to implicate or rule out a structure. Consequently, the authors recommend performing the Anterior Drawer and Lachman's Test to screen the ACL; Posterior Drawer and Clancy's Step up Test to screen for the PCL; the rotary instability tests in 70 Degrees of flexion to rule out rotational instabilities which could influence patellofemoral tracking and resultant patellofemoral pain; MCL valgus stress test and 0 and 30 degrees; and the varus stress test at 0 and 30 degrees.
FUNCTIONAL TESTING

In order to determine if a patient is safe to return to activity, activity testing should be performed, whether it be for ADLs, an ergonomic assessment, or sports performance testing. The authors recommend using a functional testing algorithm that is a systematic qualitative and quantitative functional assessment of the patient's performance abilities.54 Patients are stratified into different categories based on their activity levels. Then all patients must meet all the basic testing criteria described throughout this article such as full strength, flexibility and ROM. There are many functional tests that can be used, however, the authors recommend a sequence of the following: 2-legged jump, single-leg hop, Lower Extremity Functional Test (LEFT), and then functional specificity testing.

To begin, the 2-legged jump test is used to help the patient prepare for the concentric propulsive push-off motion and more importantly the eccentric deceleration landing phase. The patient is always instructed to perform four gradient (25, 50, 75, 100%) effort warm-ups for the jump and hop tests. It serves as a screening to make sure the patient is capable of performing the tests safely. Furthermore, having the patient perform a maximum effort test provides a positive transfer of learning and consequently increases the reliability of the test results. The data is evaluated by allometric scaling and normalizing the data relative to the patient's height. Normative values are included in Table 6.

Following the double-legged jump test, also known as a single leg hop test is performed because it is the recommended functional test by the IKDC form. There are several variation of the hop test including the single hop, triple hop, timed hop, and criss-cross (zig-zag) hop. These authors also think this test is an important psychological test for the patient to be able to eccentric land with deceleration on the involved side. The authors evaluate the results based on a bilateral comparison for limb symmetry and allometric scaling to normalize to the patient's height. The norms are listed in Table 6.

The final functional test is the LEFT test.55-60 The purpose of the LEFT test is to incorporate many different lower extremity movement patterns into one

A common compensatory indicative of an inflexible rectus femoris while in this position is seen by the hip flexing due to tightness. Some clinicians will also evaluate hip rotation in the prone position because the anterior capsule is tight which replicates the more functional standing or walking positions.

Strength Testing (Hip Extensors, Knee Flexors)
The hip extensor muscle group is tested with the patient prone. The hip is extended slightly off of the supporting surface. Pressure in the downward direction is given just proximal to the knee joint. When the knee is completely extended testing would include both hamstrings and hip extensors. Testing with the knee flexed would just test the hip extensors. The hamstrings are tested in the prone position to assess the muscle's function against gravity. By rotating the knee, the medial or lateral hamstrings can be selectively biased during the manual muscle testing.

Isokinetic Testing
If it is not contraindicated, and if isokinetic equipment is available, then dynamic muscle testing is performed in an open kinetic chain position. The rationale for such testing is because so many patients with knee conditions have significant deficits in the quadriceps strength. By performing objective dynamic muscle performance documentation of the muscle groups allows for bilateral muscle comparison, unilateral ratios, allometric scaling of the test results, and power measurements, such as time rate of torque development, torque acceleration energy, etc.
test which replicates many activities of functional performance. Important aspects of the test are: 1) subjects perform the test in all directions, 2) there is a deceleration component inherent in the test, and 3) it incorporates a fatigue factor. Most return to play tests are performed in the “fresh” state. Studies have demonstrated that when patients performed a hop test when not fatigued, 100% of the patients passed the test following ACL reconstructions.61-65 However, when the tests were performed in the fatigued state, approximately 70% of the patients failed the tests. Normative data for the LEFT test are included in Table 6.

Imaging

Often imaging studies are indicated in order to facilitate the clinical examination and diagnosis of patellofemoral pain. Commonly used radiographic views may include: AP, Lateral, Long Leg Standing, Insall-Salvanti, Merchant, and or Sunrise views. In selected cases the MRI may be indicated to assist with the definitive diagnosis. Particularly assessing the chondral surfaces of the patellofemoral joint and any soft tissue abnormalities; such as plica syndrome, hoffa’s syndrome, retinacular neuroma’s, etc.

Patient Reported Outcomes

Over the past 10-15 years it has become commonplace to utilize patient reported outcomes so that clinicians can better determine the amount of improvement in symptoms and function described from the perspective of the patient. The authors of this manuscript utilize the Kujala Anterior Knee Pain Scale for orthopedic or sports medicine populations. Both Bennel and colleagues66 and Crossley and colleagues67 have reported adequate reliability of the Kujala scale for clinical use. More recently Ittenbach et al68 have reported to have high internal consistency, equivalence across short and long forms, acceptable standard errors of measurement and moderate to high criterion related validity with use of the Kujala scale.

CONCLUSIONS

Using the guidelines presented in this manuscript the sports physical therapist can utilize the suggestions for examination and define the complicated pathology known as patellofemoral joint dysfunction. Once a clearer diagnosis can be made using procedures outlined in this manuscript, the patient will be able to be treated more appropriately based on their classification of injury type. Because of the perplexity of this pathology it is critical to use a systematic, thorough and all-inclusive examination including careful review of both proximal and distal factors that could be contributing to this problem.

REFERENCES


Table 6. *Suggested Descriptive Normative Data for Functional Tests*

<table>
<thead>
<tr>
<th>Test</th>
<th>Males Absolute</th>
<th>Males Allometric Scaled</th>
<th>Female Absolute</th>
<th>Female Allometric Scaled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double leg jump</td>
<td>Sports Specific Normative data</td>
<td>100% height ±10%</td>
<td>Sports Specific Normative data</td>
<td>90% height ±10%</td>
</tr>
<tr>
<td>Single leg hop</td>
<td>Limb symmetry index (10%)</td>
<td>90% height ±10%</td>
<td>Limb symmetry index (10%)</td>
<td>80% height ±10%</td>
</tr>
<tr>
<td>LEFT test</td>
<td>Average 100s (range: 90-125s)</td>
<td>Not applicable</td>
<td>Average 135s (range: 120-150s)</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>


59. Tabor MA, Davies GJ, Kernozek TW, Negrete RJ, Hudson V. A multicenter study of the test-retest...


ABSTRACT
Patellar tendon pain is a significant problem in athletes who participate in jumping and running sports and can interfere with athletic participation. This clinical commentary reviews patellar tendon anatomy and histopathology, the language used to describe patellar tendon pathology, risk factors for patellar tendinopathy and common interventions used to address patellar tendon pain. Evidence is presented to guide clinicians in their decision-making regarding the treatment of athletes with patellar tendon pain.

Level of Evidence: 5

Keywords: Anterior knee pain, jumper's knee, overuse injury, patellar tendinopathy, patellar tendonitis, patellar tendinosis

CORRESPONDING AUTHOR
Mark F. Reinking, PT, PhD, SCS, ATC
Professor, Dean
School of Physical Therapy
Regis University
3333 Regis Blvd., G-4, Denver, CO 80221
P 303.964.6471 | F 303.964.5474
E-mail: mreinking@regis.edu
INTRODUCTION
Patellar tendinopathy is a common overuse disorder typically occurring in athletes who participate in sports that require jumping, including volleyball and basketball, hence the label “jumper’s knee.”1-6 Cook et al reported that 7% of 14-18 year old junior Australian basketball players had clinical signs of patellar tendinopathy and 26% of the tendons (n=268 tendons, 134 players) showed a region of abnormal tendon tissue based on diagnostic ultrasound (US). A study of 760 adolescent athletes across 16 different sports revealed a prevalence of 5.8% of athletes with patellar tendon pain.8 Ferretti9 reported a 22.8% incidence of patellar tendon pain in a sample of 407 elite volleyball players, and Taunton et al found that 4.8% of 2000 runners had patellar tendon pain.10 Lian, Engebretsen, and Bahr11 studied the prevalence of jumper’s knee in 613 elite Norwegian athletes and reported an overall prevalence of 14.2% with the highest prevalence in volleyball (44.6%) and basketball (31.9%). In a study of 891 non-elite athletes representing seven different sports, the overall prevalence of patellar tendinopathy was 8.5% with the highest prevalence in volleyball athletes (14.4%)

The management of patellar tendon pain has been somewhat complicated by the terminology used to describe the condition. The term “patellar tendonitis” has been used indiscriminately by many health care providers to describe patellar tendon pain. However, multiple histopathologic studies have indicated that the primary pathologic process in most painful tendons is degenerative rather than inflammatory.12-16 Consequently, use of the “-itis” suffix appears to be questionable in describing the tendon pain as inflammatory in nature. Based on histopathology, several authors have suggested that the term “tendinitis” be abandoned in favor of the term “tendinosis”, which describes a degenerative tendon condition.17-19 This distinction regarding tendon pathology was first described by Puddu20 with regard to classifying Achilles tendon pain. In an alternate perspective, Fredberg21,22 has challenged the concept of patellar tendon pain as a degenerative condition, suggesting that a lack of inflammatory cells may not mean the lack of an inflammatory process. Other tissue research has shown the presence of pro-inflammatory chemical agents such as cyclooxygenase, growth factors, and prostaglandin in painful patellar tendons16,23 as well as macrophages and lymphocytes in chronic tendinopathy,24 suggesting that there may be an inflammatory component in patellar tendon pain. In their review of inflammation and tendon pain, Rees, Stride and Scott concluded, “The evidence for non-inflammatory degenerative processes alone as the cause of tendinopathy is surprisingly weak.”25, p1 However, these authors further stated that “We do not advocate going back to the ‘tendinitis’ model, and there is no doubt that a shift away from primarily anti-inflammatory strategies has had great benefit for tendinopathy treatments.”25,p.5 As the language used with patients can have a strong influence on how the patient and practitioner thinks about the condition,26 it is advisable that the language of “patellar tendinitis” be abandoned in favor of patellar tendinopathy to move away from a pure inflammatory mindset.

HISTOLOGY OF THE PATELLAR TENDON
The patellar tendon extends distally from the infrapatellar pole to the tibial tubercle. Some anatomists argue that as the patellar tendon appears to connect the patella and tibia, it should be termed the patellar ligament.6 However, embryologically there is a single tendon attaching the quadriceps to the tibia in which a mesenchymal condensation develops and becomes the patella, a sesamoid bone. The formation of the patella appears to separate the tendon into two regions, the quadriceps and patellar tendons although they are, in fact, a continuous, anatomic tendon entity. In an adult, the patellar tendon is 25-40 mm wide, 4-6 cm long, and 5-7 mm thick.27,28 At the site of attachment of the patellar tendon to bone (tibia and patella), there is a fibrocartilaginous enthesis with four tissue zones - dense fibrous connective tissue, uncalcified fibrocartilage, calcified cartilage, and bone.29 The collagen fibers in the tendon are arranged in a parallel fashion and the tendon appears white. The patellar tendon does not have a well-developed paratenon but the posterior surface of the tendon is intimate with the fat pad, a structure that is highly innervated and vascularized. Duri et al stated, “We believe that the intensity of pain in some patients with patellar tendonitis is related to the involvement of the fat pad.”30,p105

Patellar tendon pathology typically occurs at the enthesis site; in most cases it occurs at the inferior pole of the patella, but it can occur at the tibial tubercle
or at the proximal aspect of the patella in the quadriceps tendon. Macroscopically, the diseased portion of the tendon appears yellow-brown in color and disorganized. Microscopically, the pathology involves both matrix and cellular changes. Histologic examination of pathologic tendon tissue reveals loss of the longitudinal arrangement of collagen bundles, clefts between collagen bundles filled with mucoid ground substance, increased cellularity (fibroblasts), and neovascularization. There is also a loss of the typical demarcation between the calcified and uncalcified fibrocartilage zones at the enthesis, and there may be local foci of abnormal calcification in the tendon as well.

**RISK FACTORS**

Patellar tendinopathy is an overuse injury with the onset typically characterized by no single specific traumatic injury event but gradually increasing tendon pain. The factors that are hypothesized to contribute to the development of overuse injuries are often described in two categories, intrinsic and extrinsic. Intrinsic factors are those contained within a person, including sex, race, genetics, bone structure, bone density, muscle length, muscle strength, joint range of motion, diet, and body composition. Extrinsic factors are those outside of a person, including training volume (frequency, duration, and intensity), types of conditioning activities, specific sport activity, training surface, shoes, and environmental conditions.

Ferretti studied the factors associated with the development of patellar tendon pain in volleyball players. She found a direct relationship between the number of weekly training sessions and the percentage of players with patellar tendon pain, but there was no difference with respect to type of training (weight training versus plyometrics). She also found an influence of training surface; there was a greater incidence of patellar tendon pain in the athletes who trained on concrete courts as compared to wood surfaces. Examining intrinsic factors including sex, age, knee alignment, Q-angle, patellar position, femoral version, hypermobility, foot morphology, and body morphotype, the author found no consistent relationship between these factors and patellar tendon pain. Based on her findings, Dr. Ferretti concluded that extrinsic factors were more significant in the cause of patellar tendon pain as compared to intrinsic factors. Visnes and Barr conducted a four-year prospective cohort study with a sample of elite adolescent volleyball athletes and found the athletes who developed jumper’s knee had greater total training volume and greater match exposure as compared to those athletes who were asymptomatic.

Sport specialization has been reported as a risk factor for patellar tendinopathy. Hall et al completed a retrospective cohort study of 546 middle and high school athletes (basketball, soccer, and volleyball) and found a four time greater risk of developing patellar tendinopathy in single sport athletes as compared to multi-sport athletes.

Witvrouw et al examined the influence of selected intrinsic factors on the development of patellar tendon pain including anthropometric variables, leg alignment, flexibility, and muscle strength. In a group of 138 college physical education students followed over a two-year period, 19 developed patellar tendon pain. Using stepwise logistic regression, these researchers found the only variables associated with the development of patellar tendon pain were decreased quadriceps and hamstring flexibility. Mann et al also found limited quadriceps flexibility to be a risk factor for patellar tendon abnormality based on US imaging. Limited hamstring flexibility as a risk factor for patellar tendinopathy was supported by Cook et al in their study of elite junior basketball players. Two groups of investigators have found the intrinsic variable of leg-length inequality to be associated with patellar tendon pain.

Intrinsic factors with regard to patellar tracking and patellar position have been described as associated with patellar tendon pain. Kujala et al reported an association between patella alta and jumper’s knee. Allen et al studied the relationship between patellar tracking (evaluated with dynamic magnetic resonance imaging (MRI) and patellar tendinopathy as identified by the presence of high signal intensity in the patellar tendon. The authors reported 45% of the patients with patellar tendinopathy had abnormal tracking as compared to 29% of the patients without MRI-identified patellar tendon changes.

Several authors have considered the effect of performance characteristics on the development of patel-
The authors reported that nine factors had “some” evidence to support them as risk factors for patellar tendinopathy although none has strong evidence to support. These factors included weight, body mass index, waist-to-hip ratio, leg-length difference, arch height of the foot, quadriceps and hamstring flexibility, quadriceps strength and vertical jump performance.

**INTERVENTIONS FOR PATELLAR TENDINOPATHY**

The intervention plan for patellar tendon pain should be based on an evidence-based approach which incorporates the clinical judgment of the clinician, the patient's values, and the best available evidence. Although patellar tendinopathy is a relatively common condition in athletes, there is very little high-level evidence to support interventional choices. Consequently, the clinician's clinical reasoning should be based on impairments identified in the examination, which are related to the patient's activity and participation limitations. Based on the current histopathologic knowledge, it appears inappropriate to focus intervention solely on an inflammatory process in the tendon; rather, the intervention should be focused on tendon healing and strengthening and return of the patient to their preferred functional activities. Knowledge of the evidence-based risk factors for patellar tendinopathy can be of assistance in considering the appropriate interventions for a specific patient.

Initially, reducing load on the painful tendon is indicated to minimize further progression of pathology. Given that substantially decreasing tendon load has a negative effect on tendon strength, load reduction can be accomplished by a decrease in the overall training volume of the activity rather than completely resting the tendon. The training volume parameters – intensity, frequency, or duration – should be evaluated and adjusted based on the athlete and the circumstances of the clinical case. To maintain cardiovascular and pulmonary fitness, cross training activities that involve lower loads on the tendon are appropriate. For athletes in jumping sports such as volleyball and basketball, this may involve the use of cycling, swimming, or pool running rather than overground running and jumping.

Decision-making regarding therapeutic exercise should be based on the presence of muscle strength.
or length impairments identified in the examination. Based on the work of Witvrouw et al, Cook et al, and Mann et al, decreased hamstring and quadriceps length may be associated with patellar tendon pain. These findings suggest that if a quadriceps or hamstring muscle length impairment exists, muscle stretching exercises are indicated. Dimitrios, Pantelis, and Kalliopi found that the addition of hamstring and quadriceps stretching to an eccentric exercise program was superior in outcomes (pain and function) to eccentric exercise alone for patients with patellar tendinopathy.

The mainstay in the treatment of patellar tendinopathy over the past two decades has been eccentric quadriceps exercise, although the strength of evidence to support eccentric exercise for tendon pain varies across the specific tendons. The seminal work on the use of eccentric exercise in patients with patellar tendon pain was done by Curwin and Stanish. They advocated the use of drop squats (Figure 1) to maximally stress the tendon to increase tendon strength. Their program involved six weeks of training, progressing in the first week from a slow speed to faster speeds, and then adding resistance in weeks two through six. During the six-week training period, the patients were to perform three sets of 10 repetitions daily; after the sixth week the training was reduced to three times weekly. In a retrospective review of 66 patients treated with the eccentric program for patellar tendon pain, the authors reported complete relief of pain in 20 patients, marked decrease in symptoms in 42 patients, and four patients reported worsening of symptoms.

Jensen & DiFabio evaluated the effect of open kinetic chain (OKC) isokinetic eccentric training on quadriceps strength in two groups of subjects, healthy volunteers (n=16) and patients with patellar tendon pain (n=15). Each group of subjects was subdivided into two groups, one group that did a home stretching program and one group that completed an isokinetic eccentric training program three times per week for eight weeks. Their results showed an improvement in isokinetic eccentric work over the training period. Karlsson et al described a conservative treatment program for a group of 81 patients with patellar tendon changed as evidenced by hypoechoic lesions on US evaluation. The training program was divided into three phases, an acute phase, a rehabilitation phase, and a return to activity phase. The rehabilitation and return to

Figure 1. Drop-squat exercise, start position on left, finish on right.
activity phases included OKC eccentric knee extension exercise. They reported that 70% of the patients with patellar tendon pathology had excellent outcomes with their rehabilitation program. Cannell et al\textsuperscript{61} used a randomized controlled trial design to compare the effect of drop squats and OKC concentric leg extension/leg curl exercises in patients with jumper's knee. Over a 12-week training period, both modes of strengthening resulted in decreased tendon pain and there was no difference in the numbers of athletes returning to sport activities.

High-load eccentric training has been used successfully to treat Achilles tendinopathy.\textsuperscript{56} One feature of this eccentric training is the criticality of tendon pain during the eccentric exercise. According to the work of Alfredson et al.\textsuperscript{12,56,59} the eccentric exercise should be painful to perform, and when a patient reaches the point that the exercise is no longer painful; the load should be increased to the point that it becomes painful again. In a pilot study of eccentric exercise, Purdham et al\textsuperscript{71} compared standard squat and decline squat training (Figure 2) in athletes with patellar tendon pain. The exercise load was adjusted so that the exercises were always performed with some pain or discomfort.\textsuperscript{59}

Figure 2. Single leg decline squat.

Six of eight athletes in the decline group returned to sport, and only one of nine athletes in the standard squat group returned to sport. The authors concluded that the decline squat was superior to the standard squat training in treating patellar tendinopathy, but acknowledged that the sample size was small and it was not a randomized design. Other investigators have also reported the effectiveness of eccentric decline squats in the treatment of patellar tendinopathy.\textsuperscript{66,72-75}

Stimulated by the mounting evidence that supported use of the decline squat in the treatment of patellar tendon pain, several investigators have examined the biomechanics of the decline squat. Comparing tendon loading in the standard squat versus the decline squat (25° decline board), two studies have shown significantly greater patellar tendon loading and quadriceps activation in the decline squat.\textsuperscript{76,77} Zwerver, Bredeweg, and Hof\textsuperscript{78} examined patellar tendon loading and patellofemoral loading at different angles of decline and with/without a 10 kg backpack. Their data supported the earlier work that patellar tendon loading increases as the decline angle increases, and at angles of knee flexion higher than 60°, the patellofemoral forces rose at a higher rate than the tendon forces. The addition of the 10kg backpack caused even higher tendon loading. The authors recommended the use of a decline board between 15° and 30° decline but to keep knee flexion less than or equal to 60° to avoid excessive loading of the patellofemoral joint.

What remains unknown at this time is the optimal dosage of the decline squat eccentric training program. In the original work on high load eccentric training of the Achilles, Alfredson et al.\textsuperscript{56} used a protocol of 3 sets of 15 repetitions twice daily for 12 weeks. Most of the research on the decline squat has used the same exercise prescription, with the additional instruction to the patient to increase the load on the tendon if the exercise becomes painfree. Generally, the recommendation is that the patient should have tendon pain greater than 0 and less than 5 on a 0-10 pain scale during the single leg decline squat. As other investigators have used a lower volume of eccentric training (3-5 days/week) with similar outcomes,\textsuperscript{61,79} there is not a clear answer to the question of optimal dosage for eccentric exercise in patellar tendinopathy.
A second exercise approach that has been used for patellar tendinopathy is heavy slow resistance (HSR) training. In this exercise approach, exercise equipment is used for squats and leg press with heavy resistance. Kongsgaard et al\textsuperscript{72} compared this approach to decline squats and corticosteroid injections to the tendon. They found that both exercise groups improved significantly more than the injection group, and there was no difference in the outcomes of the two groups. One must have to consider, though, that the HSR training approach requires gym equipment and substantial weight resistance whereas the decline squat training only requires a squat board and sufficient hand-held or vest weight to load the tendon to pain.

A consideration regarding intervention for athletes with patellar tendinopathy is addressing the mechanics of jumping. The combined movements of the segments in the lower extremity kinematic chain serve both as the primary propulsive force in jumping as well as the deccelerative forces in landing from a jump. The research of Richards et al\textsuperscript{45} highlights the influence of knee dynamics on the development of patellar tendon pain. Although there is presently no strong evidence to support or refute jump training for athletes with patellar tendon pain, there is evidence that ground reaction forces in jumping can be decreased with instruction.\textsuperscript{80-83} Whether such training and improvement in the shock absorbing capacity of the lower extremity can affect patellar tendon pain needs to be subjected to further investigation. A recent case report\textsuperscript{84} described the use of a landing strategy modification and hip extensor training for a male volleyball athlete with the athlete able to return to sport without tendon pain.

Transverse friction massage (TFM) is a technique that was advocated by James Cyriax\textsuperscript{85} for tendon pain. This technique is purported to reduce adhesions within the tendon and encourage normal realignment of collagen fibers. There is basic science evidence from animal studies that soft tissue mobilization can increase fibroblastic activity,\textsuperscript{86,87} but there are no studies of the effect of TFM on patellar tendinopathy tissue in humans. Pellechia, Hamel, and Behnke\textsuperscript{88} compared a protocol of TFM and modalities with iontophoresis in the treatment of infrapatellar tendinitis. The TFM/modality group showed an increase in number of step-ups to elicit patellar tendon pain, but as this treatment group received a combined intervention, it cannot be concluded whether the effect was from the TFM, modalities, or combination. In a systematic review on the use of TFM for treatment of “tendonitis” (all anatomic types), the authors concluded that there was no evidence to support the use of deep TFM.\textsuperscript{89} In a study that compared the effect of eccentric exercise, therapeutic US, and transverse friction massage in the treatment of patellar tendon pain,\textsuperscript{79} the investigators found eccentric exercise to be far superior in decreasing pain at the end of treatment and after a three-month follow-up. Both the therapeutic US group and the transverse friction group had poor outcomes with 20% or less of the patients in those groups having a reduction in pain.

Although modality use is commonly employed in physical therapy clinics for patients with patellar tendinopathy, there is very little supporting evidence. Cryotherapy is commonly used in the clinic to treat pain and swelling and may be appropriate for patient use following a session of painful exercise. In a review of modality use for tendon pain, Rivenburgh\textsuperscript{90} describes cryotherapy as having some tissue effects such as decreasing the movement of protein from capillaries and may decrease blood flow. Kaux et al\textsuperscript{91} described a protocol for the treatment of patellar tendinopathy following platelet-rich plasma injection including cryotherapy, sub-maximal eccentrics, electrical stimulation, proprioceptive retraining, and stretching. Although the patient outcomes of the protocol were positive, the contribution of the cryotherapy after each session is unknown. Consequently, there is no direct evidence to either support or refute its use with regard to the outcome of intervention for patellar tendon pain.

Therapeutic ultrasound (US) is also a commonly utilized clinical modality for tendon pain. However, like cryotherapy, there is no direct evidence to support its use in patellar tendon pain. Therapeutic US has been shown to have positive effects on collagen production in vitro\textsuperscript{92}, but no in vivo studies were located. It has also been shown to have a significant thermal effect when using a 3 MHz treatment at 1.0 W/cm\textsuperscript{2},\textsuperscript{93} but whether this is desirable for healing of tendon pain is not known. In their systematic review
of the treatments for patellar tendinopathy, Larsson, Käll, and Nilsson-Helander concluded, "Ultrasound can likely be excluded as a treatment for patellar tendinopathy." 94, p. 1

Phonophoresis is a technique in which US is used to drive a pharmaceutical agent through the skin into a painful region. Klaiman et al.95 compared the effect of US and phonophoresis using fluocinonide (a corticosteroid) on various musculoskeletal conditions including tendon pain. They found that US alone decreased pain and increased pressure tolerance, but the addition of fluocinonide did not augment the effect. Pendergast, Kimura, and Gulick96 also examined the effect of the addition of phonophoresis to a stretching and strengthening program for patients with tendon pain. Of the 24 athletes in the study, nine had "knee tendinitis." Their results were consistent with those of Klaiman et al.95 that phonophoresis with dexamethasone/lidocaine did not appear to augment pain relief associated with exercise intervention. These studies do not support the use of phonophoresis for patients with patellar tendon pain.

Another modality that is used clinically for tendon pain is iontophoresis. This technique is similar to phonophoresis in terms of driving a pharmaceutical agent across the skin, but the motive force in iontophoresis is a direct electric current. There is evidence from an animal study that iontophoresis is effective in driving dexamethasone into patellar tendon tissue.97 Research by Pellecchia et al.98 showed that iontophoresis with dexamethasone and lidocaine was more effectiveness than modalities/TFM for decreasing pain and increasing function in patients with patellar tendon pain. However, the use of iontophoresis as a motive force to drive dexamethasone into tendon tissue is based on an inflammatory mindset of tendinopathy, which does not focus on the return of an athlete to their sporting activity.

One common intervention used for patients with patellar tendon pain is the use of counterforce bracing or taping. In spite of the very common use of this intervention, very limited evidence exists to support its use. Miller, Hinkin, and Wisnowski98 focused on the effect of counterforce bracing on knee pain in military trainees. While their results did not support use of counterforce bracing for "anterior knee pain" in the research subjects, no specific mention was made of patellar tendon pain. Recently, a randomized controlled trial compared the effect of a patellar strap, patellar taping, and sham taping on patellar tendon pain in a group of subjects with patellar tendinopathy.99 The investigators found a decrease in patellar tendon pain with a single leg decline squat and during sport activity when taped or braced as compared to no tape or brace. However, there was no difference between taping, sham taping, and bracing.

Foot orthoses are also commonly suggested for patients with patellar tendon pain, but there is no direct evidence to support or refute their use. Two investigations have suggested that a hyper-pronated foot is a risk factor for patellar tendon pain,49,100 and from these data, clinicians may infer that controlling the pronation of the foot with an orthotic will decrease the risk of developing patellar tendon pain. However, such cause and effect evidence is lacking at the present time.

As tendon pathology has been historically labeled as tendinitis, an inflammatory condition, it is not surprising that anti-inflammatory medicines are commonly prescribed for patients with tendon pain. This includes the use of oral non-steroidal anti-inflammatory medicines (NSAIDs) and injections of corticosteroids. In a systematic review of the literature on treatment of tendinitis, Almekinders and Temple101 reported that the use of oral NSAIDs may result in some pain relief but the effect on the tendon is not known as the follow-up time in all the studies was less than one month. Similarly, the use of injected corticosteroids may also result in pain relief in tendinopathy, but there is concern regarding the effect of corticosteroid on tendon strength.102,103 Fredberg et al.12 conducted a randomized, double-blind, placebo-controlled study of steroid injection in patients with patellar and Achilles tendinopathy. Forty-eight patients with chronic tendon pain who had not responded to conservative intervention served as subjects, 24 with Achilles tendon pain and 24 with patellar tendon pain. Using US guided percutaneous injection into the tendon, half of each group of patients received steroid and the other half received an identical looking placebo injection. Out-
come measures were tendon thickness measured by US and pressure algometry. The authors found a significant reduction in pain and tendon thickness comparing the steroid and placebo groups for both Achilles and patellar tendon pain. An interesting finding in this study is that only one-third of the painful tendons showed hypoechoic regions in the US examination. In a follow-up letter to this study, Fredberg\textsuperscript{21} argued that the results of this study suggest that the tendinitis-tendinosis question remains unresolved. He stated, “the most obvious explanation of the significant reduction in tendon thickness and pain after only one week can most likely be explained by a reduction in an inflammatory process, and not because of a change in a pure degenerative process.”\textsuperscript{21(P270)}

A new challenge to the injection of corticosteroids into the patellar tendon was revealed in a recent study on the effect of dexamethasone on patellar tendon stem cells.\textsuperscript{104} These authors found that the dexamethasone had a “paradoxical” effect on the tendon stem cells, inducing them to differentiate into non-tenocytes including chondrocytes and adipocytes. This evidence suggests that injection of dexamethasone into a tendon may lead to the formation of non-tendon tissue within the tendon, ultimately weakening the tendon.

In cases of recalcitrant patellar tendon pain, other options for treatment include injectables (platelet-rich plasma, whole blood, aprotinin), glyceryl trinitrate patch, extracorporeal shock wave therapy, and surgery. As these interventions are the purview of the physician, they are not presented in this commentary. Several recent reviews provide the background and evidence relative to these interventions.\textsuperscript{67,84,105}

**CONCLUSION**

Patellar tendinopathy is a common overuse condition seen among athletes, particularly those who participate in jumping sports. The management of this condition has continued to challenge health care professionals as the pathology and risk factors have not been fully elucidated. Based on the current literature and collective clinical wisdom, effective conservative intervention includes relative rest, stretching, and movement retraining. Other interventions including TFM and counterforce bracing are commonly employed, but have weak or little evidence to support their use. In the case of persistent tendon pain, which interferes with functional activities, injectables or surgery may be indicated. Further research is necessary to advance our understanding of the etiology of tendon pathology and our knowledge about the effectiveness of conservative and surgical interventions.

**REFERENCES**

12. Alfredson H, Lorentzon R. Chronic tendon pain: no signs of chemical inflammation but high concentrations of the neurotransmitter glutamate.


40. Witvrouw E, Bellemans J, Lysens R, Danneels L, Cambier D. Intrinsic risk factors for the development of patellar tendinitis in an athletic population. A


ABSTRACT

Patellofemoral instability is a painful and commonly recurring condition, which often must be managed surgically. Diagnosis can be aided by the use of a variety of physical exam signs, such as the Q angle, Beighton hypermobility score, glide test, J sign, patellar tilt test, and apprehension test. Imaging modalities including x-ray, CT, and MRI guide both diagnosis and management by revealing trochlear dysplasia, bony malalignment, and ligamentous injury that contribute to instability. Following an initial patellar dislocation, nonoperative management with bracing and physical therapy is an acceptable option, despite limited evidence that operative management may improve functional outcome and reduce recurrent dislocations.

For recurrent dislocations, operative management is indicated, and the appropriate procedure depends on the patient's anatomy and the cause of instability. Reconstruction of the medial patellofemoral ligament (MPFL) restores the primary soft tissue restraint to lateral patellar dislocations, and can be performed using a variety of techniques. In patients whose instability is related to bony malalignment, a tibial tubercle osteotomy is commonly performed to realign the extensor mechanism and establish proper patellar tracking. In patients with trochlear dysplasia, a trochleoplasty may be performed to create a sufficient groove for the patella to traverse. Often these procedures must be combined to address all causes of instability. The reported outcomes following all three of these procedures are generally very good, with the majority of patients experiencing functional improvements and a low rate of recurrent instability, although more large randomized controlled trials are needed to determine which techniques are most effective. The purpose of this clinical commentary is to provide an overview of the current methods employed by orthopedic surgeons to diagnose and manage patellar instability.

Level of Evidence: 5

Keywords: knee instability, patella, trochlea, patellofemoral, patella alta, medial patellofemoral ligament
INTRODUCTION
Recurrent patellofemoral instability is a painful and often chronic condition following dislocation of the patella from its position within the trochlear groove. This condition has been estimated to affect 5.8 per 100,000 individuals and is more prevalent among females and 10-17 year olds (29 per 100,000).1 Once a single dislocation has occurred, patients are nearly seven times more likely to experience subsequent dislocations.1 Patellar dislocations are commonly associated with damage to articular cartilage, which can lead to chronic knee pain.2,3 Patellar instability has been associated with a number of anatomical factors including: ligamentous laxity, genu valgum, femoral anteverision, excessive tibial torsion, trochlear dysplasia, patella alta, and insufficiency or rupture of the medial patellofemoral ligament (MPFL). Patellofemoral instability often responds poorly to nonoperative management and must be addressed surgically. The purpose of this clinical commentary is to provide an overview of the current methods employed by orthopedic surgeons to diagnose and manage patellar instability.

CLINICAL EVALUATION
History and Physical Exam
The first step in managing a patient with patellofemoral instability is to perform a thorough clinical evaluation. Critical elements of the patient’s history include the precise mechanism of injury and whether this was their first dislocation. If patients have experienced recurrent instability, they should be questioned about the frequency, mechanism, duration, and prior management of these events.

There are a number of physical exam signs and maneuvers which can help diagnose patellofemoral instability.4 Knee alignment should be assessed, particularly for presence of genu valgum. The Q angle is an important indicator of knee alignment; it comprises the angle between a line drawn from the anterior superior iliac spine to the center of the patella and line from the center of the patella to the tibial tubercle (Figure 1). This angle is typically larger in women, 15-20° compared to 10-15° in men. An abnormally large Q angle imposes a lateral direction of force on the extensor mechanism, causing a predisposition for lateral patellar instability and dislocation.

The Beighton hypermobility score can be obtained to assess for overall generalized ligamentous laxity.5 This involves a 9-point scale on which a score greater than 5 indicates hypermobility; one point is assigned for each of the following findings: passive hyperextension of each small finger >90°, passive abduction of each thumb to the volar/radial surface of the forearm, hyperextension of each elbow >10°, hyperextension of each knee >10°, and forward flexion of the trunk with the ability to place both palms flat on the floor with full knee extension.5 The passive patellar glide test is a simple maneuver to evaluate for patellar hypermobility. With the patient supine and the knee in extension, the examiner pushes the patella medially and laterally; the patella is divided into four vertical quadrants, and a glide longer than the width of three quadrants is consistent with hypermobility. The J-sign is demonstrated when the patient sits on the edge of the examination table and moves their knee from a position of flexion to extension; in patients with a tight lateral retinaculum, the patella may appear to shift laterally as the knee extends. The patellar tilt test can also be performed to identify a tight lateral retinaculum. With the patient supine and the knee in extension, the examiner pushes on the...
patella in an attempt to flip the lateral edge upwards. In a normal patient, the lateral edge may elevate up to 20°; however, in a patient with a tight lateral retinaculum, the lateral edge will not elevate past neutral. The apprehension test is another useful test for instability; it is performed with the patient supine and the knee extended. The examiner pushes the patella laterally as though to dislocate it. The test is considered positive when the patient verbally expresses apprehension or involuntarily contracts the quadriceps to maintain stability. Finally, Bassett's sign may indicate a rupture of the MPFL; it consists of pain with palpation of the adductor tubercle, which is the femoral attachment of the MPFL.4

**Diagnostic Imaging**

Imaging also plays a critical role in the diagnosis and management of patellofemoral instability. Imaging should begin with weight bearing anteroposterior (AP), posteroanterior (PA) (45° flexion), and true lateral (30° flexion) radiographs of the knee. AP and PA views are valuable for assessing knee alignment and congruity, while the lateral view provides insight into patellofemoral anatomy. Trochlear dysplasia can be appreciated on a true lateral view. The crossing sign occurs when a line drawn along the floor of the trochlear groove crosses the anterior surface of the femoral condyles (Figure 2).6,7 Other signs of trochlear dysplasia include a trochlear depth less than 4 mm and an anterior trochlear bump greater than 3 mm.7 Patella alta can also be noted on the lateral view. There are a number of methods for measuring patella alta.8 On a true lateral view, Blumensaat's line (along the roof of the intercondylar femoral notch) will normally meet the inferior pole of the patella (Figure 3A). The Insall-Salvati index is obtained by dividing the length of the patellar tendon by the length of the patella; the normal range is between 0.8 and 1.2, with an index >1.2 indicating patella alta (Figure 3B).9 Alternative methods for identifying patella alta include the Caton-Deschamps, Blackburne-Peel, and the modified Insall-Salvati indices.10-12

A Merchant view is also useful for identifying patellar tilt, trochlear dysplasia, and lateral subluxation; this view is obtained with the knee in 30° flexion and the beam directed distally to view the patella as it sits within the trochlear groove.13 Patellar tilt can be evaluated by measuring the lateral patellofemoral angle, which is formed by a line drawn between the anterior points of the medial and lateral femoral condyles, and a line that goes along the lateral articular facet of the patella (Figure 4B). Normally these lines open laterally; however, the lines may be parallel or open medially in the presence of abnormal patellar tilt. The sulcus angle is the angle between two lines drawn from the medial and lateral condyles to the deepest part of the intercondylar sulcus (Figure 4C).14 A normal sulcus angle is approximately 36°.

**Figure 2.** The crossing sign and a shallow trochlea are indicators of trochlear dysplasia.

**Figure 3.** Blumensaat’s line (A), the Insall-Salvati ratio, and Caton index (B) can be used to identify patella alta.
of the tibial tuberosity and the trochlear groove and measuring the medial-lateral distance between the tibial tuberosity and the deepest point of the trochlear groove. A TT-TG distance >15-20 mm is generally considered abnormal; an increased TT-TG has been associated with instability, as it represents a lateralized insertion of the patellar tendon relative to the trochlear groove. Additionally, MRI is useful for identifying injuries to the MPFL and articular cartilage. MRI may reveal whether the etiology of a patient's instability is bony or ligamentous in nature, dictating which surgical intervention is most appropriate.

**TREATMENT**

**Nonoperative Management**

Conservative management is most appropriate in patients who have experienced their first episode of instability and have no evidence of an osteochondral injury. A variety of rehabilitation protocols have been described, ranging from full mobilization with a bandage or neoprene sleeve to short-term immobilization with a brace or a cast. Physical therapy is also commonly recommended to improve neuro-muscular control of the knee; exercises should focus on stretching, range of motion, and strengthening, particularly of the quadriceps muscles. A number of small randomized controlled trials have compared the outcomes of nonoperative versus operative management of primary acute patellar dislocations. These studies have provided mixed results; some have reported no significant difference in the rate of

130-140°; abnormal values have been associated with trochlear dysplasia. The congruence angle is measured by drawing a line that bisects the sulcus angle and another line from the apex of the sulcus angle to the deepest point of the patellar articular surface; the angle between these two lines is considered negative if it is medial to the line bisecting the sulcus and positive if it is lateral to this line (Figure 4A). An angle greater than -6° has been associated with lateral patellar subluxation.

Advanced imaging modalities such as magnetic resonance imaging (MRI) and computed tomography (CT) provide valuable information that may guide surgical interventions. Osseous anatomy and limb alignment can be assessed by both MRI and CT. The tibial tuberosity-trochlear groove (TT-TG) distance is a useful indicator of malalignment (Figure 5). This can be assessed by superimposing two axial images

![Figure 4. The congruence angle (A), lateral patellofemoral angle (B), and sulcus angle (C) are used to evaluate patellar tilt.](image)

![Figure 5. The TT-TG distance can be used to determine the presence of bony malalignment.](image)
recurrence or subjective functional outcome (Kujala score). However, others have reported significantly lower rates of recurrence and improved outcomes with surgery. A Cochrane meta-analysis reported a significant risk reduction for recurrent dislocation (RR = 0.53, 95% CI: 0.33-0.87) and higher Kujala scores (mean difference 13.93, 95% CI: 5.33-22.53) at 2-5 years for patients undergoing operative treatment; although the authors cautioned that the quality of this evidence was poor due to the limitations of available data. The overall rate of recurrence in this meta-analysis was 24% for nonoperative patients and 13% for operative patients at 2-5 years after initial injury. However, there is currently no consensus regarding the utility of nonoperative management, and it remains an acceptable option in patients with a primary acute patellar dislocation.

**MPFL Reconstruction**

The MPFL is a major soft tissue restraint to lateral patellar translation when the knee is in 0-30° of flexion, and it is commonly injured during a patellar dislocation. Its femoral origin lies 1 cm distal to the adductor tubercle, approximately 9 mm proximal and 13 mm posterior to the medial epicondyle, and it inserts along the superomedial border of the patella. Reconstruction or repair of the MPFL is indicated in patients who have a torn or incompetent MPFL and those who have recurrent instability without evidence of bony malalignment. Techniques utilizing various grafts and fixation methods have been described; however, the goal with all reconstructions is to restore the soft tissue restraint to lateral patellar motion. A diagnostic arthroscopy should also be performed before MPFL reconstruction to identify any osteochondral lesions or loose bodies.

One method of MPFL reconstruction involves a hamstring autograft being passed through a patellar bone tunnel. A hamstring tendon such as the gracilis or semitendinosus is harvested from the distal insertion on the pes anserinus. A bone tunnel is then drilled from the anterosuperior surface to the midpoint of the medial surface of the patella, and the graft is passed through. The femoral attachment of the MPFL is then identified proximal and posterior to a line joining the medial epicondyle and adductor tubercle. A hole is drilled into the femur, the graft is inserted, and its positioning is checked at 30° flexion. If the graft is tight in flexion, the insertion site is either too proximal or anterior; whereas, if the graft is loose in flexion, the insertion is either too distal or posterior. The graft should not be tensioned, as this may interfere with knee range of motion and impose harmful joint reactive forces. Once optimal positioning has been achieved, the graft is fixed into the femur using an interference screw.

Another method also makes use of a hamstring autograft, except the graft is fixed to the patella with suture anchors rather than via a bone tunnel (Figure 6). In this procedure, a gracilis or semitendinosus graft is harvested from its distal insertion. The superomedial border of the patella is then exposed and two suture anchors are inserted. The graft is then placed through the suture anchors and tightened down. The femoral origin of the MPFL is identified, a hole is drilled, and the graft is positioned and fixed using an interference screw.

Alternatively, the quadriceps tendon may be used to create a new MPFL. This method involves separating a strip of the quadriceps tendon and releasing

---

**Figure 6. An illustration demonstrating MPFL reconstruction.**
involves altering the position of the tibial tubercle on the tibia, thereby realigning the extensor mechanism of the knee and correcting malalignment and instability. This procedure is indicated in patients with recurrent instability who have an increased T-TG distance, patella alta, or high grade osteochondral lesions in the patellofemoral joint.

One of the most prominent surgical techniques is the anteromedialization osteotomy described by Fulker-son et al. This procedure is indicated for patients with instability due to maltracking, particularly those who have an increased T-TG distance, patella alta, or patellofemoral osteochondral lesions. The procedure involves making a bony cut beneath the tibial tubercle, translating the fragment anteromedially 1-2 cm, and fixing it in place with screws (Figure 7). If patella alta is present, distalization may also be performed to restore proper patellar tracking.

Medialization of the tubercle, also known as the Elmslie-Trillat procedure, is an option to address maltracking in patients without patella alta. Although authors generally report positive outcomes for MPFL reconstruction, the numerous techniques currently being used complicate the comparison between studies; more large randomized controlled trials are needed to determine whether any technique is superior to others.

Tibial Tubercle Osteotomy
Tibial tubercle osteotomy is another option for treating patients with patellofemoral instability. This procedure involves altering the position of the tibial tubercle on the tibia, thereby realigning the extensor mechanism of the knee and correcting malalignment and instability. This procedure is indicated in patients with recurrent instability who have an increased T-TG distance, patella alta, or high grade osteochondral lesions in the patellofemoral joint.

A number of studies have reported the outcomes of patients who have undergone some form of MPFL reconstruction. Outcomes are generally positive, with most authors reporting improvements in pain and functional outcome and a low incidence of recurrent dislocation. Complications most often arise from poor graft positioning, which can cause abnormal joint forces that result in cartilage damage, pain, and graft failure; other complications include patella fracture and stiffness. A meta-analysis of 320 patients in nine studies examining outcomes after MPFL reconstruction with a double-bundle hamstring tendon autograft reported a mean postoperative Kujala score of 92.0/100 (Standard error = 1.4, p = 0.001) and a complication rate of 12.5%, with stiffness being the most common complaint. However, the authors cautioned that the study was limited by small and limited design of many existing studies. Although authors generally report positive outcomes for MPFL reconstruction, the numerous techniques currently being used complicate the comparison between studies; more large randomized controlled trials are needed to determine whether any technique is superior to others.

Figure 7. An illustration and AP and lateral radiographs demonstrating a tibial tubercle osteotomy.
minimized by proper surgical technique but include tibia fracture, overmedialization, nonunion, painful hardware, and wound complications.\textsuperscript{62-65}

**Trochleoplasty**

Various procedures exist to alter the bony architecture of the trochlear groove, including proximal open trochleoplasty, deepening trochleoplasty, and trochlear lengthening osteotomy. Since trochlear dysplasia has been found in 85\% of patients with recurrent patellofemoral instability, these surgical techniques may be of benefit for specific patients.\textsuperscript{7} Some experts consider trochleoplasty to be a salvage procedure and recommended in cases of severe trochlear dysplasia, given the associated pain and technical complexity.\textsuperscript{66} Specific indications include patients with a flat or convex lateral trochlear facet with hypoplasia of the medial trochlear facet, in the presence of normal or near normal articular cartilage. Normal or near normal articular cartilage within the trochlear groove is required to allow for successful reshaping.\textsuperscript{67,68} A trochleoplasty is contraindicated in patients with open physes or those with diffuse patellofemoral arthritis.\textsuperscript{69} This procedure is also contraindicated in patients with patellofemoral pain with no history of patellar dislocation.\textsuperscript{69}

There are a number of trochleoplasty techniques that have been described in the literature. Proximal open trochleoplasty is used in cases where instability is related to a supratrochlear spur. The goal of this procedure is to create a concave surface on the proximal trochlea.\textsuperscript{70} A line is measured from the proximal trochlea distally to the top of the center of the intercondylar notch and a V-shaped outline is formed on the trochlear groove; this serves as a guide for the removal of cartilage and bone.\textsuperscript{67} A deepening trochleoplasty may be done to address a shallow trochlear groove. This procedure is performed by elevating the articular cartilage from the femur and using a burr to deepen the sulcus; the sulcus may also be narrowed and lateralized to improve patellofemoral tracking (Figure 8).\textsuperscript{69} The supratrochlear spur is also removed, and the cartilage flap is then secured with biocompression screws or suture anchors through the medial and lateral trochlear facets.\textsuperscript{68,69,71} In patients who have a hypoplastic lateral trochlea, a trochlear lengthening osteotomy may be appropriate.\textsuperscript{72} This procedure involves lengthening the lateral trochlear facet by means of an osteotomy; the facet may also be elevated by inserting cancellous autograft.\textsuperscript{67,70}

Complications associated with trochleoplasty include overcorrection, arthritis as a result of damage to the trochlear cartilage, and arthrofibrosis.\textsuperscript{68} There are varying reports with regard to the incidence of postoperative stiffness, which is likely correlated to the postoperative rehabilitation protocol instituted by the operating surgeon.\textsuperscript{73} The risk of intraarticular fracture at the patellofemoral joint has been described in the literature as well, and has a higher likelihood of occurrence in older patients with degenerative changes at baseline.\textsuperscript{53,73}

**SUMMARY**

Following an initial patellar dislocation, nonoperative management with bracing and physical therapy is an acceptable option, despite limited evidence that operative management may improve functional outcome and reduce recurrent dislocations. For recurrent dislocations, operative management is indicated, and the appropriate procedure depends on the patient's anatomy and the cause of instability. Reconstruction of the MPFL restores the primary soft tissue restraint to lateral patellar dislocations, and can be performed using a variety of techniques. In patients whose instability is related to bony malalignment, a tibial tubercle osteotomy is commonly performed to realign the extensor mechanism and establish proper patellar tracking. In patients with trochlear dysplasia, a trochleoplasty may be performed to create a sufficient groove for the patella to traverse. Often these procedures must be combined to address all causes of instability. The reported outcomes following these three procedures are generally very good, with the majority of patients experiencing functional improvements and a low rate of recurrent instability. Many of
the reported postoperative complications are related to technical errors in surgery that generate abnormal joint forces. Although there are many studies demonstrating the benefits of operative management for patellar instability, there is considerable heterogeneity among surgical techniques, and larger randomized controlled trials are needed to determine the most effective methods for managing this complex condition.

REFERENCES


25. Camanho GL, Viegas Ade C, Bitar AC, Demange MK, Hernandez AJ. Conservative versus surgical treatment for repair of the medial patellofemoral...


ABSTRACT

Patellofemoral pain (PFP) has historically been a complex and enigmatic issue. Many of the factors thought to relate to PFP remain after patients' symptoms have resolved making their clinical importance difficult to determine. The tissue homeostasis model proposed by Dye in 2005 can assist with understanding and implementing biomechanical interventions for PFP. Under this model, the goal of interventions for PFP should be to re-establish patellofemoral joint (PFJ) homeostasis through a temporary alteration of load to the offended tissue, followed by incrementally restoring the envelope of function to the baseline level or higher.

High levels of PFJ loads, particularly in the presence of an altered PFJ environment, are thought to be a factor in the development of PFP. Clinical interventions often aim to alter the biomechanical patterns that are thought to result in elevated PFJ loads while concurrently increasing the load tolerance capabilities of the tissue through therapeutic exercise. Biomechanics may play a role in PFJ load modification not only when addressing proximal and distal components, but also when considering the involvement of more local factors such as the quadriceps musculature.

Biomechanical considerations should consider the entire kinetic chain including the hip and the foot/ankle complex, however the beneficial effects of these interventions may not be the result of long-term biomechanical changes. Biomechanical alterations may be achieved through movement retraining, but the interventions likely need to be task-specific to alter movement patterns. The purpose of this commentary is to describe biomechanical interventions for the athlete with PFP to encourage a safe and complete return to sport.

Level of Evidence: 5

Keywords: Foot, hip, knee, rehabilitation, running
BACKGROUND
Patellofemoral pain (PFP) has historically been a complex and enigmatic issue. Many factors have been identified to correlate with symptoms including variations in strength, flexibility, patellar tracking, quadriceps angle, and patellofemoral joint (PFJ) morphology. There are also known correlations with psychological factors such as depression, fear-avoidance, and anxiety which complicate the presentation further.1

Factors thought to relate to PFP often remain after patients’ symptoms have resolved making their clinical importance difficult to determine.2 Further complicating assessment, the pain source in PFP may involve multiple structures and is highly controversial.2 As such, a thorough clinical assessment of an individual is paramount to fostering successful patient outcomes in this population. Although this commentary will explore biomechanical interventions for PFP, this pathology may be better understood in the context of the tissue homeostasis model.

HOMEOSTASIS MODEL OF PATELLOFEMORAL PAIN
In 2005, Dr. Scott Dye proposed a tissue homeostasis model for understanding PFP.2 When any tissue is in homeostasis, it is maintaining a constant physiological condition of its internal environment. Although very successful at self-regulation, sufficient disruption of homeostasis can result in pathophysiologic processes. Instead of considering the presentation of PFP strictly from a perspective of structural failure, Dye suggested that the pathophysiologic processes that occur in response to sudden bouts of increased training loads or stressors should be seen as the true driver of symptoms.2

Homeostasis can be described as a zone, or “envelope of function”, where the tissue is capable of tolerating loads.2 It has been suggested that this zone is established through chronic loads to which the PFJ and related structures have adapted in response to consistent and incremental exposure.3 Acute increases in training loads that exceed the established envelope of function are thought to disrupt homeostasis of the PFJ, ultimately resulting in pain. A central tenet of the envelope of function is that high PFJ loads are not inherently dangerous; rather loads that exceed a tissue’s conditioned capacity may be what are potentially injurious. Indeed, acute increases in training load that exceed chronic training loads appear to play a role in the development of many sports-related injuries.3,4

Once this homeostasis of the tissue is disrupted by sudden increases in training loads, the PFJ and associated structures may no longer tolerate levels of loading even during routine activities, such as descending stairs or previously well-tolerated running distances.2 The goal of intervention at this point should be to re-establish homeostasis through a temporary alteration of PFJ loads, followed by incrementally restoring the envelope of function to the baseline level or, preferably, higher. The biomechanical interventions described in this commentary can be particularly helpful at temporarily reducing loads while trying to re-establish homeostasis of the PFJ.6 Further, an understanding of the biomechanics of therapeutic interventions for PFP can also assist the clinician with planning a rehabilitation program that incrementally restores a patient’s envelope of function. The purpose of this commentary is to describe biomechanical interventions for the athlete with PFP to encourage a safe and complete return to sport.

BIOMECHANICAL OVERVIEW OF PATELLOFEMORAL PAIN
High levels of patellofemoral loads, particularly in the presence of an altered PFJ environment,7 are thought to be a factor in either the development or chronicity of PFP.8-10 A PFJ that has relatively low PFJ contact area9 or diminished cartilage thickness and properties,7,12 transfers greater loads to the subchondral bone.8 Indeed, individuals with PFP demonstrate increased water content13 and metabolic activity14 in the subchondral bone of the patella. Therefore, clinical interventions often aim to alter the biomechanical patterns that are thought to result in elevated PFJ loads while concurrently increasing the load tolerance capabilities of the tissue through therapeutic exercise.

Interventions that address biomechanical loading of the PFJ should encompass multiple loading parameters. Clinicians should familiarize themselves with the sport-specific loading demands that their athlete...
mometry during testing, either handheld (isometric) or isokinetic. Handheld dynamometry is a reliable measure of quadriceps strength (ICC = 0.72)\textsuperscript{24} with even greater reliability when straps are used to stabilize the dynamometer (ICC = 0.96).\textsuperscript{25} As clinicians in non-research settings typically lack access to isokinetic dynamometers, the use of an inexpensive handheld dynamometer is highly advisable in the assessment of quadriceps strength in athletes with PFP.

Progressive quadriceps strengthening is a foundation of rehabilitation of the athlete with PFP. In high quality studies, there is consistent evidence that progressive quadriceps strengthening improves symptoms and function in these patients.\textsuperscript{26} Progressive quadriceps resistance exercises have been shown to reduce PFP by 44-90%.\textsuperscript{26,27} While targeted strengthening of the vastus medialis oblique (VMO) is often prescribed, there is inconclusive evidence supporting its superiority to generalized quadriceps strengthening for the treatment of individuals with PFP.\textsuperscript{26,28} Therefore, the authors of this commentary have considered the literature on generalized quadriceps strengthening and VMO-targeted strengthening together.

The results of a quadriceps strengthening program may be enhanced through the use of patellar taping or bracing. The effect of patellar taping on PFJ kinematics and PFP remains somewhat controversial. Although the application of patellar tape results in large and immediate reductions in pain,\textsuperscript{29} pain reductions occur with either directionally applied or non-directionally applied tape.\textsuperscript{30} These findings are suggestive of a non-biomechanical mechanism for the reduction in pain that is often observed with patellar taping. Patellar taping may enhance the ability to perform quadriceps resistance exercises in individuals with PFP,\textsuperscript{31} presumably by reducing pain-related quadriceps inhibition. Thus, patellar taping may enable greater PFJ loading during quadriceps resistance exercises that would ordinarily result in pain.\textsuperscript{29} In support of this rationale, recent systematic reviews indicate that patellar taping enhances patient outcomes, but only in the first 12 weeks of rehabilitation\textsuperscript{6,52} when pain would be expected to be the greatest. Patellar bracing may also have a similar influence on outcomes in individuals with PFP through the 6 and 12 week time points.\textsuperscript{33} As such,
it appears that recovery from PFP may be bolstered by the addition of patellar taping or patellar bracing, but only in the first 6-12 weeks of a patellofemoral rehabilitation program.

THE QUADRICEPS STRENGTHENING PARADOX

Despite the consistent improvements in pain associated with quadriceps strengthening, the mechanism behind reported pain reductions is unclear. For instance, quadriceps strengthening exercises may potentially expose the PFJ to high reaction forces which are thought to exacerbate PFP. Conversely, it has been proposed that quadriceps strengthening may alter patellar kinematics, potentially increasing the contact area between the patellar and trochlear articular surfaces. To date, preliminary evidence suggests that eight weeks of quadriceps strengthening may result in increased contact area of the PFJ. Thus, quadriceps strengthening may reduce PFJ stress by increasing the contact area of the PFJ.

Ultimately, the process of quadriceps strengthening, rather than the quadriceps strength gains that result, may reduce PFP by improving load tolerance of the patient and the PFJ structures. For instance, quadriceps strengthening results in a desirable increase in glucosaminoglycan content in articular cartilage of the knee. In an animal model, eccentric quadriceps muscle contractions result in protective adaptations in distal femoral articular cartilage. Taken together, these findings suggest that a loading program may increase the tissue quality of the articular cartilage of the PFJ. Emerging evidence also suggests that progressive loading of the PFJ may reduce local hyperalgesia and may alter central pain processing in individuals with PFP. Therefore, progressive quadriceps strengthening may improve a patient’s envelope of function by enhancing load tolerance of the PFJ. Clearly, further study is necessary to better understand the mechanisms of pain reduction that are observed in individuals with PFP that result from a quadriceps strengthening program.

THE BIOMECHANICS OF QUADRICEPS STRENGTHENING

Prescription of quadriceps strengthening for the treatment of PFP requires a working knowledge of the biomechanics of various progressive resistive exercises. Specifically, clinicians should consider carefully the interactions between external moment arms, external and internal loads, knee joint angles and articular contact area of the PFJ when prescribing quadriceps strengthening exercises. In either open or closed kinetic chain, contact area of the PFJ is the lowest in the first 20 degrees of knee flexion and steadily increases as knee flexion increases. Interestingly, the external moment arm acting on the knee also increases as an individual moves deeper into a closed kinetic chain squat. As a result, PFJ stress (the quotient of PFJ reaction force and PFJ contact area) increases fairly linearly from full knee extension to approximately 45 degrees of knee flexion during a squatting maneuver. However, PFJ reaction forces increase rapidly from approximately 45 degrees to 100 degrees of knee flexion with either a squat or leg press with a disproportionate lower rate of increase in PFJ contact area. The net result is that PFJ stress is considerably higher when squatting and leg presses in knee flexion angles in excess of approximately 45 degrees when compared with squatting with comparatively less knee flexion (Figure 2 and 3A). Thus in the early stages of rehabilitation of PFP, the PFJ is particularly well-suited to closed chain loads, in approximately the first 45 degrees of knee flexion.

Quadriceps strengthening can also be achieved with open kinetic chain exercises. However, PFJ loads during open chain exercises are highly dependent on the configuration of force application. During open chain knee extension with a weight attached to the ankle, the external moment arm increases as the knee nears full extension. This loading configuration results in a highly variable level of external resistance throughout the knee extension motion (EXT-VR) as shown in Figures 2 and 3B. Thus, PFJ reaction forces increase rapidly as the knee nears full extension in the open chain whereas PFJ contact area decreases precipitously. This loading scenario results in a large increase in PFJ stress in the last 20 degrees of knee extension, which is exactly opposite of what occurs during a squatting maneuver. In contrast, a knee extension machine that uses a cable system applies external resistance in a fairly uniform manner throughout the knee range of motion, via a constant external moment arm (EXT-CR) as shown in Figure 2 and 3C. Knee exten-
of the quadriceps\textsuperscript{45} necessitates peak quadriceps forces estimated at 5 times body weight during the stance phase of endurance-paced running.\textsuperscript{46} Muscle forces of this magnitude are attainable with select rehabilitation exercises. Single leg squats performed to at least 65 degrees of knee flexion without added weight yields peak quadriceps forces of approximately 4-5 times body weight.\textsuperscript{47} However, squats to this depth of knee flexion may result in pain in individuals with PFP\textsuperscript{41} and peak knee flexion during running rarely exceeds 40-45 degrees.\textsuperscript{47} Thus, clinicians should opt for added weight to a single leg squat to attain peak quadriceps that are relevant to running. Adding resistance to body weight exercises is absolutely required if a clinician wishes to attain peak quadriceps forces that are of same magnitude as those seen during jumping. For instance, a bilateral drop vertical jump results in peak quadriceps forces of 7 times body weight.\textsuperscript{48}

Provided the added resistance is sufficient, open kinetic chain knee extension exercises can also generate peak quadriceps forces that are similar to forces noted during running and other activities. For instance, therapists may find it difficult to provide sport-relevant resistance between 45-90 degrees of knee flexion\textsuperscript{41} with the EXT-VR load configuration. Once past the early stages of rehabilitation, the constant resistance supplied by a knee extension machine using the EXT-CR configuration may thus provide the best means to strengthen the quadriceps between 45-90 degrees of knee flexion\textsuperscript{41} with the EXT-VR load configuration. When selecting appropriate resistance levels, clinicians should keep in mind that large internal muscle forces often result from counteracting much lower external loads. Regardless of the sport, clinicians should seek to achieve activity-relevant quadriceps loads with therapeutic exercise in athletes with PFP prior to return to sport initiation. During running, for instance, peak vertical ground reaction forces are typically around 2.5 times body weight, yet the external moment arm acting on the knee is rather large. In contrast, the much smaller internal moment arm of the quadriceps\textsuperscript{45} necessitates peak quadriceps forces estimated at 5 times body weight during the stance phase of endurance-paced running.\textsuperscript{46} Muscle forces of this magnitude are attainable with select rehabilitation exercises. Single leg squats performed to at least 65 degrees of knee flexion without added weight yields peak quadriceps forces of approximately 4-5 times body weight.\textsuperscript{47} However, squats to this depth of knee flexion may result in pain in individuals with PFP\textsuperscript{41} and peak knee flexion during running rarely exceeds 40-45 degrees.\textsuperscript{47} Thus, clinicians should opt for added weight to a single leg squat to attain peak quadriceps that are relevant to running. Adding resistance to body weight exercises is absolutely required if a clinician wishes to attain peak quadriceps forces that are of same magnitude as those seen during jumping. For instance, a bilateral drop vertical jump results in peak quadriceps forces of 7 times body weight.\textsuperscript{48}

Provided the added resistance is sufficient, open kinetic chain knee extension exercises can also generate peak quadriceps forces that are similar to forces noted during running and other activities. For instance, therapists may find it difficult to provide sport-relevant resistance between 45-90 degrees of knee flexion\textsuperscript{41} with the EXT-VR load configuration. Once past the early stages of rehabilitation, the constant resistance supplied by a knee extension machine using the EXT-CR configuration may thus provide the best means to strengthen the quadriceps between 45-90 degrees of knee flexion\textsuperscript{41} with the EXT-VR load configuration. When selecting appropriate resistance levels, clinicians should keep in mind that large internal muscle forces often result from counteracting much lower external loads. Regardless of the sport, clinicians should seek to achieve activity-relevant quadriceps loads with therapeutic exercise in athletes with PFP prior to return to sport initiation. During running, for instance, peak vertical ground reaction forces are typically around 2.5 times body weight, yet the external moment arm acting on the knee is rather large. In contrast, the much smaller internal moment arm

![Figure 2. Patellofemoral joint stress during three different types of quadriceps strengthening exercises: EXT-VR represents a free weight attached to the distal lower leg. EXT-CR represents a knee extension machine that applies constant resistance. Squat relates to a squatting maneuver. Patellofemoral joint stresses is dependent on the external moment arm, amount of resistance and the direction of force application. Figure reprinted with permission from Powers CM, Ho KY, Chen YJ Souza RB, Farrokhi S. Patellofemoral joint stress during weight-bearing and non-weight-bearing quadriceps exercises. J Orthop Sports Phys Ther. May 2014; 44(5): 320-327.](image-url)
Reduced posterolateral hip strength is often observed in individuals with PFP. Proposed interventions to address the proximal mechanism contribution to PFP aim to reduce contralateral pelvic drop and reposition the femur, via reduced hip adduction and medial rotation. Smartphone applications and open source movement analysis software provide the means to readily analyze an athlete’s mechanics in the clinic. During running, close proximity of the medial femoral condyles during midstance (Figure 4), known as a “reduced knee window,”\cite{58} is suggestive of excessive hip adduction and hip internal rotation of the stance limb. Results of movement analyses can assist with clinical decision making in developing targeted rehabilitation programs.

Recent literature has evaluated interventions designed to address the proximal mechanisms of PFP. The interaction between external loads and the external moment arm during common quadriceps strengthening exercises is shown in Figure 3.

![Figure 3. The interaction between external loads and the external moment arm during common quadriceps strengthening exercises.](image)

**Figure 3A:** During the single leg squat, the external moment arm (MA) increases as the depth of the squat also increases resulting in increasing quadriceps forces and patellofemoral joint stress through 90 degrees of knee flexion. Corresponds with “Squat” in Fig. 2.

**Figure 3B:** Patient performing open chain knee extension with a weight mounted at the level of the lower leg (non tap figure). The external moment arm (MA) increases as the knee extends, resulting in increasing quadriceps forces and patellofemoral joint stress as the knee nears full extension. Corresponds with “EXT-VR” in Fig. 2.

**Figure 3C:** During open chain knee extension on knee extension machine with a cable and weight stack system, the external moment arm (MA) remains constant throughout the range, resulting in relatively stable quadriceps forces and patellofemoral joint stress. Corresponds with “EXT-CR” in Fig. 2.

Real-time magnetic resonance imaging studies suggest relative lateral tracking of the patella as the femur adducts and internally rotates during a squatting or step down maneuver in females with PFP.\cite{52, 53, 54, 55} Contralateral pelvic drop is thought to increase tension in the lateral patellar retinaculum\cite{56} via the iliotibial band,\cite{57} potentially contributing to lateral patellar tracking.
There is a growing body of evidence of moderate to high quality that supports the prescription of posterolateral hip strengthening for the treatment of PFP. Hip strengthening programs result in moderate to large reductions in PFP with moderate to large improvements in function in the short- to medium-term. To date, only one study has evaluated long-term outcomes after a hip strengthening program for PFP. At one-year post-intervention, Fukuda and colleagues reported that individuals who completed a hip and quadriceps strengthening program demonstrated greater improvements in PFP and lower limb function compared with quadriceps strengthening alone. Evaluating interventions for PFP that employ hip strengthening can also be challenging as the quadriceps are also loaded during most hip strengthening exercises, such as step ups or single leg squats. Future study that delineates hip strengthening and quadriceps strengthening exercises is needed to better understand the mechanism(s) of pain reduction noted after these rehabilitation programs. As proximal strengthening does not appear to alter proximal mechanics, non-biomechanical mechanisms may explain the reduction in PFP that is widely reported with rehabilitation programs that employ hip strengthening.

When approached from a tissue homeostasis perspective, long-term correction of proximal mechanics may not be required. As higher levels of hip adduction and internal rotation increase PFJ stress, these mechanics may hinder recovery from PFP. However, precipitating factor in the development of PFP in many athletes may be the application of load beyond the amount that the PFJ has been conditioned to tolerate. For example, a runner may have always had elevated hip adduction and internal rotation, yet the actual culprit for the development of PFP may be increasing running mileage faster than the PFJ and associated structures can adequately adapt. Along these lines, an athlete who runs with greater levels of hip adduction and hip internal rotation may be more susceptible to rapid changes in training loads than a runner who does not exhibit similar mechanics. Thus, the promising clinical outcomes of proximal exercise interventions for PFP may be better explained as simply the systematic conditioning of the PFJ and supportive musculature.
to tolerate more load rather than actually changing hip frontal and transverse plane mechanics.62

MOVEMENT RE-EDUCATION FOR THE TREATMENT OF PFP

When attempting to restore tissue homeostasis, reducing PFJ loads through movement re-education may be particularly helpful in the early to intermediate stages of rehabilitation. Recent work suggests that various mechanics associated with PFP are modifiable with the use of motor learning techniques. As a premise for movement re-education for the proximal mechanism of PFP, individuals with PFP demonstrated delayed onset and reduced duration of gluteus medius activation.77,78 Thus, currently described movement re-education interventions for the proximal mechanism aim to alter the neuromuscular control of the gluteal musculature in an effort to control proximal mechanics, if implicated. In contrast to hip strengthening, movement re-education has been shown to reduce proximal mechanics during running and other functional tasks, such as step descent or a single leg squat.69 Providing mirror and verbal feedback, for instance, has been shown to be effective at reducing contralateral pelvic drop, hip adduction and hip internal rotation during a single leg squat.62 Interestingly, changes in proximal mechanics during a single leg squat did not transfer to running.62 Thus, patients are able to achieve improved control of proximal mechanics during common therapeutic exercises may not necessarily transfer these movement skills to an unrelated task, such as running. These findings suggest that changes in lower extremity mechanics require a motor learning component and that movement retraining likely needs to be task-specific.

The movement re-education literature for the treatment of PFP has largely focused on retraining running gait. Proximal mechanics79,80 have been targeted in published gait retraining studies with runners with PFP. Realtime kinematic80 or mirror feedback,79 coupled with verbal cueing, result in reductions in hip adduction and contralateral pelvic drop in female runners with PFP (Figure 5). These reductions in proximal mechanics were accompanied by improvements in reported pain and lower limb function that were associated with large effect sizes.49 Importantly, these previous investigations targeted females with PFP who also demonstrated a proximal mechanism during running. This criterion for enrollment in the respective studies underscores the importance of a targeted intervention in response to a thorough clinical gait analysis.58

Cueing a modest increase in step rate (cadence) during running has been shown to reduce PFJ contact forces and stress in individuals with and without PFP.16,81-83 Clinically, most runners find that employing modest increases in running cadence is a relatively easy skill to learn. An increase in step rate by 5-10% over preferred levels reduces PFJ loads in part by decreasing peak knee flexion and quadriceps forces during the stance phase of gait.16,81 Again, a clinical gait analysis is highly recommended in determining runners who would benefit the most from an increase in step rate. Specifically, runners who exhibit high amounts of vertical oscillation of the estimated center of mass between flight phase and mid-stance, have footfalls that are far in front of the estimated center of mass, and reach high levels of knee flexion during stance phase may benefit the most from an increase in step rate.81,84 An increase in step rate also results in a reduction in peak hip adduction, albeit smaller in magnitude than the aforementioned kinematic and mirror feedback.

Figure 5. Open source software and a webcam can be used to provide real-time feedback on frontal plane running mechanics. This video technique is useful if the treadmill has a large controller console that prevents the runner from seeing their reflection in a full-length mirror.
studies. Thus, running with increased step rate primarily reduces PFJ forces through a reduction in quadriceps forces rather than a large effect on lateral tracking of the PFJ.

Adopting a forefoot strike pattern during running has also been suggested as a means to reduce PFJ loads. However, clinicians should be aware, that conversion to a forefoot strike increases the demand of the ankle plantarflexors while reducing demand of the knee extensors. Adopting a forefoot strike pattern has been shown to result in 11% greater Achilles tendon forces per step, which equates to an additional 47.7 times body weight impulse loading of the Achilles tendon per mile of running. Because adopting a 5-10% increase in running cadence reduces PFJ loads by 10-20% while also reducing Achilles tendon loads, cueing an increase in running cadence may be preferred over adoption of a forefoot running pattern.

Clinical reasoning should guide movement re-education prescription. If frontal and transverse plane hip mechanics are thought to be the main biomechanical factor contributing to a runner's current PFP, then visual feedback to cue reductions in these mechanics are warranted. If sagittal plane running mechanics are primarily implicated in a runner's PFP, then cueing an increase in step rate during running may be the most effective gait modification. Clinically, cueing a reduction in proximal mechanics can easily be done with a full-length mirror or with a live video stream. Similarly, cueing an increase in step rate can be accomplished via matching the rhythm of a metronome or in response to real time feedback from commercially available wrist mounted running computers that calculate step rate via an accelerometer mounted in a footpod or within the device itself (Figure 6).

**THE ROLE OF FOOT ORTHOSES IN THE TREATMENT OF PATELLOFEMORAL PAIN**

While there appears to be some support for the use of foot orthoses for the treatment of PFP, the biomechanical rationale supporting their use is less clear. For instance, a 6° medially wedged orthosis did not reduce peak frontal plane kinematics or joint moments of the knee or hip in runners with and without PFP. Interestingly, greater standing calcaneal eversion posture was not predictive of any changes in frontal plane hip or knee mechanics in response to orthotics. Despite these findings, foot orthoses, combined with exercise therapy, resulted in improved outcomes over six weeks in individuals with PFP compared with exercise therapy alone. In an interesting clinical trial, Lewinson and colleagues randomized runners with PFP to either medially or laterally wedged foot orthoses. Regardless of foot orthoses assignment, both groups of runners reported 33% reductions in PFP after six weeks of using the foot orthoses during routine training runs. Non-uniform reductions in frontal plane knee moments during running with the foot orthoses were observed across the cohorts. These data, considered along with aforementioned studies, suggest that foot orthoses may enhance short term outcomes in PFP rehabilitation programs, but clinical results may be due to either individualized responses or non-biomechanical mechanisms. Patients with PFP who experience a reduction in pain with the use of foot orthoses may be able to tolerate greater levels of resistance during therapeutic exercises, potentially improving their envelope of function.

**BIOMECHANICAL CONSIDERATIONS FOR RETURN TO SPORT**

As described previously, peak quadriceps loads associated with an athlete's sport of choice are readily achieved with targeted resistance exercises. How-
ever, a progressive return to sport program is necessary to replicate the rate of loading and cumulative loads that are experienced by the PFJ during sporting tasks. For example, slow jogging is associated with a knee angular velocity in excess of 500 deg/sec with much higher velocities associated with faster running and jumping. Knee angular velocities of this magnitude are difficult and potentially unsafe to simulate clinically with isokinetic knee extension devices. Similarly, sport-specific cumulative PFJ loads can be equally difficult to achieve with resistance training alone. For instance, running just 1 km alone requires approximately 800-1000 steps. Thus, progressive return to sport programs are necessary to specifically mimic the loading rate and cumulative demands of a sport in order to fully restore the athlete’s envelope of function.

Sample return to sport programs are readily available in the literature to assist clinicians in objectively guiding an athlete’s return to jumping or running sports. Progressive jumping programs are available for the jumping athlete that advance jump repetitions, depth and height of jumps as well as progressing from bilateral to single leg jumps as symptoms allow. Typically, return to running programs progress run:walk ratios in response to patient-reported discomfort. While return to running programs are often based on time or distance, consideration of the number of loading cycles per training session may better quantify cumulative knee loads. Quantifying loading cycles in return to running programs can easily be done with a wearable activity monitors or running computers. PFJ loads during running are not different between overground and treadmill running. Thus, treadmills may offer greater convenience and the advantage of enhanced control of running speed and number of loading cycles when compared to overground running. Individuals recovering from PFP may also benefit from running at a faster speed as opposed to slow jogging. Faster paced running requires shorter stance times and fewer steps to travel a given distance, resulting in lower cumulative PFJ loads when compared with jogging. Therefore, running athletes recovering from PFP may have greater success with bouts of moderately fast- to fast-paced running for a prescribed number of steps rather than focusing on slow jogging for a set amount of time.

To guide clinical decision making, a criterion-based progression should be implemented that evaluates pain during activity and in the 24 hours after the return to sport session. There are no formal guidelines available for acceptable pain in athletes with PFP completing a return to sport program. Care should be taken during return to sport tasks to avoid acute aggravation of knee pain, which can increase hyperalgesia in individuals with PFP. Thus, it is the authors’ recommendation that pain should remain at or below 2/10 on the visual analog scale during return to sport activity, with trace to absent pain after the activity session.

CONCLUSION
The mechanisms of PFP are complex and enigmatic. The presentation may be best described by considering a tissue homeostasis model. Biomechanical interventions that reduce PFJ loading may be most helpful during early rehabilitation to allow progressive quadriceps strengthening as tissue homeostasis is re-established.

Biomechanical considerations should include the entire kinetic chain including the hip and the ankle, however the beneficial effects of these interventions may not be the result of long-term biomechanical changes. True biomechanical alterations may be achieved through movement retraining, but the interventions must be extremely specific to the desired task.

REFERENCES


29. Salsich GB, Brechter JH, Farwell D, Powers CM. The effects of patellar taping on knee kinetics, kinematics, and vastus lateralis muscle activity during stair ambulation in individuals with


36. Pazzinatto MF, de Oliveira Silva D, Barton C, Rathleff MS, Briani RV, de Azevedo FM. Female adults with patellofemoral pain are characterized by widespread hyperalgesia, which is not affected immediately by patellofemoral joint loading. *Pain Med*. 2016;epub ahead of print 2016, Apr 25.


ABSTRACT

Patellofemoral disorders, commonly encountered in sports and orthopedic rehabilitation settings, may result from dysfunction in patellofemoral joint compression. Osseous and soft tissue factors, as well as the mechanical interaction of the two, contribute to increased patellofemoral compression and pain. Treatment of patellofemoral compressive issues is based on identification of contributory impairments. Use of reliable tests and measures is essential in detecting impairments in hip flexor, quadriceps, iliotibial band, hamstrings, and gastrocnemius flexibility, as well as in joint mobility, myofascial restrictions, and proximal muscle weakness. Once relevant impairments are identified, a combination of manual techniques, instrument-assisted methods, and therapeutic exercises are used to address the impairments and promote functional improvements. The purpose of this clinical commentary is to describe the clinical presentation, contributory considerations, and interventions to address patellofemoral joint compressive issues.

Keywords: Flexibility, knee, patellofemoral pain, patellofemoral compression

CORRESPONDING AUTHOR

Michael J. Mullaney
Mullaney & Associates Physical Therapy, LLC
Matawan, NJ 07747
Phone: 732-970-4974
E-mail: mullaneypt@gmail.com
INTRODUCTION

Patellofemoral disorders comprise nearly 25% of all knee injuries evaluated in orthopedic clinics.1-3 Patellofemoral disorders encompass a large spectrum of pathologies, including chondral injuries, arthritis, instability, and patellofemoral pain syndrome (PFPS).4 Patellofemoral pain syndrome may be a result of an insidious compressive dysfunction or, less commonly, direct trauma. Annual incidence of PFPS in males is 3.8% and 6.5% in females.2 This pathology is often associated with a poor prognosis and multiple treatment plans have been proposed.5-9 Successful treatment of patellofemoral compressive dysfunction requires a strong understanding of the osseous and soft tissue anatomy of this joint. Abnormalities of these osseous or soft tissue structures may predispose patients to biomechanical abnormalities. In most instances, these compressive disorders may be addressed with a comprehensive treatment plan addressing soft tissue flexibility and mobility, lower extremity strength, and biomechanical impairments.

Elevated patellofemoral joint compressive force can result in patellofemoral pain from numerous soft tissue structures: synovial plicae, infrapatellar fat pad, retinaculacae, joint capsule, and patellofemoral ligaments.10 Patellofemoral compressive forces can also elevate subchondral bone stress in the patellofemoral joint. It is also believed that, because of high concentration of pain receptors in the subchondral bone, increased stress from high patellofemoral force may also result in pain.10-12 This compressive force, if prolonged, can result in articular cartilage degeneration and decrease in the ability of the cartilage to appropriately distribute patellofemoral joint contact forces.11 As a rehabilitation specialist, it is important to understand the stress levels in the patellofemoral joint during activities of daily living and rehabilitation exercises when treating patients with patellofemoral compressive dysfunction. The purpose of this clinical commentary is to describe the clinical presentation, contributory considerations, and interventions to address patellofemoral joint compressive issues.

CLINICAL PRESENTATION

Patellofemoral compressive pain typically affects younger adults but can also be problematic for adolescents and adults. Typically, in adolescents, this pain is evident during periods of rapid growth.13 In adults, degenerative changes in the patellofemoral joint may also be present, adding to the complexity of the compressive disorder. Patients typically describe a gradual onset of anterior knee pain. This pain is usually associated with the knee being in conditions that lead to increased patellofemoral compression: knee flexion and quadriceps loading. Such activities include squatting, stair climbing, hiking, running and prolonged sitting. Symptoms are rarely present when the patellofemoral joint is not being loaded and compressed (e.g. sleeping, standing, resting).14

Patellofemoral pain is a clinical diagnosis, based on the presence of anterior knee pain while compressive forces are elevated during activities that load the patellofemoral joint. Physical examination usually reveals normal knee range of motion without effusion, and patellar mobility may or may not be normal. While there are a multitude of special tests to help develop a diagnosis, no single clinical test definitively confirms the diagnosis of patellofemoral compression pain. Although there is no single definitive test, pain during squatting is highly prevalent in patients with patellofemoral pain.14,15 It is also important to note that patellofemoral pain is evident in 71-75% of patients with tenderness on palpation of the edges of the patella.15 Palpation of the medial and lateral facets of the patella should be included in the clinical exam of patients suspected of having patellofemoral pain. Patellar grinding/crepitus and apprehension tests have low sensitivity and limited diagnostic accuracy.15 These tests should be used with caution when determining a working diagnosis.

The core criterion required to define a compressive dysfunction of the patellofemoral joint is pain around or behind the patella, which is aggravated by at least one activity that loads the patellofemoral joint during weight bearing on a flexed knee: squatting, stair ambulation, jogging/running, and hopping/jumping.14 Additional criteria that are non-essential, but may be helpful in establishing a diagnosis include crepitus emanating from the patellofemoral joint during knee flexion movements, tenderness on patellar facet palpation, small peri-patellar effusion, and pain while sitting or rising from sitting.16
The patella is convex on its anterior surface, but is divided by a longitudinal median ridge on the articular side. It resides within the trochlear groove and links the extensor mechanism through connections to the quadriceps tendon at the superior pole and the patellar tendon at its inferior pole. The patella has seven total facets but is primarily divided into two large facets located medially and laterally. These medial and lateral facets are important considerations regarding the compressive dysfunction mechanism and time should be taken to palpate the facets during examination. (Figure 1) The lateral facet is longer and more sloped to match the lateral femoral condyle, while the medial facet is smaller, with a shorter and steeper slope. The patellar cartilage has greater congruency in the axial plane as compared to in the sagittal plane, contributing to the gliding capability of the joint itself. This is important to consider during clinical evaluation of the patella mobility.

The stability of the patella is also dependent on the characteristics of the trochlear groove. The trochlear groove depth is approximately 5.2mm, with the lateral femoral condyle being 3.4mm higher than the medial femoral condyle in the axial plane. The trochlear groove deepens as it extends distally and deviates laterally before it terminates at the femoral notch. The facets transition into the medial and lateral femoral condyles. Trochlear dysplasia is characterized by a loss of the normal concave anatomy and depth of the trochlear groove. This loss of normal anatomy creates a flat trochlea with highly asymmetric facets. This asymmetry predisposes to patellar dislocation during knee flexion secondary to loss of bony restraints within the groove.

Medial soft tissues of the patellofemoral joint include the vastus medialis obliquus, medial patellofemoral ligament, the medial patellotibial ligament and the medial retinaculum. The medial patellofemoral ligament is the primary passive restraint to lateral patellar translation. The medial patellofemoral ligament is vital to patellar stability and laxity in this structure may result in altered compressive forces in the patellofemoral joint. Assessment of these medial structures may be performed by a patella mobility test as well as medial border and medial facet palpation. Pain elicited may be indicative of elevated compressive forces on the medial side of the patella.

The lateral soft tissue restraints are composed of the superficial and deep layers of the retinaculum. The superficial layers are comprised of the oblique lateral retinaculum and the deep layer is comprised of

**Figure 1. Palpation of the medial facet joint of the patella.** The patella should be medially gilded to allow for proper palpation of the underside medial facet.
The oblique and transverse fibers of the lateral retinaculum. These fibers are referred to as the patellotibial and the epicondylolapatellar bands. Tightness of these lateral structures may cause a pull on the patella in the lateral direction causing a lateral tilt of the patella. A lateral tilt may increase compressive forces to the lateral facet on the patella and cause progressive degenerative changes over time. Assessment for lateral tightness should be a component of an evaluation for patellofemoral pain. This assessment should include palpation of the lateral border and lateral patellar facet. It should also include assessment of iliotibial band (ITB) tightness. The ITB is intricately involved with the lateral soft tissue structures of the patellofemoral joint and plays a supportive role in the lateral stability. Specifics of ITB assessment will be covered later in this clinical commentary.

MECHANICAL CONSIDERATIONS
Patellofemoral motion requires a complex interaction between the bony and soft tissue structures. Since the patella is a sesamoid bone, abnormalities of the bony congruency, femoral control and the soft tissue structures can cause malalignment and contribute to patellar tracking issues. This maltracking may cause an increase in compressive forces during knee flexion. From 0° to 30° of knee flexion, the primary restraints to lateral patellofemoral translation are soft tissue structures, including the medial patellofemoral ligament, vastus medialis obliquus and the medial retinaculum. From 0 to 30°, the medial patellofemoral ligament becomes the primary restraint to lateral translation, while the primary soft tissue restraints on the lateral side, including the superficial and deep layers of the lateral retinaculum, increase compressive forces and stability. During initiation of knee flexion, a medial patellar shift occurs allowing the patella to engage in the trochlear groove. As the knee continues to flex from 20° to 30° of knee flexion, patellar stability increases due to bony contributions and soft tissue structures, as the patella engages in the trochlea. Progressing flexion to 60°, contact pressure increases and moves from distal to proximal.

Once the knee flexes to 90° there is increasing posteriorly directed force exerted from the patellar and quadriceps tendon, which increase the overall joint reactive force and create a high level of compressive force. Escamilla et al showed that, between 80° and 90° of knee flexion, the short wall squat (feet closer to the wall) produced the greatest patellofemoral compressive force as compared to a long wall squat (feet away from wall). Rosenberg et al. and Andriacchi et al showed that the highest patellofemoral load during stair climbing is seen at 60° of knee flexion. Based on these studies, it can be assumed that these positions and activities between 60° and 90° degrees of knee flexion manifest the greatest compressive forces in the patellofemoral joint and should be considered during assessment and treatment.

TREATMENT OF PATELLOFEMORAL COMPRESSION
Treatment of patellofemoral compressive issues starts with identification of relevant impairments through a physical therapy examination. Impairments in muscle-tendon flexibility, joint mobility, and myofascial restrictions can be reliably examined using established tests and measures. Proximal and distal joint factors also influence patellofemoral stress and this topic of regional interdependence is briefly summarized in this commentary and covered in depth by other authors throughout this journal issue. Once relevant impairments are found, a combination of manual techniques, instrument-assisted methods, and therapeutic exercises are used to address the impairments and promote functional improvements. Select impairments and strategies to address these impairments will be discussed in the following sections.

Hip Flexor and Quadriceps Flexibility
Impaired hip flexor and quadriceps flexibility has been documented in patients with PFPS. In a case-control study, Piva et al. showed that patients diagnosed with PFPS had significantly less quadriceps length when compared to healthy subjects. Decreased quadriceps flexibility results in increased patellofemoral compression, as the tight quadriceps muscle and tendon compresses the patella into the trochlea via its posterior direction of pull. Further, hip flexor tightness is associated with an anterior pelvic tilt posture, which may result in femoral internal rotation, patellar maltracking, decreased patellofemoral contact area, and therefore, increased patellofemoral stress.
Two special tests are particularly useful in testing hip flexor and quadriceps flexibility. The modified Thomas test, performed with the patient in the supine position at the edge of an exam table, determines hip flexor flexibility by measuring hip flexion/extension angle relevant to the horizontal line parallel to the table surface. It is important for the physical therapist to passively and maximally flex the non-tested hip to ensure that the pelvis is set in a posteriorly tilted position. The tested leg should be lowered only after this standard pelvic position is established, and this position should be maintained throughout the test procedure. The posteriorly tilted pelvic position helps to standardize lumbar spine position into that of minimal lordosis, thereby eliminating the influence of spine position on apparent flexibility of psoas major, which is attached to all lumbar spinal segments. The modified Thomas test can be quantified using a standard goniometer or an inclinometer, with high intra- and inter-rater reliability (Figure 2). In addition to assessing hip flexion angle, knee extension angle is assessed in the same position as in the Thomas test as a measure of rectus femoris flexibility.

Ely’s test, performed with the patient in prone position, determines rectus femoris flexibility by the clinician passively flexing the knee and looking for the anterior surface of the hip to lift up from the table surface, indicating increased anterior pelvic tilt. This test can be quantified using a goniometer or inclinometer to measure knee flexion angle or tibial angle relevant to the table surface, with moderate to good reliability.

Many stretching techniques are available for addressing hip flexor and quadriceps flexibility. Choosing which techniques to be prescribed to a patient depends on the patient’s positional preference, patient’s tolerance to stretch, and effectiveness of the stretch. The authors routinely use the Thomas test position with the involved leg stabilized as an intervention technique (Figure 3). The patient must be instructed to hold the contralateral thigh in maximum hip flexion in order to ensure the posteriorly tilted pelvic position. Another effective stretching technique is the half-kneeling hip flexor stretch (Figure 4). For this stretch, it is important that the patient keeps his/her trunk in the upright position.

Figure 2. Modified Thomas Test: evaluation of the hip flexion angle using a goniometer or digital level. The rectus femoris mobility may also be objective with a knee angle measurement.

Figure 3. Stretching Thomas Test: The Thomas Test may be transitioned into a manual hip flexor stretch; a rectus femoris stretch may be included with using leg to increased involved lower extremity flexion angle.
nificantly less hip adduction during Ober's test compared to healthy subjects. Tightness in the tensor fascia latae and its dense fascial extension, the ITB, is theorized to cause lateral patellar displacement, decreased patellofemoral contact area, and therefore, increased patellofemoral stress. In addition, tight ITB and lateral patellar retinaculum may lead to ITB friction syndrome, although the etiology of this pathology has been contested.

The ITB is continuous on its proximal end with tensor fascia latae anteriorly and gluteus maximus posteriorly. Tests of ITB flexibility must encompass both the anterior and posterior aspects of this complex structure. Ober's test, performed in the side-lying position, tests for tensor fascia latae and ITB flexibility by measuring the hip adduction angle due to gravity. It is important that the patient flexes the non-tested hip and stabilizes this leg in this position by hooking the hand around the leg and holding onto the edge of the table (Figure 5). This ensures that the pelvic position is standardized in the posteriorly tilted position. In this position, the tested (top) leg is held in the examiner's arm and the patient's hip is passively abducted, extended, then allowed to adduct due to the force of gravity. Because passive hip extension past neutral is required to clear the ITB over the greater trochanter, Ober's test is valid only if the Thomas test is negative to allow this amount of hip extension. Performing Ober's test

Several authors have shown that addressing hip flexor flexibility is associated with symptomatic improvement and functional recovery in patients with PFPS. Peeler et al, in a prospective cohort study, showed that a three-week home stretching program targeting the quadriceps was effective at significantly improving functional outcomes scores in patients with PFPS.

**Tensor Fascia Latae and Iliotibial Band (ITB) Flexibility**

Flexibility of the tensor fascia latae and ITB has been implicated in PFPS. In a case-control study, Hudson et al found that patients with PFPS had sig-
used to perform a therapist-assisted stretch. The supine crossover test position can be used as a therapist-assisted stretch or self-stretch by using a strap or propping the leg up against an immovable object (e.g., wall or chair). The stretch can also be performed in the standing position by crossing the legs and laterally leaning the trunk. Adding the trunk and arm movement can enhance the stretching effect and promote stretching of the entire lateral myofascial line.50,51

Addressing ITB flexibility is associated with relief in patellofemoral pain.6,52 Tyler et al., in a prospective cohort study; found that normalizing Ober’s test was one of the significant predictors of treatment success after six weeks of physical therapy for patients with PFPS.6

Hamstrings and Gastrocnemius Flexibility

Other types of soft tissue flexibility that influence patellofemoral compression and pain include limitations of the hamstrings and gastrocnemius. Hamstring tightness theoretically causes posterior glide of the proximal tibia on the femur, therefore, an alteration in the quadriceps vector, which results in increased compression of the patella on the femur. This association has been supported in cross-sectional studies of patients with patellofemoral pain.25,27,53 Whyte et al. showed in a biomechanical study that individuals with hamstring tightness had increased patellofemoral stress and reaction force during a squat task, compared to individuals without hamstring tightness.53 Gastrocnemius tightness may have a similar influence on patellofemoral biomechanics as the hamstrings, however, this mechanism has not been empirically demonstrated. Witvrow et al. identified in a prospective study that gastrocnemius inflexibility at baseline resulted in increased risk of developing patellofemoral pain during a one-year period in college athletes.26 Additionally, it should be noted that gastrocnemius tightness may be compensated for during gait by increased motion at the midtarsal joints, leading to increased subtalar joint motion, tibial and femoral rotation, and patellofemoral compression.54

Flexibility of the hamstrings and gastrocnemius can be readily assessed with several examination techniques. To assess hamstring flexibility, the straight leg raise and 90/90 knee extension tests have been previously used by different groups and have estab-
and medial glide. It is important to examine patellar mobility in all directions and document pertinent findings (i.e., hypo-mobile, within normal limits, or hyper-mobile), as subsequent treatment should target only the directions that are restricted.

Patellar mobilization is the mainstay of treatment for patellar hypo-mobility. Patellar mobilizations are typically performed manually by a physical therapist; however, some of the techniques may be instructed to the patient to be performed at home. Self-mobilization may be an effective method because of increased dosage of treatment and improved patient self-efficacy. The patella is manually held and moved in the direction of restriction, using oscillatory motions or static holds. By combining patellar mobilization with therapist-assisted static stretching is effective, particularly for the iliotibial band (ITB) and lateral patellar retinaculum.

Patellar mobilization is commonly used in the treatment of patellofemoral pain, however, empirical evidence showing its effectiveness is limited. This may be due to the lack of a valid and reliable clinical examination technique for patellar position or mobility without the use of specialized instrumentation.59,60 Presence of joint mobility impairment in patients with patellofemoral pain has been questioned, with one cross-sectional study showing no difference in patellar mobility between adults with and without patellofemoral pain.59 It is possible that subsets of patients with patellofemoral pain exist with different impairment patterns, and not all patients with the same pathology present with impaired joint mobility.61

**Joint Mobility**

Patellofemoral joint mobility is tested by qualitative assessment of joint accessory motions. Patellar glide in superior, inferior, medial, and lateral directions can be assessed with the patient's knee in full extension in order to disarticulate the patella from the femoral condyles and allow for passive glides. The physical therapist manually moves the patella in each direction and assesses the excursion of movement, as well as the quality of the end-feel. Limited patellar medial glide has been implicated in the etiology of patellofemoral pain.41 Patellar tilt, in medial or lateral directions, may be assessed by respectively pressing the lateral or medial border of the patella and assessing the excursion of patellar rotation in the transverse plane. Patellar rotation in the frontal plane may be assessed by manually holding the patella with two hands and rotating the patella in each direction. Simultaneous patellar mobility restrictions in two or more planes is common, especially the combination of decreased medial tilt and medial glide. It is important to examine patellar mobility in all directions and document pertinent findings (i.e., hypo-mobile, within normal limits, or hyper-mobile), as subsequent treatment should target only the directions that are restricted.

**Myofascial Considerations**

Myofascial restrictions may contribute to patellofemoral compression and pain. Fascia lata, the deep fascia of the thigh, is extensive and structurally strong, and continuous deeply with the lateral intermuscular septum and superficially and laterally with the ITB.62 Myofascial tightness in the thigh may lead to over-constraining of the patella and increased compression in the patellofemoral joint and under the lateral retinaculum.63 Additionally, active myofascial trigger points in the thigh may directly refer pain into and around the knee.64 Myofascial restrictions may be assessed by direct palpation of the soft tissues and trigger points. An

Intervention for hamstring and gastrocnemius flexibility follows the same stretching guidelines as in the previous sections. Hamstrings can be stretched in the straight leg raise position by the patient using a strap or with therapist assistance. Proprioceptive neuromuscular facilitation techniques (e.g., hold-relax or contract-relax) may enhance the stretch by improving the patient's tolerance to stretch.57,58 Gastrocnemius is optimally stretched in the standing position, with the involved foot behind the uninvolved foot, and the knee extended on the uninvolved side. Care must be taken to avoid abducting the involved foot, which causes excessive motion at the midtarsal joints. Shoes or additional arch support may be used to ensure that the stretch is applied to the gastrocnemius instead of at the midtarsal joints.

Gastrocnemius flexibility can be assessed with the patient in supine or prone position using the Silfverskiöld test.55 This test involves taking the difference in ankle dorsiflexion range of motion between the knee slightly flexed and the knee fully extended. A difference of 10 degrees or larger suggests a gastrocnemius contracture.56 Gastrocnemius flexibility may also be assessed in a standing, weight-bearing position.26

Joint Mobility

Patellofemoral joint mobility is tested by qualitative assessment of joint accessory motions. Patellar glide in superior, inferior, medial, and lateral directions can be assessed with the patient's knee in full extension in order to disarticulate the patella from the femoral condyles and allow for passive glides. The physical therapist manually moves the patella in each direction and assesses the excursion of movement, as well as the quality of the end-feel. Limited patellar medial glide has been implicated in the etiology of patellofemoral pain.41 Patellar tilt, in medial or lateral directions, may be assessed by respectively pressing the lateral or medial border of the patella and assessing the excursion of patellar rotation in the transverse plane. Patellar rotation in the frontal plane may be assessed by manually holding the patella with two hands and rotating the patella in each direction. Simultaneous patellar mobility restrictions in two or more planes is common, especially the combination of decreased medial tilt and medial glide. It is important to examine patellar mobility in all directions and document pertinent findings (i.e., hypo-mobile, within normal limits, or hyper-mobile), as subsequent treatment should target only the directions that are restricted.

Patellar mobilization is the mainstay of treatment for patellar hypo-mobility. Patellar mobilizations are typically performed manually by a physical therapist; however, some of the techniques may be instructed to the patient to be performed at home. Self-mobilization may be an effective method because of increased dosage of treatment and improved patient self-efficacy. The patella is manually held and moved in the direction of restriction, using oscillatory motions or static holds. By combining patellar mobilization with therapist-assisted static stretching is effective, particularly for the iliotibial band (ITB) and lateral patellar retinaculum.

Patellar mobilization is commonly used in the treatment of patellofemoral pain, however, empirical evidence showing its effectiveness is limited. This may be due to the lack of a valid and reliable clinical examination technique for patellar position or mobility without the use of specialized instrumentation.59,60 Presence of joint mobility impairment in patients with patellofemoral pain has been questioned, with one cross-sectional study showing no difference in patellar mobility between adults with and without patellofemoral pain.59 It is possible that subsets of patients with patellofemoral pain exist with different impairment patterns, and not all patients with the same pathology present with impaired joint mobility.61

**Myofascial Considerations**

Myofascial restrictions may contribute to patellofemoral compression and pain. Fascia lata, the deep fascia of the thigh, is extensive and structurally strong, and continuous deeply with the lateral intermuscular septum and superficially and laterally with the ITB.62 Myofascial tightness in the thigh may lead to over-constraining of the patella and increased compression in the patellofemoral joint and under the lateral retinaculum.63 Additionally, active myofascial trigger points in the thigh may directly refer pain into and around the knee.64 Myofascial restrictions may be assessed by direct palpation of the soft tissues and trigger points. An
active trigger point is characterized as a tender nodule in a taut band within a muscle, where manual compression triggers a local muscle twitch response or referred pain to an area other than where the compression is applied.\textsuperscript{65} Identification of an active trigger point following the criteria above has moderate inter-rater reliability.\textsuperscript{66,67}

Once myofascial restrictions are found, several intervention strategies are available. Active trigger points may be treated by direct manual compression, passive stretch of the involved muscle, and neuromuscular re-education by performing therapeutic exercises which target that involved muscle. This combination of interventions in physical therapy may be as effective as dry needling in relieving myofascial pain.\textsuperscript{68}

Foam roller and stick roller are popular tools used in physical therapy to address myofascial restrictions, improve flexibility, and increase joint range of motion. Several groups of researchers have reported that applying a foam roller or stick roller on the thigh resulted in an increase in quadriceps, hamstrings, or hip flexor flexibility and knee or hip joint range of motion in healthy subjects.\textsuperscript{69-74} However, it is unknown if these effects were sustained in the long term or the results are generalizable to a clinical patient population. Instrument-assisted soft-tissue mobilization may also be beneficial in addressing myofascial restrictions. In one randomized trial, an instrument-assisted technique was superior to foam rolling in increasing knee flexion range of motion and hamstring flexibility after one intervention session in healthy subjects.\textsuperscript{75} Further scientific inquiry is warranted to establish the clinical utility and the mechanisms of action of these various myofascial intervention techniques.

**Strengthening Component to Compressive Issues**

Soft tissue mobility is one of the primary clinical considerations when assessing patella compressive dysfunction, however, as early as 1976, Nicholas et al recognized that patients with patellofemoral dysfunction presented with the greatest amount of muscle weaknesses of all the injured groups tested. These weaknesses included hip flexors, hamstring and quadriceps.\textsuperscript{76} Nicholas et al noted the linkage weakness from the hip to the ankle in these patients.\textsuperscript{76} Overall lower extremity assessment and strengthening is a key component to proper treatment of patellofemoral conditions.

Multiple authors have highlighted the importance of proximal hip strengthening for patients with patellofemoral dysfunction. Fukuda et al. showed that adding hip strengthening to a conventional knee rehab program in patients with PFPS produced better results in pain, lower extremity scores, and functional tests compared to those simply using a knee rehab program.\textsuperscript{8} Dolak et al showed faster improvement in anterior knee pain with the addition of a hip strengthening program, compared to a standard knee rehab program.\textsuperscript{7} Khayambashi et al. showed that simply prescribing hip external rotation and hip abduction strengthening exercises to patients with PFPS resulted in normalized pain, improved function, and significant gains in hip strength after eight weeks.\textsuperscript{77}

Work by Tyler et al showed not only was it important to normalize hip flexibility, but normalizing hip flexion strength was a key component to a successful outcome in patients with patellofemoral pain.\textsuperscript{6} By resolving three key factors, namely normalizing Ober's test side to side, normalizing the Thomas test side to side, and improving hip flexion strength by more than 20% (measured with a hand held dynamometer), a successful outcome was reached in 93% of patients. If only two of these factors were resolved, a success rate of 75% was reached. If only one of these goals was reached, there was only a 27% success rate. Each of these factors plays a large part in successful outcomes in these patients, by identifying these factors and normalizing them, a high success rate is attainable.

**CONCLUSION**

Each patient with patellofemoral compressive issue presents with a unique set of impairments. Key impairments associated with patellofemoral compressive issues can be reliably assessed using the established tests and measures described in this paper. Once these key impairments are identified, a wide range of intervention techniques, including therapeutic exercises, manual therapy, and instrument-assisted methods, can be implemented to address the impairments and promote functional recovery. Once a decrease in compression and improvement in soft tissue mobility have been achieved, strengthening of the hip and lower extremity muscles is a key component.
that should be considered. Selection of specific intervention techniques must take into account patient's preferences, skills and tools available to the therapist, and available evidence as summarized in this clinical commentary.

REFERENCES


ABSTRACT
Identification, protection, and management of patellofemoral articular cartilage lesions continue to remain on the forefront of sports medicine rehabilitation. Due to high-level compression forces that are applied through the patellofemoral (PF) joint, managing articular cartilage lesions is challenging for sports medicine specialists. Articular cartilage damage may exist in a wide spectrum of injuries ranging from small, single areas of focal damage to wide spread osteoarthritis involving large chondral regions. Management of these conditions has evolved over the last two centuries, most recently using biogenetic materials and cartilage replacement modalities. The purpose of this clinical commentary is to discuss PF articular cartilage injuries, etiological variables, and investigate the evolution in management of articular cartilage lesions. Rehabilitation of these lesions will also be discussed with a focus on current trends and return to function criteria.

Level of Evidence: 5

Keywords: Articular cartilage, anterior knee pain, osteochondral defect, osteochondritis dissecans, patellofemoral pain
INTRODUCTION
Although the patellofemoral (PF) articular cartilage is the thickest in the human body, it is not immune to breakdown and injury. When in healthy condition, this amazing anatomical structure is able to resist and disperse tremendous loads as well or better than any man-made material. The co-efficient of friction is almost zero, which allows articular cartilage to transmit forces with relative ease. Unfortunately, when breakdown occurs, there is little or no healing capacity of articular cartilage. Articular cartilage injuries may limit sporting activities as symptoms develop that limit peak performance and/or create the inability to maintain a healthy lifestyle of exercise. Factors that influence this breakdown may include: 1) articular cartilage injury during knee ligament disruption, 2) excessive body weight with sporting activity or exercise, 3) PF dislocation 4) knee arthrofibrosis 5) and joint geometry/limb alignment.

Although exciting surgical techniques and rehabilitation advances have been developed, often simply gaining normal strength, flexibility, and modifying sporting activities may yield good results with this difficult to treat problem. When those efforts fail, thankfully surgical intervention techniques exist that have been developed to assist articular cartilage injury recovery. These procedures often require a prolonged rehabilitation process that commonly includes a period of non-weight bearing and gradual return to activity. Having expert knowledge of the biomechanics of the PF joint, articular cartilage, and muscle forces about this joint allows the sports medicine clinician to help patients focus their energy and efforts towards the most efficient pathway towards recovery. Far too often, patients waste time performing inappropriate and sometimes-harmful exercises and techniques that only retard their progress.

The purpose of this clinical commentary is to discuss PF articular cartilage injuries, etiological variables, and investigate the evolution in management of articular cartilage lesions. Rehabilitation of these lesions will also be discussed with a focus on current trends and return to function criteria. There are two main sub-focal points of this commentary, osteochondritis dessicans (Odessicans), and osteochondral defects (Odefect) of the PF joint. A general overview will be presented that will cover both maladies then specific information for each diagnosis.

HISTORICAL EVOLUTION OF THE TREATMENT APPROACHES FOR ARTICULAR CARTILAGE LESIONS
Articular cartilage lesions have been a dilemma for treating physicians dating back to the initial medical reports, in 1743, by Dr. William Hunter. Hunter described the appearance of an “ulcerated cartilage” in the knee. Of particular concern, Hunter described the lesion as lacking native regenerative potential. Dr. Paget echoed these concerns, reporting that there is no known intervention able to restore or completely repair injured cartilage due to a lack of substantial vascular response and the relative absence of undifferentiated cells available to respond to injury. Compounded by the large biomechanical forces seen by the PF joint during normal daily activities, articular cartilage lesions may become a debilitating problem.

Early Cartilage Procedures: Debridement and Reparative Procedures.
Sixty years ago, in 1945, Haggart and Magnuson sought to reduce mechanical symptoms and pain in the knee caused by articular cartilage defects via cleaning the joint and joint surfaces. This open procedure involved joint lavage and simple debridement of the joint surfaces. Reports of short-term pain reduction were overshadowed by failure of the arthritic joint due to disease progression. Development of arthroscopic techniques sought to improve results, however never offering the possibility to actually promote articular cartilage repair. Arthroscopic debridement continues to be utilized today as a technique for diminishing mechanical symptoms and joint irritation, capable of producing success in short term pain management.

Abrasion Drilling and Early Phase Microfracture
In 1946, Pridie revolutionized what would eventually become a hallmark of cartilage reparative treatment, ten years after Haggart and Magnusson, Pridie with the assistance of Johnson, described the procedure of drilling into the defective cartilaginous area and penetrating the subchondral bone.
Lateral Retinacular Release: Realignment Techniques

Isolated lateral retinacular release procedures are a controversial surgical option. This procedure involves incising and thus releasing part of the lateral retinaculum in an attempt to centralize the patella in the trochlea to decrease the lateral tilt of the patella, and enhance patellar tracking. Researchers have debated whether releasing the lateral patellar restraint actually leads to altered patellar contact pressures or aids in patellar stability. Short term data was encouraging initially, although research is sparse and inconsistent with respect to long-term outcomes and function. This procedure is not without complications, one being a too aggressive release creating hypermobility of the PF joint with increased instability, dysfunction, and pain. The only indication for such a procedure is the presence of a tight lateral retinaculum.

Autologous Matrix Induced Chondrogenesis (AMIC)

The final phase of marrow stimulation, AMIC, was introduced in 2005, and was the next technological advancement following the microfracture procedure. AMIC utilized a collagen scaffold that was placed over the defect, which serves to hold the blood clot and mesenchymal stem cells in place following microfracture drilling. Current research seems to support the value of the AMIC procedure in retropatellar defects, when unresponsive to microfracture alone. Described below, various chondrocyte implantation procedures have evolved from this procedure.

Modern Microfracture

Nineteen ninety-two marked a pivotal point in arthroscopic surgical techniques that addressed articular cartilage lesions. Steadman developed, a widely utilized technique, called the microfracture procedure. This technique utilizes a controlled drilling into, but not through, subchondral bone with careful focus on drilling using precise specifications. A major concern and overwhelming disadvantage with the microfracture procedure is the loss of structural integrity of the cartilage produced by the procedure. Furthermore, unlike hyaline cartilage found in native articular cartilage, microfracture produces fibrocartilage composed of primarily Type I collagen that has significantly different biomechanical properties than hyaline cartilage. This structural difference in tissue is the primary criticism and motivation for continued evolution of restorative and replacement cartilage procedures, throughout the body, most typically in the tibiofemoral and the PF joints. Although more advanced techniques and procedures have been developed, microfracture continues to be a popular technique due used to treat both retro-patellar and trochlear cartilage lesions.

Restorative and Reconstructive Procedures

With the start of the 21st Century, cartilage restorative, replacement, and stem cell propagation have become increasingly more popular and ultimately the forefront of research and intervention.

Autologous Cartilage Implantation (ACI) & Matrix-Induced Autologous Chondrocyte Implantation (MACI): Restorative Techniques

A landmark animal study presented by Peterson et al in 1984 reported early positive outcomes of bio-engineered tissue implantation for chondral defects.
that did not penetrate the subchondral bone. After a
decade of research, the FDA approved the first cell
therapy for use in restoring articular cartilage, Car-
ticel, in 1997.

ACI is a staged procedure, which utilizes an arthroscopic
biopsy of normal hyaline cartilage or bone marrow to
be used to culture chondrocytes, in vitro, for implanta-
tion at a second staged surgery. These maturing cells
are placed in the cartilage defect beneath an autologous
periostial patch, an evolution of the scaffolding patch
described for use in the AMIC component of micro-
fracture. Based on early success, ACI saw an increase
in utilization, specifically in treatment for cartilage
damage of the femoral condyles, trochlea, and patella.
Since Peterson’s original description, there have been
several modifications of the technique of autologous
chondrocyte implantation (ACI).15

The 3rd generation in autologous cartilage implanta-
tion, matrix-induced autologous chondrocyte implant-
tion (MACI), has become more frequently used,
especially in European medicine. MACI uses tempo-
rary, biodegradable scaffolds to enhance the implanted
chondrocytes by reducing graft hypertrophy, lessening
chondrocyte leakage, creating a more homogenous
chondrocyte matrix, and an overall shorter operative
time.

ACI is a common treatment approach for PF lesions
considered too large for microfracture, however suc-
cess in PF lesions remain inferior to those performed
elsewhere in the tibiofemoral joint.16 Of note, ACI
and MACI procedures combined with an unloading
tibial tubercle osteotomy (AMZ) have produced sig-
nificantly higher improvements in functional out-
comes and overall patient satisfaction.16

Osteochondral Plug Autograft Procedures:
Osteochondral Autograft Transfer System
(OATS) & Mosaicplasty: Restorative
Techniques
Osteochondral autograft transplantation (OATS) was
initially described by Judet et al16 in 1908. OATS and,
mosaicplasty, involve the harvesting of multiple indi-
gual osteochondral plugs from the patients’ donor
site, typically the non-weight-bearing area of the fem-
oral condyle in the knee. The grafts are pressed into
the debrided lesion in a “mosaic-like” fashion within
the same-size drilled tunnels. The resultant surface
consists of transplanted hyaline cartilage. Fibrocar-
tilage arising from abrasion arthroplasty is theorized
to act as a “grout” between the individual autografts.
Consequently, this procedure is dependent on the
availability of quality donor tissue for the transplant.
Typically, harvest sites for the PF joint are the medial
and lateral margins of the trochlea, the intercondylar
notch, and the posterior femoral condyles. Garretson
et al reported that the medial trochlea had the lowest
contact pressures, followed by the distal lateral troch-
lea, and that these two areas could provide desirable
donor grafts.17 Limited research exists regarding out-
comes after OATS procedures for PF joint lesions.
The procedure is considerably more challenging and
complicated for patellar lesions (as compared to tib-
iofemoral lesions) in large part due to the difficulty
of correctly matching the surface concavity and con-
vexity of the PF articulation.

Osteochondral Allograft: Restorative
Technique
Initially reported by Lexar18 in 1908, osteochondral
allograft transplantation utilizes similar principles
as the autograft procedures, OATS and mosaicplasty.
Although the initial results seemed promising, the
logistical problems of tissue acquisition (fresh, un-
irradiated osteochondral grafts) compounded by
the high risk of disease transmission, has limited
the plausibility of these techniques throughout the
century. Cryopreserved grafts allowed for appropri-
ate processing and lowered the risk of disease trans-
mission, however also decreased the viability of the
chondrocytes in the transplant.

In the late 1990’s, transplants were made commer-
cially available in the United States with a change in
the FDA’s harvesting procedure techniques substan-
tially increasing the utility of allografts. This innova-
tion involved a type of refrigeration method that led
to a significant increase in allograft implementation,
more commonly on the femoral condyles. However,
small utility does exist for trochlear cartilage lesions
but is a more complicated procedure than tibiofem-
oral implantation.

Patellofemoral Arthroplasty: Replacement
Techniques
Patellofemoral arthroplasty (PFA) has been avail-
able for approximately 30 years, although outcomes
and clinical indications are scattered. The procedure sought to correct an isolated PF compartment failure by replacing this compartment using low friction components. This was an intervention was ultimately designed for younger patients, with isolated PF lesions, and were too young for a complete total joint replacement. A thin metallic shield covers the trochlear groove and a dome-like plastic implant is placed on the retropatellar surface. Both components are held in place by bone cement. Unfortunately, in many cases, chondral changes eventually progressed to include the medial and lateral compartments. This led to controversy over outcomes, and ultimately PFA has become less popular in recent years.

**Biologic Agents: Mesenchymal Stem Cells (MSC’s)**

In 1994, the use of bone marrow mesenchymal stem cells (MSC’s), rather than chondrocytes, during the ACI procedure was described with the intention of producing a more homogenous hyaline cartilage state. This marked the first autologous implantation of stem cells for treatment of cartilage defects. Initial proposed successes of these procedures suggested the use of biologic agents as a medium to enhance or augment other procedures.

MSC’s utility generically revolves around two criteria: the ability to self-replicate in the placed environment (proliferation), and ability to differentiate to suit the necessary tissue (maturation). Friedenstein et al first demonstrated that bone marrow cells (MSC’s) could differentiate into bone and cartilage. Furthered by Johnstone et al and Pittenger et al respectively, it was determined that MSCs harvested from bone marrow could ultimately differentiate into bone, cartilage, tendon, ligament, fat, and other tissues of mesenchymal origin. MSC’s can be harvested from a variety of sources, such as peripheral blood, or bone marrow and adipose (both of which being significantly more successful and higher concentration than blood based harvesting).

First-generation MSC’s were used via direct implantation under a periosteal patch, similar to ACI procedures. Second-generation techniques removed and differentiated the MSCs in vitro, typically using a biotype matrix and were implanted into the affected lesion once matured. These procedures failed to succeed with evidence now suggesting that non-expanded MSC therapies are not effective to produce viable articular cartilage. New-generation techniques have begun that include implanting the cells and bio scaffolding in association with platelet rich plasma (PRP) fibrin glue into the lesion. Evidence has shown initial support, but cell differentiation, reproduction, mechanical integrity, and ultimately the longevity of the materials remains unknown. Despite a growing body of evidence, the use of MSC’s continues to need further research. Most typically, MSC’S are used in procedures as a supplement to enhance success, such as meniscal repairs, cruciate reconstructions, cartilage transplantation, primary restorative interventions, as well as agents to prevent graft-versus-host failures.

**Biologic Agents: Platelet Rich Plasma (PRP)**

Reports of PRP utilization can be found as early as the 1970’s, although the concepts of platelet count and volume are more recent evolutions. PRP is simply withdrawing peripheral blood and, by centrifugation, obtaining a highly concentrated sample of platelets to re-introduce as an inflammatory and growth factor supplement. Current research is related to improving platelet count, increasing concentration of growth factors, and examining mechanisms by which sustained activation of the mediating factors can be achieved.

Current PRP trends have seen an exponential influx in use over the last decade for a variety of musculoskeletal pathologies, although literature is inconclusive at this time related to clinical outcomes and indications. PRP is relatively easy and convenient to extract, as well as relatively inexpensive when compared to other biologic stem cell agents, which makes it a viable option for first line treatment in non-surgically indicated pathologies, such as retro-patellar chondromalacia or small partial thickness defects.

**Future Trends**

The use of autologous MSCs for the treatment of musculoskeletal conditions is currently unproven, and its clinical efficacy and safety are yet to be determined, despite a proliferation of clinics offering and actively marketing MSCs for treatment of several musculoskeletal problems. Currently, evidence is lacking to rec-
Collagen is the key protein providing the structural and mechanical properties of general connective tissue. The abundant proteoglycan molecules found in various concentrations throughout articular cartilage, due to their large size and immobility within the collagen fiber meshwork, act as the ‘pump’ of the highly pressurized system. This is the mechanism by which water (as well as the nutrients it carries) is introduced within the tissue. Articular cartilage is roughly 2-4 mm thick and contains four separate zones: superficial (tangential), middle (transitional), deep, and calcified.

- The superficial zone makes up 10-20% of the cartilage thickness. This zone contains a high concentration of flattened chondrocytes, providing protection to the deeper layers. It is also responsible for absorption of the majority of the tensile and sheer forces applied to the tissue. This is due in large part to the tightly packed, high concentration of collagen fibrils aligned parallel to the joint surface. The chondrocytes in the superficial zone are more spherical and found in lower concentration.

- The middle zone of the articular cartilage provides a functional bridge between the superficial and deep zones. It is the largest of the zones, accounting for 40-60% of the total volume. It contains a higher concentration of proteoglycans as well as collagen fibrils thicker than those found within the superficial zone. These fibrils are arranged obliquely and account for the first line of resistance to compressive forces. The chondrocytes in the middle zone are more spherical and found in lower concentration.

- The deep zone makes up the final 30% of the articular cartilage, and gives the greatest resistance to compressive forces. This is due to the high concentration of proteoglycan within this zone as well as the collagen fibrils, which are larger here compared to the other zones, and are arranged perpendicularly to the joint surface. The chondrocytes in the deep zone are arranged columnar, and parallel to the collagen fibrils. The calcified zone anchors the collagen fibrils of the deep zone to the subchondral bone. The calcified and noncalcified collagen fibrils within these deep two layers are separated by a boundary called the tidemark.
**PATHOPHYSIOLOGY**

Articular cartilage itself has no innervation or blood supply, therefore it requires motion for nutrition from joint fluid. The nearest pain receptors to the articular surface are located in the subchondral bone. The natural effects of aging on articular cartilage involve collagen framework damage due to the loss of proteoglycans. During the breakdown of the collagen framework, the arthritic process begins with fibrillation, the formation of scar tissue-like fibrocartilage, poorly suited for managing compressive and shear forces. As earlier stated, articular cartilage exists without vascularity and lymphatics. Nutrition is supplied via the surrounding synovial fluid through diffusion, enhanced by joint loading and motion. When a load is applied across the joint, tissue compression occurs, displacing water molecules from within the tissue. When the load is removed, the proteoglycans are allowed to swell, drawing in new water molecules (and nutrients) and restoring equilibrium.

Although the anatomy of articular cartilage provides resistance to wear and tear, breakdown will eventually occur. Many risk factors have been suggested to contribute to cartilage pathology including age, heredity, joint malalignment, obesity, metabolic diseases, and joint trauma. This commentary will focus on articular cartilage injury in the PF joint due to its relatively high incidence in sports.

It is important to note that lack of knee extension or flexion range of motion post-operatively can be a factor in the development of PF chondral injury. For example, lack of extension is most often caused by posterior joint tightness/stiffness or anterior interval impingement and patellar hypomobility. This lack of extension directly leads to a flexed-knee gait pattern that places the PF articular surfaces at risk. As the individual bears weight through a flexed knee, the PF joint reaction forces increase and lead to increased compression of the patella in the trochlear groove. These excessive compressive forces can lead to damage of the articular side of the patella.

**OSTEOCHONDRAL DEFECTS (ODEFECTS)**

Within the athletic population, cartilage injury often occurs due to acute or chronic mechanical overloading, malalignment causing asymmetrical loading patterns, or chronic under loading leading to disuse atrophy. Injury to the articular cartilage most typically occurs due to a twisting injury or high impact forces sustained through the joint during sporting activities. In these cases, the area of injury is often localized and termed a **focal articular cartilage, or chondral injury.** Although the exact pathophysiology is not completely understood, it is widely speculated that focal injury causes damage to the chondrocytes, proteoglycans, and collagen fibrils located in the deeper layers of articular cartilage. When joint forces surpass the threshold of compressive or shear loading for this tissue, irreparable harm is done to the deep layers, which can include the subchondral bone. This insult to the subchondral bone can lead to the death of local chondrocytes and calcification of the involved hyaline cartilage, as well as fibrillation within the margins of the defect. Over time, these traumatic focal lesions can take the appearance of a progressively degenerative wear patterns.

Due to its avascular qualities, articular cartilage injuries have low affinity for independent regeneration. Partial-thickness defects (those not penetrating through to the sub-chondral bone) may worsen over time as degeneration happens in addition to the focal damage. Full-thickness defects can potentially fill with a form of secondary scar tissue by way of native stem cell differentiation due to the vascularity of the underlying bone. This scar tissue is largely fibrocartilage, containing different load compliance than native hyaline cartilage, which originates from the marrow cavity and local stem cells. Because this Type I collagen is not as durable as the Type II hyaline cartilage that existed previously, the resulting surface of the bone is vulnerable to additional deterioration and pain.

As the articular surfaces of a joint sustain injury and or deteriorate, pain and functional limitations may increase. The severity of these symptoms depends on the scale of the damage to the chondral surface. This can be graded based on depth and size of the cartilaginous defect. The Outerbridge Classification is commonly used to describe the extent of chondral damage, and is scored as follows: 0 = Normal cartilage; I = Cartilage with softening and swelling; II = Fragmentation and fissuring in an area half and inch or smaller in diameter; III = Fragmenta-
tion and fissuring in an area larger than half an inch; IV = Erosion of cartilage down to subchondral bone. Typically, the higher the lesion, the more impact it has on a person’s functional tolerance.

Chondral damage can result from various etiologies, but these generally fall into two categories: traumatic and insidious. In an orthopedic setting, traumatic injuries during athletic activities are among the most common causes of chondral lesions. A less common cause typically found in younger populations, is Odisssecans. Odisssecans have been found to be more commonly associated with structural abnormalities, including patellar malalignment or instability. These abnormalities must be corrected in order to provide the best possible outcomes following cartilage repair. Valgus or varus malalignment of the lower extremity is a good example of such an abnormality, and can result in overload of the medial or lateral compartment and lead to degeneration of the articular surface.

Ligamentous compromise (i.e. anterior cruciate ligament [ACL] injury) and/or meniscal insufficiency leads to increased shear forces on the articular cartilage of the knee, and can result in subsequent chondral degeneration. This is an important consideration when evaluating the need for cartilage procedures. In the case of previous meniscal damage or meniscectomy, up to three times the joint forces can be placed on the involved compartment, leading to the advancement of arthritic changes. In certain patients with insufficient meniscal tissue, transplantation of allograft meniscal tissue can be used to allow for improved function and decreased pain.

Noyes et al found an incidence rate for chondral damage of 6-20% in arthroscopic examinations of knees with acute hemorrhage. They also found a higher incidence of chondral damage in knees that sustained a mechanism of injury consistent with those that produce ACL tears. These chondral lesions led to greater instances of long-term symptoms including pain, catching and swelling, especially with impact activities. Curl et al looked at the prevalence of chondral injuries in a review of over 31,000 knee arthroscopies. Not only did they find that 63% of patients had sustained hyaline cartilage lesions, but discovered a total of over 53,000 lesions, a number far larger than the observed knees indicating that many had multiple sites of damage. The most common sites reported were the medial femoral condyle and the patella.

In young athletes, traumatic hemorrhage is associated with chondral defects in up to 10% of knee injuries. Due to the mechanism of injury, patellar dislocations are strongly associated with Odisssecans to the articular surface, and occur at a rate up to 95% of the time. Odisssecans is estimated to occur in 30-60 cases per 100,000. Most of the time, these defects are initially found upon arthroscopic examination of the knee during meniscal or ligament reconstruction procedures. It is important to note that although this incidence may seem high, many of these defects are asymptomatic and found to be incidental.

**OSTEOCHONDROSIS (ODISSECANS)**

Odisssecans describes the pathologic condition involving delamination and/or sequestration of the subchondral bone from the underlying tissue. It is important to understand this condition as a different and specialized chondral injury separate from...
that of an Odefect, which identifies any breakdown of the articular cartilage. Although the conditions can present symptomatically similar, treatment and management are notably different.

The initial reports of the condition date back to 1870 by Paget who deemed the condition “Quiet Necrosis”, only to be further expanded and coined Osteochondritis Dissecans by Konig in 1887, reporting the pathologic process as the result of inflammation of the subchondral bone and articular cartilage.32,45,54 Research and epidemiological studies over the last century have somewhat disproven this hypothesis and thus identified the term “chondritis” as incorrect, dispelling the condition as inflammatory. However, subsequent comprehensive research has failed to completely identify the etiology and natural history for the pathology.45,54,55 Areas of interest include: genetic predisposition, defective skeletal development, vascular insult, repeated trauma, and altered joint/cartilage loading mechanics. With respect to the disease process, the death of the subchondral bone as a primary or secondary factor eludes current understanding and leaves a large area of future focus.32,55

Statistically, the incidence of Odissecans has been reported by multiple sources to be around 15 to 29 per 100,000 patients, with the knee being the joint most affected.55 Odissecans pathology is most frequently seen in patients in the second decade of life, affecting males greater than females (5:3, respectively).55 There is reason to believe the incidence is a result of higher activity participation within the second decade, while statistical gender trends are shifting, with comparable female to male shifts due to the increasing sports participation in females.55,56 Risk factors, historical markers, and genetic identifiers are important to consider, although their exact contribution is unclear at this time.

The pathology is commonly associated with mechanical symptoms, joint effusion, pain, and significant functional limitation involving a spectrum of daily activities. Management is largely based on the combination of all of the above factors ranging from age and activity of the patient, to the type of injury, and ultimately the stability of the involved area. Odissecans pathology is often divided into juvenile Odissecans, occurring in an individual with open physes (average age 14 years) and reported as more common, or adult Odissecans, those with closed physes (average age 26 years).32 A shift in the average age has expanded in both directions as sports participation has seen a shift in early sports participation specialization as well as increases sport longevity and participation later through life.55,57

PF Odissecans, accounting for a large majority of the epidemiological Odissecans cases, varies in treatment recommendation due to the lack of empirical data and breadth of the etiological risk factors. Three distinct locations can be identified within this region: the retro-patellar region, the medial femoral condyle, and lateral femoral condyle. Although the general rehabilitation philosophy remains consistent, certain factors will be adjusted based on PF joint mechanics and loading patterns with exercise. The trochlear groove of the PF joint is the rarest location in the knee for Odissecans and accounts for 0.6% of all Odissecans in the knee.

EXAMINATION AND DIAGNOSIS

Physical Exam and Subjective Reports
Diagnosis of articular cartilage lesions of the knee can be a protracted process as symptoms are often vague and intermittent depending on the activity level of the patient, and at first, presentation can be mistaken for more innocuous PF instability or general dysfunction. Despite its challenges, prompt identification of these lesions is critical to successful management as earlier application of the most appropriate intervention provides superior clinical outcomes with prevention of continued joint degradation.58,59

Odissecans and Odefects have similar clinical presentations, and distinction between the two lesions is difficult to establish through physical examination alone. Diagnostic imaging, however, reveals clear distinctions between the two pathologies and requires varying surgical and rehabilitation protocols depending upon the type of lesion. As such, Odissecans and Odefects will be treated as one entity during the physical examination review but will be handled separately for the imaging discussion.

Individuals with cartilage lesions typically complain of activity-related pain, recalcitrant effusion, and catching or locking of the joint.58 Symptoms are
usually exacerbated by weight-bearing and high-impact activities and alleviated by a period of rest. The clinical examination can assist with ruling out ligamentous instability and meniscal pathology, but it remains difficult to rule in chondral defects, as common clinical tests are unreliable (i.e. Wilson’s Sign, Clark’s Sign). Common findings include bony tenderness with palpation on or near the chondral lesion, antalgic gait pattern, and loss of range of motion secondary to effusion, prolonged guarding, or loose body entrapment.\(^\text{50,60}\)

**Imaging: Osteochondral Defects (Odefects)**
The mainstay of clinical diagnosis remains with radiographic and magnetic resonance imaging (MRI) studies as these provide the most accurate insight to allow proper identification and staging of the cartilage lesion apart from arthroscopic investigation. Although with less diagnostic accuracy than MRI, plain radiographs are indispensable in early diagnostic work-up and are typically the first line of imaging ordered. For patellar lesions and assessment of PF articulation, sunrise or merchant views are of greatest utility, and weight-bearing anterior-posterior views can also be valuable. These primary images can rule out other bony pathology, reveal lesion location and extent of degradation, and guide decisions regarding further diagnostic workup.\(^\text{58}\)

Secondary imaging via MRI is recommended to allow more accurate pre-operative classification of chondral lesions with regard to severity and size, which will then guide pre-operative decisions on which reparative or restorative surgical technique to implement. Additionally, for any articular cartilage pathology of traumatic origin, MRI can allow more complete assessment of the underlying subchondral bone and the osteochondral interface than arthroscopy alone, which can miss microtrabecular fractures (bone bruises).\(^\text{61}\)

Once a diagnosis has been established, treatment recommendations can be made based on size, stability, and location of the lesion. Other prognostic factors that must be included in the surgical decision-making process include age, skeletal maturity, BMI, and the patient’s desired activity level; however, for most high-level athletes, surgical intervention is essential to enable unrestricted return to play.\(^\text{59}\)

**Imaging: Osteochondritis Dissecans (Odissecans)**
As with Odefects, plain radiographs are typically the first diagnostic imaging ordered prior to advanced imaging via MRI. Lateral and tunnel (notch) profiles are best suited in visualization of Odissecans lesions. These primary radiographs allow for gross assessment of cartilage integrity, localization of larger lesions, staging of the lesion. These films also allow assessment of bone age in the youth population, which is of particular value in determining patient

---

**Figure 2.** Trochlear chondromalacia on radiographs. Lateral (A) and merchant (B) radiographs of the knee demonstrate undulation of the articular surface of the medial trochlea (white arrows), representing reactive proliferation of the subchondral bone indicating overlying chondromalacia.
Figure 3. Trochlear microfracture. A) Preoperative sagittal proton density fat-saturated knee MR image shows a full-thickness cartilage defect at the superior aspect of the trochlea with mild subarticular marrow edema (white arrow). B) Post-operative sagittal proton density fat-saturated knee MR image performed 3 months after microfracture demonstrates partial fibrocartilage fill of the microfracture site with minimal residual subarticular marrow edema (white arrowhead). C) Follow-up sagittal proton density fat-saturated knee MR image performed almost 3 years after the microfracture shows near complete fill of the microfracture site with a combination of fibrocartilage and reactive subarticular bone proliferation (black arrowhead). There is complete resolution of the subarticular marrow edema.

Figure 4. Trochlear osteochondral allograft. A) Pre-operative sagittal proton density fat-saturated knee MR image shows a large full-thickness cartilage defect in the inferior central trochlea with minimal reactive proliferation of the subchondral cortical bone (white arrow). B & C) Post-operative sagittal proton density fat-saturated (B) and T1 non-fat saturated (C) images of the same region demonstrates interval placement of osteochondral allograft in region of previous full-thickness cartilage loss. The osteochondral graft is flush to the native cartilage with small fluid clefts at the interface between the native and transplanted cartilage (white arrowheads). There is complete osseous incorporation of the graft with normal bone marrow signal within the graft and absence of linear fluid-like signal or cystic change at the interface between the graft and native bone (black arrowheads).
prognosis as younger individuals with open physes have a much stronger prognosis with conservative management alone.45,50

After plain films have been obtained, MRI is required for complete investigation of the lesion. Key imaging findings include distinct chondral fragments, discrete loose bodies, high T2 signal intensity between parent and progeny bone, and disruption of the chondral surface.50 The value of MRI can be superior to that of direct visualization via arthroscopy as it allows more complete assessment of the underlying subchondral bone and the osteochondral interface, which can be missed intraoperatively with stable Odissecans lesions.50,59

SURGICAL INTERVENTION
Surgical management is generally considered after adequate nonoperative management has failed to provide acceptable pain relief or if after establishing that a patient's symptoms are secondary to a full thickness (Grade 3 or 4) cartilage defect. It is important to remember that one must view the management of PF cartilage injuries in a slightly different manner. The current literature unfortunately reveals that the PF compartment is a difficult location for cartilage repair and that all recognized techniques performed here have lower success rates than similar techniques performed on the femoral condyles. While microfracture, osteochondral autograft transfer, osteochondral allograft transplantation and ACI have shown good clinical outcomes in the femoral condyles, there exists a growing consensus that these procedures should all be used prudently in the PF compartment, except in certain specific situations.62 In one study, microfracture in the PF compartment demonstrated transient improvement, with worsening outcomes after eighteen to thirty six months.63 Osteochondral autograft transfer used in the PF joint has mixed results with one study showing only slightly worse results than that seen in the femoral condyle,64 yet another study demonstrated disastrous results with nearly universal failure with OATS performed for a defect in the patella.65 Osteochondral allografts performed in the PF compartment have shown good results, with 60% good to excellent outcomes reported by Jamali et al.66 ACI has recently demonstrated much improved outcomes with >80% success seen in the PF joint despite initial studies reporting disappointing results.67-70 While a defect in the patella remains an off-label indication for ACI, this repair option now represents the procedure of choice for all but the smallest defects in the PF joint. However, it remains crucially important to correct any malalignment and abnormal patellar tracking, regardless of which surgical repair option is used, as these predisposing conditions will likely lead to a universal failure of any procedure performed if not appropriately addressed.

Small and Medium Sized Cartilage Defects ( <2-4 cm²)
The initial treatment for small to medium sized (<4 cm²) symptomatic cartilage lesions, after a patient fails nonoperative management, generally begins with an arthroscopic debridement and chondroplasty of the defect. This involves excising degenerative tissue around the defect and creating a mechanically stable lesion with the use of arthroscopic shavers, basket forceps and curettes. This can be the definitive treatment for the majority of patients or an initial procedure before contemplating more invasive repair options. Patients recover from this procedure quickly, can be made full weight bearing as tolerated and can return to full activity, including return to running and cutting sports when pain and swelling have disappeared.

Microfracture and OATS (speaking to Odefects specifically) are also viable options in the presence of slightly larger defects or having failed a previous debridement with chondroplasty. These procedures involved graduated weight bearing progression and long-term rehabilitation time frames. This will be discussed at more below.

Large Sized and Complex Cartilage Defects ( >2-4 cm²)
When managing larger (3-4 cm²), full thickness focal chondral lesions in the trochlea (or femoral condyles), ACI is a good technique that is indicated for these more complex injuries. This is accomplished via a two staged procedure, first assessing the lesion arthroscopically to make sure it is contained and that the depth of the lesion does not exceed 8 to 10 mm, which would require bone grafting. The second stage of the operation, a limited or more extensive medial or lateral parapatellar arthrotomy is required because adequate exposure is paramount.
OATS in the PF joint is typically reserved for use in younger patients without signs of arthritic changes when revising a prior failed cartilage repair. This is done to implant a side and sized matched, fully developed cartilage that does not need to heal. The allograft bone requires healing, however, and acts as a scaffold, which incorporates over time. However, OATS at the trochlea or patella becomes challenging given the complex anatomy to be transplanted. A shell allograft, much like used when performing PF arthroplasty, can be used for more extensive lesions in the trochlea. Press fit cylindrical plugs are typically used for isolated patellar facet lesions or for more extensive patellar defects, patellar allograft resurfacing is a good option using double pitched screws placed from anterior to posterior. This procedure requires adequate visualization, so an open approach is performed. Contraindications to OATS include inflammatory arthropathies (rheumatoid or other systemic arthritis), advanced degenerative changes, corticosteroid induced osteonecrosis, knee instability or malalignment.

Odessicans is managed based on the pathoanatomy of each individual lesion. These are typically addressed arthroscopically. If the lesion demonstrates intact articular cartilage, it is best to drill the lesion in a retrograde fashion to not violate the articular cartilage. This promotes revascularization and healing. For separated lesions, these can be managed by curetting and drilling the base of the crater, followed by replacing the fragment and using a stabilizing fixation technique with compression screws, bone pegs or biodegradable pins. Excision is reserved for small fragments, which are not amenable to fixation.

**MANAGEMENT: APPRECIATING PATELLOFEMORAL BIOMECHANICS**

Having a working knowledge of the PF joint allows the clinician a distinct advantage when designing and implementing an appropriate rehabilitation program for those patients suffering from PF articular cartilage lesions. The goal of the following section is to merge current science to practical application of rehabilitation exercise and functional progression.

The primary function of the patella is to increase the efficacy of the quadriceps muscle via increasing the moment arm, thus producing greater knee extension torque. When the knee is extended in an non weight bearing (NWB) position, the patella is pushed forward by the trochlear groove of the femur. When extending the knee beyond 45 degrees, the lever arm function of the patella diminishes (height of the patella decreases as the patella begins to exit the trochlear groove). This has significant impact when considering contact forces during traditional exercise selection.

Goodfellow et al described the various contact regions of the patella during various knee flexion angles. These angles were identified according to the articular facets viewed on the posterior surface of the patella. Initial contact of the patella was identified at 10 degrees of flexion. From full extension to 90 degrees flexion, the area of contact migrated consistently from the inferior articular portion to the superior portion of the patella. After greater than 90 degrees flexion, the odd medial facet began to experience consistent contact stress. And finally, at approximately 135 degrees of flexion, contact moves and is distributed on the patella’s lateral and odd facets. Any imbalance in contact and compressive stresses that has occurred can lead to articular degenerative changes.

Appreciating the forces applied to the PF joint throughout biomechanical knee range of motion is important to understand the compressive loads and stresses sustained by the articular surfaces of the patella. As the knee articulates from terminal extension to flexion, the pull of the quadriceps tendon (either actively or passively) and the pull of the patellar tendon further compresses the patella into the femur. This patellofemoral joint reaction (PFJR) force is then expressed as the resultant vector force equal and opposite to the pull of the quadriceps and the patellar tendon. This patellofemoral joint reaction (PFJR) force is then expressed as the resultant vector force equal and opposite to the pull of the quadriceps and the patellar tendon. As knee flexion increases, the angle between the quadriceps tendon and the patellar tendon becomes less and thus increases the resultant vector force. Excessive compressive forces can produce damaging stresses on the articular cartilage of the patella, specifically when tissue healing is a priority.

**Weight-Bearing Exercises and Patellar Function**

PF compressive forces have been shown to increase as knee flexion increases during weight bearing.
exercises, such as the squat, leg press, and stationary bicycle, as well as normal daily activities such as stair climbing/descent and walking.\textsuperscript{73,74,77}

Reilly and Martens\textsuperscript{76} calculated forces present with normal activities of daily living. Walking on level ground showed minimum PFJR force (PFJR = 0.5 \times \text{body weight} [BW]) because minimum knee flexion is required. When knee flexion angles increase, such as squating to 90 degrees, the PFJR forces increased to 2.5 to 3 times body weight. Descending stairs always is difficult for an individual with PF pain. During descent, the peak PFJR forces reach 3.3 \times BW at 60 degrees of knee flexion. When descending stairs with articular cartilage lesions, maximum quadriceps force occurs near 30 degrees of flexion. This is the region where most lesions are present. When you combine large quadriceps eccentric loading with this “kissing lesion” position, pain is much more prevalent when descending stairs. The opposite is true with stair ascending. The maximum quadriceps compressive load occurs near 80 degrees of flexion during stair climbing where there is normally no PF articulation or a lesion. As the PF joint passes through the lesion of 30-40 degrees, there is very little compressive force being applied, thus less pain and discomfort with ascending stairs. Additionally, activities such as the leg press are much more comfortable than open chain knee extension. With closed kinetic chain activities such as this, PFJR force increases with increased flexion, and the area of contact also increases. This increased area of contact can respond effectively to disperse these forces.\textsuperscript{73,75}

Nisell and Ekholm\textsuperscript{75,78} determined that squatting in flexion ranges greater than 90 degrees produces significant compressive forces between the quadriceps tendon and the intercondylar notch of the femur due to increased muscular recruitment of the quadriceps and hamstrings, however it also increased gluteal recruitment. It is important to note that the magnitude of force is affected by variables in squatting mechanics (positioning of the ankles, knees, and hips).\textsuperscript{79,80} As the knee migrates forward, beyond the toes, the PF joint will sustain higher loads compared to a more posteriorly oriented pattern; however this does transfer larger forces to the hip and low back regions, while decreasing the PFJR.\textsuperscript{81} The PF compressive forces are greatest at 70°-120° of knee flexion.\textsuperscript{74,75} with the magnitude described by Thambyah et al\textsuperscript{82} to be as high as a 4 times body mass at 90 degrees and as high as a 5 times body mass at 120 degrees. Wrentenberg\textsuperscript{83} and associates studied the effects of low-bar and high-bar positioning during the squat. The high-bar position produced significantly greater PF compressive forces, as the high-bar position tended to produce a more upright trunk posture and required more knee extensor torque to complete the squat (and less hip extensor torque). For individuals with PF arthritic symptoms, limiting the magnitude of knee flexion to an appropriate symptom-free range can minimize PF stresses. Individuals with PF articular cartilage concerns may need to avoid squatting into angles greater than roughly 60 degrees as it increases the compressive force exposures.\textsuperscript{84-86}

**Non-Weight-Bearing Exercises and Patellar Function**

Understanding the forces that act on the PF joint at different positions (weight bearing (WB) and NWB) allows the clinician to develop a program based on empirical evidence. Biomechanical knowledge in action is illustrated by the interaction between the PF contact area and the PFJR force during the leg press (and other WB exercises) and leg extension (NWB) exercises.

Steinkamp and coworkers\textsuperscript{77} showed mathematically that maximal PFJR forces during the leg press occur when contact between the PF surfaces is greatest (60 and 90 degrees), whereas the maximal PFJR forces during a leg extension occur when the PF contact is the least (0 and 30 degrees). Although compressive forces may be lower for leg extensions, patients with patellar articular degeneration and arthritic changes often experience pain during NWB extensions of 30 to 0 degrees as a result of the relatively large compressive forces being applied to minimal contact areas.

Steinkamp\textsuperscript{77} concluded that patients with PF joint arthritis may tolerate leg press exercises (or similar WB squatting exercises) better than leg extension exercises in the final 30 degrees of knee extension because of the lower PF joint stresses. These investigators also determined that the PFJR forces are less in open chain exercises than closed chain exercises.
from 90 to 60 degrees, which Brownstein and associates found to be the range in which the greatest vastus medialis EMG activity was registered.44

MANAGEMENT: POST-OPERATIVE
CONSIDERATIONS AND PROTOCOL
Careful consideration should be taken post-operatively to protect the repaired lesion and promote tissue healing. The tenuous status of the tissue in conjunction with loads experienced throughout PF articulation make this area more difficult to manage. General healing timelines must be respected and are provided in most protocols, however, the timelines must also consider the variability in operative procedures and patient demographics as part of the rehabilitation continuum.

Appreciating this concept, the use of specific clinical tests or criteria in physical therapy, along with healing timelines, is prudent to assess the patient's progress towards beginning certain functional activities. For example, adequate knee range of motion and neuromuscular control of the quad are needed in order to begin walking without an assistive device and without compensation. Through the therapist's guidance (with approval from the surgeon), chondral graft healing times and evidence based criteria are used in each phase of the recovery to identify when the patient is ready to walk, run, perform agility drills, jump, cut and finally return to sport. The post-operative milestones provided contain the criteria and measurement tools needed for treating patients undergoing various chondral procedures. Modifications are necessary for patients who have undergone concomitant ligamentous repair or reconstruction as well as other procedures and/or injuries, which may influence or delay their recovery. The surgeon in these situations typically makes specific recommendations.

MANAGEMENT: POST-OPERATIVE HEALING
TIMEFRAMES AND PHASES OF LOADING
The following tables represent post-operative recommendations, tissue-healing timeframes, and biomechanical loading literature based on surgeon collaboration (Table 1).

Progression should always involve the corresponding surgeon, as they will have perspective on the tissue quality and recovery expectation. Healing timeframes should always supersede criteria, regardless of the patients' level of function. Table 1 represents three distinct time frames based on the type of intervention performed.

Biomechanical loading principles should also be incorporated into the rehabilitation progression as to promote protection or gradual tolerance of the involved region. Table 2 outlines three phases pertaining to PF joint load while also providing examples of these exercises for each phase.

MANAGEMENT: PROGRESSION USING
LOADING PHASES
The following describes the loading phases in more detail while providing insight into rationale pertaining to the protocol's progression.

Phase I: Acute or Unloading
The goal of the initial phase is protection of the surgical site, while promoting general joint nutrition and fluid dynamics within the protected ranges of motion and, most importantly, avoiding excessive compressive and sheer forces to the surgical site. Phase I exercises should utilize the biomechanical principles outlined above to mitigate any unnecessary force to the area. This includes avoidance of specific ranges of motion and/or strength exercises that involve joint load.

The acute post-operative phase of knee rehabilitation is the most essential to patient success, as early complications are commonly predictive of long-term impairments. The goals of the acute phase are to eliminate effusion, emphasize ambulation without asymmetries, obtain full knee extension, progress flexion range of motion, and restore normal quad activation. This terminal extension is extremely important to achieve as early as possible, as it may become increasingly difficult to obtain as time passes. Elevation of the involved extremity for the first few days will help control swelling. Cryotherapy can also be used up to 4-5 times per day for 10-20 minutes each time to help control pain and swelling. Quad sets are a staple of early post-operative rehabilitation. If performed correctly, they not only help with quad activation but can also provide terminal knee extension. Special attention should be
recommended the patient progress weight bearing using crutches while avoiding stair negotiation and incline ramps in this phase.

Towards the end of this phase, approximately 3-6 weeks post-operatively, gradual weight bearing is initiated with the release from the surgeon. It is

---

### Table 1. Procedure Specific Timeframe Considerations

<table>
<thead>
<tr>
<th>Weight-Bearing Status</th>
<th>Microfracture</th>
<th>OATS / Mosaicplasty</th>
<th>Osteochondral Auto and Allograft Transplantation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NWB Weeks 0 – 6</td>
<td>NWB Weeks 0 – 6</td>
<td>NWB 0 – 6</td>
</tr>
<tr>
<td><strong>Brace</strong></td>
<td>Locked in extension during ambulation, unlocked during PROM as indicated below</td>
<td>Locked in extension during ambulation, unlocked during PROM as indicated below</td>
<td>Locked in extension during ambulation, unlocked during PROM as indicated below</td>
</tr>
<tr>
<td><strong>Unloaded PROM</strong> (i.e. CPM, heel slides)</td>
<td>0-30°</td>
<td>Week 1</td>
<td>Week 1</td>
</tr>
<tr>
<td></td>
<td>0-60°</td>
<td>Week 2-3</td>
<td>Week 2-3</td>
</tr>
<tr>
<td></td>
<td>&gt; 60° progress as tolerated</td>
<td>Week 4+</td>
<td>Week 4+</td>
</tr>
<tr>
<td><strong>Loading in Flexion</strong></td>
<td>0-30° (i.e. mini squats, 4-inch step ups)</td>
<td>Week 6</td>
<td>Week 6</td>
</tr>
<tr>
<td></td>
<td>&gt;30° (i.e. chair squats, deeper leg press)</td>
<td>Week 8</td>
<td>Week 10</td>
</tr>
</tbody>
</table>

### Post-Operative Progression Time Frames

<table>
<thead>
<tr>
<th>Phase I: Unloading</th>
<th>Phase II: Moderate Loading</th>
<th>Phase III: Advanced Loading</th>
<th>Phase IV: Return to Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weeks 0 – 6</td>
<td>Weeks 0-8</td>
<td>Weeks 8-20</td>
<td>Weeks 0-8</td>
</tr>
<tr>
<td>Weeks 6 – 12</td>
<td>Weeks 8-20</td>
<td>Weeks 20-32</td>
<td>Weeks 8-24</td>
</tr>
<tr>
<td>Weeks 12 – 24</td>
<td>Weeks 20-32</td>
<td>Weeks 24-36</td>
<td>Weeks 24-36</td>
</tr>
<tr>
<td>Week 24+</td>
<td>Week 32+</td>
<td>Week 36+</td>
<td>Week 36+</td>
</tr>
</tbody>
</table>

paid to posterior capsule tightness in the knee and anterior interval mobility, in order to ensure the restoration of normal biomechanics of the joint. Open kinetic chain strengthening, such as short and long arc quadriceps should be avoided in this phase.
<table>
<thead>
<tr>
<th>Exercise Selection Based on Tissue Loading</th>
<th>Phase I: Unloading</th>
<th>Phase II: Moderate Loading</th>
<th>Phase III: Advanced Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight-Leg Isometrics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(quadriceps, hamstrings, gluteals)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft Tissue Stretches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(gastroc, hamstring)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unloaded Knee ROM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(heel slides, CPM, HS curl)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quad Strengthening</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(quad set, straight leg raise, prone TKE)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Strengthening</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(hip abduction, hip extension, fire hydrants, clamshells)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bicylce <em>(if PROM allows)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loaded Straight-Leg Quad Engagement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(single-leg balance, TKE, contrakicks, single-leg RDL)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loaded Knee Flexion with gradual ROM progression</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(chair squat, leg press, step up)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Strengthening</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(band walks, side planks)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Phase III: Advanced Loading

Advanced loading, occurring between 12 weeks to 24 weeks, represents the time frame focused on restoring normal kinematics. Focus is set on normalizing the patient's gait pattern, progression to full ranges of motion, and advancement of Phase II strengthening exercises. It is important to note that forced flexion should still be monitored throughout the phase. Cycling can be initiated in this phase with no resistance and controlled revolutions per min (RPM's).

Phase III: Advanced Loading

Progression of flexion range of motion is extremely important to prevent joint contracture. The patient should be educated on proper form and to avoid forced flexion if pain is felt. Strengthening should utilize closed chain strength modalities, such as leg press (with focus on the knee remaining posterior to the ankle joint), high table sit-to-stands (around 30 degrees initially), single leg balance, and minimal range open kinetic chain hamstring and gluteal exercises. Squatting to greater than 45 degrees should be closely monitored as this begins to place load on the joint. Bilateral strengthening should begin at less than the patients' body weight and progress to unilateral challenges as tolerated. It is recommended wall slides, heel slides, squats, step ups, lunges, and open kinetic chain knee extension exercises, be avoided in this phase. Cycling can be initiated in this phase with no resistance and controlled revolutions per min (RPM's).

Table 2. Exercise Selection Based on Tissue Loading (continued)

<table>
<thead>
<tr>
<th>Exercise Selection Based on Tissue Loading (continued)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I: Unloading</td>
</tr>
<tr>
<td>Phase II: Moderate Loading</td>
</tr>
<tr>
<td>Phase III: Advanced Loading</td>
</tr>
<tr>
<td>Eccentric and Unilateral Loading in Flexion (step downs, lunges, single-leg squats, dips)</td>
</tr>
<tr>
<td>Sagittal Plane Agility</td>
</tr>
<tr>
<td>Jogging (Alter-G progression)</td>
</tr>
<tr>
<td>Plyometric &amp; Cutting Progression</td>
</tr>
<tr>
<td>Functional Testing (Sport Cord, LESS, SportsMetrics, Y-balance)</td>
</tr>
<tr>
<td>Sport-Specific Activity</td>
</tr>
<tr>
<td>Return to Sport Testing</td>
</tr>
</tbody>
</table>

**Chart Key** – each color block indicates the level of focus or emphasis that should be placed on the corresponding exercises. The newest activities for any given phase are the ones given greater weight during treatment sessions. This schema demonstrates that earlier exercises should not be discontinued as the individual progresses, but should be continued as secondary priorities or on a maintenance schedule.
progressed when the patient can demonstrate normal gait pattern and when they can jog without any increase in pain or swelling in the involved knee. Straight-line running is recommended for the first few weeks, and treadmill or track surfaces are preferred over pavement, due to the decreased ground reaction forces. The treating physician will provide recommendations on the use of orthotics, as well as determine which activities these devices would be needed for.

Phase IV: Return to Function
It is important to keep in mind that individual patients will have a wide variety of outcome goals. For someone whose goal is to return to work activities and activities of daily living, the later power/agility and sport specific phases will be unnecessary. Even for athletes, the time spent on each phase will be partially determined by a needs analysis (sport specific demands) for their specific sport. For example, volleyball or basketball players need to perform more explosive and higher impact movements than that of a cross-country runner. Although the general principles of exercise apply throughout the rehabilitation program, individualized programs are used to allow for return to activity at a high level, with minimized risk of re-injury.

Power and agility. The functional goals of this phase are to initiate dynamic agility, power and sport specific movements. These activities should be performed in a controlled manner and with proper body mechanics at all times. These programs typically begin with single plane movements (i.e. forwards, lateral) and progress to multidirectional and reactionary movements. Restoring power and strength in the involved lower extremity is essential to progressing to higher level sports specific activities in the next phase of the rehabilitation program. The primary variable throughout this phase is graded exposure of impact forces. Careful monitoring of the knee should be performed, in order to identify any effusion, pain or other adverse effects that may occur. Developing the patients' confidence and ability to perform higher-level movements safely and under control is paramount during this phase, as it has been shown to affect performance and risk of re-injury.
Sport-specific. During this phase, functional tests will be utilized for both training and assessment purposes. Functional testing, such as hop testing, functional movements screens, strength testing, and agility drills, is considered "best practice" to determine limb symmetry for strength and dynamic/agility movements. Athletes should be gradually transitioned from individual to team-based activities; and from practice to in-game competition. Movements should be progressed from anticipated to unanticipated to ensure the utilization of proper movement strategies. Towards the end of this phase, simulating sport-like activities is important in order to ensure the patient is comfortable with the demands of their sport.

Return to Sport Testing. For those patients wishing to return to athletic competition, our practice uses a cluster of tests to determine the readiness of the athlete to return to sport. The philosophy of these tests is to combine strength and functional assessments in order to gather an overall picture of the patients' athletic capacity. These tests include: The Y-balance anterior reach test, a single-leg hop for distance, the Landing Error Scoring System (LESS) test, a 40-yard Figure of 8 run, a 5-10-5 shuttle run, and an isokinetic test. The goal for clearance is less than a 10% deficit on the Y-balance, single-leg hop and isokinetic testing, and good body control and mechanics on the LESS, Figure of 8 run and shuttle run. Age-related norms are also used for the Figure of 8 and shuttle runs. The athlete should not have any symptoms throughout testing, and should have already achieved full range of motion and manual muscle testing values with no effusion or pain with activity. Typically, our physicians instruct our athletes to wear a functional brace until at least one-year post-operative. If the athlete fails to complete any phase of the return to sport testing, they are not cleared and should return to therapy until another test can be performed.

SUMMARY
The objective criteria outlined within this protocol were selected based on their known relationships with re-injury and complication rates after surgery. These progressions are undertaken with consideration of normal healing timelines and the procedures performed in surgery. Once completing the goals of each functional phase, the surgeon and therapist should give final approval prior to transition of the next phase.

CONCLUSION
Despite advances in cartilage procedures and techniques, the PF joint remains a difficult area to protect and restore to its pre-injury condition. PF pain can be very debilitating to any athlete and may progress to a level that causes cessation of a particular sporting activity. If possible, modification of activities to an unloading sporting activity such as cycling or swimming will help preserve and extend the life of the articular cartilage. The goal as rehabilitation professionals is to educate and inform patients regarding their lesions, build strength and endurance via an appropriate unloading program, and gradually load the competitive athlete with stress so that their injury will be able to accommodate the building phases of activity. Lastly performing functional and strength measures to objectively determine readiness for play. Understanding the risk factors and identifying at-risk behavior may help decrease PF joint loading and extend articular cartilage longevity. This commentary has presented a spectrum of available interventions, as well as proposed timeframes for post-operative progression. Biogenetic materials continue to be used in managing PF articular cartilage lesions, and as science validates their efficacy, future interventions using these modalities will be more clearly evident. Managing patient expectations, selecting appropriate joint loading exercises, and collaborating with physician partners is vital to achieve the desired outcome – return to pre-injury activity. Unfortunately with PF articular cartilage lesions, some athletes are unable to return to the pre-injury activity. Helping these athletes choose a competitive sport or recreational endeavor to continue an active lifestyle completes the rehabilitation effort, and to prevent a more rapid destruction of their disease.

REFERENCES


ABSTRACT

**Background:** Hip exercise has been recommended for females with patellofemoral pain (PFP). It is unknown if males with PFP will benefit from a similar treatment strategy.

**Hypotheses/Purpose:** The purpose of this study was to compare improvements in pain, function, and strength between males and females with PFP who participated in either a hip/core or knee rehabilitation program. The directional hypothesis was that females would respond more favorably to the hip/core rehabilitation program and males to the knee program.

**Study Design:** Randomized-controlled clinical trial

**Methods:** Patients were randomly assigned to a six-week hip/core or knee rehabilitation program. Visual analog scale (VAS), Anterior Knee Pain Scale (AKPS), and hip and knee isometric strength were collected before and after subjects completed the rehabilitation program. Data were analyzed using an intention-to-treat basis. Separate mixed-model analyses of variance (ANOVA) with repeated measures were used to determine changes in VAS and AKPS and strength changes for subjects classified as treatment responders (successful outcome) and non-responders (unsuccessful outcome).

**Results:** Regardless of sex or rehabilitation group, VAS ($F_{1,181}=206.5; p<.0001$) and AKPS ($F_{1,181}=160.4; p<0.0001$) scores improved. All treatment responders demonstrated improved hip abductor ($F_{1,122}=6.6; p=0.007$), hip extensor ($F_{1,122}=19.3; p<0.0001$), and knee extensor ($F_{1,122}=16.0; p<0.0001$) strength. A trend ($F_{1,122}=3.6; p=0.06$) existed for an effect of sex on hip external rotator strength change. Males demonstrated a 15.4% increase compared to a 5.0% increase for females. All treatment non-responders had minimal and non-significant ($p>0.05$) strength changes.

**Conclusion:** On average, males and females with PFP benefitted from either a hip/core or knee rehabilitation program. Subjects with successful outcomes likely had hip and knee weakness that responded well to the intervention. These males and females had similar and meaningful improvements in hip extensor and knee extensor strength. Only males had relevant changes in hip external rotator strength. Clinicians should consider a subgroup of males who may benefit from hip extensor and external rotator exercise and females who may benefit from hip extensor exercise.

**Level of Evidence:** 2b

**Keywords:** Anterior knee pain, hip, rehabilitation, sex
INTRODUCTION
Patellofemoral pain (PFP) is one of the most common and clinically challenging knee pathologies to manage.1-3 Individuals with PFP report peripatellar and/or retropatellar pain exacerbated by activities like stair ambulation, jumping, and running that require loading on a flexed knee.3 PFP is thought to result from abnormal patella tracking that increases lateral patellofemoral joint stress.4,5

Historically, clinicians believe that a delay in vastus medialis activation relative to the vastus lateralis can cause excessive lateral patellofemoral joint loading.6,7 This theory has led to interventions designed to improve quadriceps function. While quadriceps exercise is important,8 as many as 70% to 90% of individuals with PFP who complete rehabilitation have ongoing symptoms.8-11

Powers12 has theorized that excessive hip adduction and/or internal rotation from hip weakness can lead to increased patellofemoral joint loading. This perspective has segued to investigations focusing on hip exercise.13-15 While an important treatment strategy,16 many hip exercises have been performed in weight bearing and most likely affected the knee muscles.

To address this concern, more recent investigations have compared the isolated effects of hip and quadriceps strengthening exercise on PFP.17,18 A large scale, multicenter randomized-controlled clinical trial was conducted to compare pain, patient-reported function, and muscle performance in subjects with PFP who completed either a hip/core or knee strengthening program.18 All subjects, regardless of exercise group, had significant improvements in pain, patient-reported function, and muscle performance.

Most studies that have examined the benefits of hip exercise on PFP have either excluded males13-15,19 or included a relatively low number of males.18 A main reason for excluding males has been strong evidence of a high prevalence of PFP in females20,21 and associated hip weakness.22,23 Although more prevalent in females, males develop PFP and limited data exist regarding patterns of hip and knee weakness in this cohort. Bolgla et al24 compared isometric hip and knee strength in males with and without PFP. They found that males with PFP demonstrated significantly less knee extensor, but similar hip strength when compared to controls. These data highlighted that males with PFP may respond better to a knee-focused rehabilitation program, supporting the need for sex-specific interventions.25 Additional studies are needed to make this determination.

The primary purpose of this study was to compare improvements in pain and patient-reported function between males and females with PFP who participated in either a hip/core or knee rehabilitation program. The secondary purpose was to compare changes in isometric hip and knee strength following rehabilitation. The directional hypothesis was that females would respond more favorably than males to the hip/core rehabilitation program and males would respond more favorably to the knee program.

METHODS
Study Design
This study was a secondary analysis of cross-sectional data from a larger randomized-controlled clinical trial18 comparing outcomes in subjects with PFP who participated in either a six-week hip/core or knee strengthening rehabilitation program. For the current study, separate 2 (male or female) X 2 (hip/core or knee program) X 2 (baseline and post-rehabilitation) mixed-model analyses of variance (ANOVA) with repeated measures on time were used to determine any interaction effect between sex and exercise group on the primary variables of pain and patient-reported function.

Separate 2 (male or female) X 2 (baseline and post-rehabilitation) mixed-model ANOVAs with repeated measures on time were used to determine changes in the secondary variables of hip and knee isometric strength. The purpose of this analysis was to identify any interaction effect of sex on treatment response (i.e., treatment success or nonsuccess) based on strength changes. Subjects were grouped as either responders (treatment success) or non-responders (treatment nonsuccess) based on recommendations from Crossley et al.26 Responders were defined a priori as follows: at least a 2-cm decrease in visual analog scale (VAS) score for pain and/or at least an 8-point improvement in the Anterior Knee Pain Scale (AKPS) score.18,26 Subjects who did not meet any of these criteria were classified as non-responders.
Subjects
One hundred eighty-five subjects were included for this analysis. Subjects were recruited from a sample of convenience in the following geographic areas: Augusta, GA; Calgary, AB, CA; Chicago, IL; and Milwaukee, WI. Inclusion and exclusion criteria were consistent with those previously described. Briefly, subjects were recreationally-active (exercised a minimum of 30 minutes three times a week for at least 6 months prior) and between the ages of 18 and 35 years. Additional inclusion criteria were an insidious onset of PFP for at least 1 month, self-reported pain during activity at least 3-cm on a 10-cm VAS, and pain during activities that required loading on a flexed knee (e.g., running, jumping, squatting, or stair ambulation). Exclusion criteria included a history of back or lower extremity pathology (including patella tendinopathy, patella instability, and/or iliotibial band stress syndrome) other than PFP. The most affected extremity was used for subjects with bilateral symptoms (N = 88). Subjects were randomly assigned to exercise group and examiners were blinded to subject group assignment. All subjects signed an informed consent document provided by each individual site’s Institutional Review Board prior to participation.

Outcome Measures
Pain
Pain was assessed using a 10-cm VAS. The extreme left side of the VAS stated “no pain” whereas the extreme right side stated “worse pain imaginable.” Subjects drew a perpendicular line on the scale at the position that best described their pain during activity over the previous week. The distance from the left side (e.g., no pain) of the VAS to the vertical mark made by the subject was measured to the nearest 1/10th of a centimeter and used for statistical analysis. The VAS for pain during activity over the prior week has represented a reliable, responsive, and valid instrument for assessing pain in individuals with PFP. The composite score on the AKPS was used for statistical analysis.

Isometric Hip and Knee Strength
Isometric hip abductor, hip extensor, hip external rotator, and knee extensor strength was assessed using a hand-held dynamometer and stabilization straps using methods previously described. Peak force measures were recorded in kilograms and expressed as a percentage of body mass (%BM). The average of three trials was used for statistical analysis.

Rehabilitation Protocol
A random number generator was used to assign subjects to either the hip/core or knee program, a sequence that was used at each research site. All subjects met with a trained rehabilitation specialist up to three times a week over a six-week period. The rehabilitation specialist supervised all exercises sessions and progressed the subjects based on their feedback and symptoms (e.g., pain, swelling, crepitus). Subjects were instructed to perform the exercises at least six times a week (e.g., a subject who attended three supervised sessions completed at least three additional sessions independently at home) and used Theraband® (The Hygenic Corp, Akron, OH) for resistance. Resistance was based on a subject’s ability to complete 10 repetitions of the exercise with good form but feeling challenged to complete the last three repetitions. Subjects performed all exercises bilaterally.

For the hip/core program, subjects initially performed non-weight bearing exercises designed to target the hip muscles and activate the core muscles (Table 1). They then progressed to weight bearing exercises. While subjects indirectly activated the quadriceps during the weight bearing exercises, the exercises were designed to specifically target the hip and core muscles. The knee program had a similar progression (Table 2). Subjects initially performed non-weight bearing knee extensor exercises and progressed to weight bearing. While some of the exercises indirectly activated the hip muscles, they also were designed to primarily target the knee extensors. Subjects were not given any verbal cue to activate the core during the knee extensor weight bearing exercises.
and patient-reported function (AKPS score). Separate mixed-model 2 (sex) X 2 (rehabilitation group) X 2 (time) ANOVAs with repeated measures on time were used to determine differences in the primary variables (VAS and AKPS scores). Separate mixed-model 2 (sex) X 2 (time) ANOVAs with repeated measures on time also were used to determine differences in the sec-

Table 1. Hip/core Exercise Protocol\textsuperscript{18} (reproduced with permission from the Journal of Athletic Training, National Athletic Trainers’ Association, Carrollton, TX)

<table>
<thead>
<tr>
<th>Week</th>
<th>Exercise</th>
<th>Sets, No.</th>
<th>Repetitions or Seconds, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hip abduction - standing</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Hip external rotator - standing</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Hip external rotator - seated</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Hip abduction - standing</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Hip internal rotator - standing</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Hip external rotator - standing</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Hip abduction - standing</td>
<td>3</td>
<td>10 (with stronger band)</td>
</tr>
<tr>
<td></td>
<td>Hip internal rotator - standing</td>
<td>3</td>
<td>10 (with stronger band)</td>
</tr>
<tr>
<td></td>
<td>Hip external rotator - standing</td>
<td>3</td>
<td>10 (with stronger band)</td>
</tr>
<tr>
<td></td>
<td>Balancing 2 feet-Airex\textsuperscript{a} pad</td>
<td>3</td>
<td>30-45 sec</td>
</tr>
<tr>
<td>4-6</td>
<td>Hip extension @ 45\textdegree - standing</td>
<td>3</td>
<td>10-15</td>
</tr>
<tr>
<td></td>
<td>Hip internal rotator - standing</td>
<td>3</td>
<td>10-15</td>
</tr>
<tr>
<td></td>
<td>Hip external rotator - standing</td>
<td>3</td>
<td>10-15</td>
</tr>
<tr>
<td></td>
<td>Balancing 1 foot-Airex\textsuperscript{a} pad</td>
<td>3</td>
<td>45-60 sec</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Airex AG, Sins, Switzerland.

Table 2. Knee Exercise Protocol\textsuperscript{18} (reproduced with permission from the Journal of Athletic Training, National Athletic Trainers’ Association, Carrollton, TX)

<table>
<thead>
<tr>
<th>Week</th>
<th>Exercise</th>
<th>Sets, No.</th>
<th>Repetitions or Seconds, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Isometric quadriceps setting</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Knee extensions -standing</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Double-legged, one-quarter squats</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Isometric quadriceps setting</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Double-legged, one-half squats</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Terminal knee extension with Theraband\textsuperscript{a}</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Double-legged, one-quarter squats</td>
<td>3</td>
<td>30 s</td>
</tr>
<tr>
<td>3</td>
<td>Double-legged, one-half squats</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Single-legged, one-quarter squats</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Double-legged, one-quarter squats</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Terminal-knee extension with Theraband\textsuperscript{a}</td>
<td>3</td>
<td>10 (with stronger band)</td>
</tr>
<tr>
<td>4</td>
<td>Single-legged, one-half squats</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Forward, one-quarter lunges</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Lateral step-down (4-in [3.6-cm] step)</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Forward step-down (4-in [3.6-cm] step)</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Double-legged, one-half wall squats</td>
<td>3</td>
<td>30 s</td>
</tr>
<tr>
<td>5-6</td>
<td>Double-legged wall squats (to maximum 90\textdegree knee flexion)</td>
<td>3</td>
<td>45-60 s</td>
</tr>
<tr>
<td></td>
<td>Lateral step-down (6-10-in [5.6-9.6-cm] step)</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Forward step-down (6-10-in [5.6-9.6-cm] step)</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Forward one-half full lunge (to maximum 90\textdegree knee flexion)</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Single-legged one-half full lunge (to maximum 90\textdegree knee flexion)</td>
<td>3</td>
<td>15</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Theraband, Hygenic Corp, Akron, OH.

Statistical Analysis
An intention-to-treat analysis, using a conservative method where missing data were replaced with the last score carried forward, was used. Separate Chi-square analyses were conducted to determine if any between-group differences existed with respect to demographic data as well as baseline pain (VAS score)
females (29%) and 25 males (41%) responded unfavorably. For the primary variables (pain and patient-reported function), a significant reduction in VAS ($F_{1,181} = 206.6; p < 0.0001$; Table 4) and improvement in AKPS ($F_{1,181} = 160.4; p < 0.0001$; Table 4) scores occurred regardless of sex or rehabilitation group. These differences also had large effect sizes (Cohen’s $d$ exceeding 0.80 (Table 4).

For the secondary variables (isometric hip and knee strength), male and female responders exhibited improved hip abductor ($F_{1,122} = 6.6; p = 0.007$), hip extensor ($F_{1,122} = 19.3; p < 0.0001$), and knee extensor ($F_{1,122} = 16.0; p < 0.0001$) strength (Table 5). While a similar pattern occurred for the hip external rotators ($F_{1,122} = 13.7; p < 0.0001$), a trend for an interaction between sex and time ($F_{1,122} = 3.6; p = 0.06$) existed. Males had small-to-medium effect sizes for changes in isometric hip extensor (Cohen’s $d = 0.36$) and external rotator (Cohen’s $d = 0.38$) strength (Table 5). Effect sizes for changes in female isometric hip and knee strength ranged from 0.15 to 0.28 (Table 5). No significant changes existed for males or females classified as non-responders ($p > 0.05$; Table 5). Their effect sizes were small, ranging from -0.05 to 0.18 (Table 5).

### DISCUSSION

The primary purpose of this study was to compare improvements in pain and patient-reported function between males and females with PFP who participated in either a hip/core or knee rehabilitation program. The directional hypothesis was that females

<table>
<thead>
<tr>
<th>Table 3. Mean ± (standard deviation) of demographic data for subjects who completed either a hip/core- or knee-based rehabilitation program.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Sex, Female</td>
</tr>
<tr>
<td>Age, y</td>
</tr>
<tr>
<td>Mass, kg</td>
</tr>
<tr>
<td>Height, cm</td>
</tr>
<tr>
<td>VAS$^a$, cm</td>
</tr>
<tr>
<td>AKPS$^a$, Points</td>
</tr>
<tr>
<td>Knee, Right</td>
</tr>
</tbody>
</table>

$^a$ Chi-square statistic

### RESULTS

Both groups were equal with respect to demographics, pain, and function (Table 3). One-hundred-twenty-four patients (67%) met the a priori definition for treatment success (responders). Eight-eight females (71%) and 36 males (59%) responded favorably; 36

### Table 4. Mean ± (standard deviation) for pain and patient-reported function before and after completion of either a hip/core or knee rehabilitation program. All subjects, regardless of group or sex, exhibited similar improvements in visual analog scale (VAS) and Anterior Knee Pain Scale (AKPS) scores. |

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>6-week</th>
<th>% Change</th>
<th>Cohen’s $d$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>VAS$^a$, cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip/Core</td>
<td>5.0 (1.7)</td>
<td>5.3 (1.7)</td>
<td>2.6 (2.4)</td>
<td>2.4 (2.2)</td>
</tr>
<tr>
<td>Knee</td>
<td>4.4 (1.5)</td>
<td>4.3 (1.6)</td>
<td>2.0 (2.1)</td>
<td>2.8 (2.3)</td>
</tr>
<tr>
<td>AKPS$^a$, Points</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip/Core</td>
<td>76.3 (9.5)</td>
<td>74.5 (10.1)</td>
<td>86.6 (13.8)</td>
<td>87.9 (9.6)</td>
</tr>
<tr>
<td>Knee</td>
<td>78.0 (8.8)</td>
<td>75.2 (9.6)</td>
<td>87.1 (10.4)</td>
<td>87.0 (11.3)</td>
</tr>
</tbody>
</table>

$^a p < 0.0001$
female responders showed the greatest gain, the increase was only 7.4% compared to 5.7% for male responders. Differences for male and female non-responders were even smaller. This pattern suggested that hip abductor strength improvement was not clinically important and not necessarily as important as previously thought.37

Another reason may be that subjects had no hip abductor weakness. Researchers have reported isometric hip abductor weakness in females with PFP ranging from 22.5%BM29 to 29.0%BM.38 On average, all females in our study had values exceeding 30%BM, suggesting no hip abductor weakness. The same reason most likely explained the difference noted in males. Although baseline strength measures for male responders (38.8%BM) and non-responders (39.3%BM) were slightly less than reported controls (40.0%BM),29 the difference was negligible. Interestingly, all males, regardless of treatment effect, had average hip abductor strength similar to reported controls34 after completing rehabilitation.

Although 124 (67%) subjects responded favorably to treatment, one-third of subjects did not. It was noteworthy that only 36 (29%) females responded unfavorably compared to 25 (41%) males. Different patterns of strength gains between males and females who responded favorably or unfavorably may explain this disparity (Table 5).

### Isometric Hip and Knee Strength Changes

#### Hip Abductor Strength

Overall, all subjects made minimal, if any, improvements in isometric hip abductor strength. Although female responders showed the greatest gain, the increase was only 7.4% compared to 5.7% for male responders. Differences for male and female non-responders were even smaller. This pattern suggested that hip abductor strength improvement was not clinically important and not necessarily as important as previously thought.37

Another reason may be that subjects had no hip abductor weakness. Researchers have reported isometric hip abductor weakness in females with PFP ranging from 22.5%BM29 to 29.0%BM.38 On average, all females in our study had values exceeding 30%BM, suggesting no hip abductor weakness. The same reason most likely explained the difference noted in males. Although baseline strength measures for male responders (38.8%BM) and non-responders (39.3%BM) were slightly less than reported controls (40.0%BM),29 the difference was negligible. Interestingly, all males, regardless of treatment effect, had average hip abductor strength similar to reported controls34 after completing rehabilitation.

### Table 5. Mean ± (standard deviation) for isometric force measures (% body mass) for responders and non-responders, regardless of intervention assignment

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>6-week</th>
<th>% Change</th>
<th>Cohen’s d</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>Responder</td>
<td>N = 36</td>
<td>N = 88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Responder</td>
<td>N = 25</td>
<td>N = 36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip Abductors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Responders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a)</td>
<td>38.8 (13.0)</td>
<td>32.2 (10.6)</td>
<td>41.0 (13.6)</td>
<td>34.6 (10.7)</td>
</tr>
<tr>
<td>b)</td>
<td>39.2 (10.4)</td>
<td>33.8 (11.7)</td>
<td>40.4 (9.9)</td>
<td>34.0 (11.6)</td>
</tr>
<tr>
<td>Hip Extensors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Responders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a)</td>
<td>27.4 (10.6)</td>
<td>22.1 (9.8)</td>
<td>31.4 (11.5)</td>
<td>25.0 (11.4)</td>
</tr>
<tr>
<td>b)</td>
<td>31.8 (10.9)</td>
<td>23.6 (11.7)</td>
<td>31.3 (11.1)</td>
<td>25.2 (12.4)</td>
</tr>
<tr>
<td>Hip External Rotators</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Responders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a)</td>
<td>13.0 (5.7)</td>
<td>12.0 (4.1)</td>
<td>15.0 (4.9)</td>
<td>12.6 (3.9)</td>
</tr>
<tr>
<td>b)</td>
<td>14.1 (3.4)</td>
<td>11.6 (4.0)</td>
<td>14.7 (3.1)</td>
<td>12.0 (4.5)</td>
</tr>
<tr>
<td>Knee Extensors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Responders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a)</td>
<td>44.9 (16.0)</td>
<td>37.4 (13.9)</td>
<td>50.0 (14.9)</td>
<td>41.3 (14.3)</td>
</tr>
<tr>
<td>b)</td>
<td>47.5 (14.7)</td>
<td>39.7 (18.5)</td>
<td>47.8 (15.1)</td>
<td>40.5 (17.4)</td>
</tr>
</tbody>
</table>

---

* Significant increase in strength regardless of sex; p = 0.007
* No change in strength regardless of sex; p > 0.05
* Significant increase in strength regardless of sex; p < 0.0001
**Hip Extensor Strength**

More meaningful comparisons in hip extensor strength occurred between responders and non-responders. Hip extensor strength improved 14.6% and 13.1% for male and female responders, respectively, compared to -1.6% and 6.8% for male and female non-responders. It was noteworthy that baseline values for male and female responders were 16% and 7% less than male and female non-responders. This finding suggested that responders exhibited hip extensor weakness that improved with rehabilitation and achieved strength values similar to reported controls.24

Unlike isometric hip abductor strength values, more limited data exist for hip extensor strength for females with and without PFP. Robinson and Nee34 reported strength values of 23%BM and 48%BM for females with and without PFP. Although none of our females achieved strength gains similar to Robinson and Nee controls, female responders almost had a two times greater (13.1% versus 6.8%) percentage increase in hip extensor strength than non-responders. Like males, these females may have represented a cohort with hip extensor weakness that improved with rehabilitation.

**Hip External Rotators**

The most interesting comparison was hip external rotator strength changes. Though not significant, a trend ($F_{1,122} = 3.6; \ p = 0.06$) for an interaction between sex and strength gains existed for responders. Male responders had an 8% lower baseline value than non-responders that increased by 15.4%. This strength increase also had the highest effect size (Cohen’s $d = 0.38$) of all other strength measures and exceeded values for reported controls (14.3%BM).24 Like hip abductor and extensor strength changes, this cohort most likely had weakness that improved with rehabilitation.

Unlike males, female responders had a modest 5.0% increase in hip external rotator strength. This increase also was over 2.5 times less compared to the 13.1% strength increase observed for the hip extensors. This finding suggested that hip external rotator strength may be less important for females than males. This result also aligned with the importance of hip extensor function in females with PFP during running and a single-leg step-down task.33,39

**Knee Extensors**

Knee extensor strength patterns between responders and non-responders were similar to the hip extensors. Knee extensor strength improved 11.4% and 10.4% for male and female responders, respectively, compared to 0.6% and 2.0% for male and female non-responders. Baseline values for male and female responders both were 6% less than male and female non-responders. This finding suggested that responders exhibited knee extensor weakness that improved with rehabilitation. At the end of rehabilitation, only male responders had strength values similar to reported controls.24 Post-rehabilitation knee extensor strength for female responders exceeded non-responders. All females, regardless of treatment response, had higher strength values than reported controls.40

**Clinical Implications**

Although a very common problem, PFP has been one of the most clinically challenging pathologies to manage because of its multifactor nature. Its complexity has led to emerging evidence aimed at identifying clinical subgroups to direct treatment.41,42 Findings from the current study have provided preliminary data for a possible effect of sex on treatment development and implementation.

Interestingly, hip abductor strength gains did not appear as important as previously thought. However, responders could have experienced improvements in neuromuscular factors. A certain cohort of subjects could have alterations in gluteus medius, vastus medialis and/or lateralis onsets or amplitudes during functional activities that improved with rehabilitation.27,43,44

The most compelling finding was the pattern of change with hip extensor and hip external rotator strength. While male and female responders experienced similar hip extensor strength gains, only male responders had meaningful hip external rotator strength increases. This result suggested that male responders exhibited both hip extensor and hip external rotator strength deficits that improved with rehabilitation. Therefore, interventions that target the hip external rotators may be more beneficial for males than females. Finally, all male and female responders exhibited baseline knee extensor
weakness compared to non-responders. The fact that responders benefited from either exercise program further highlighted the importance of exercise and quadriceps function.45

Limitations
This study was not without limitations. First, isometric hip and knee strength, instead of other measures such as eccentric strength and muscle endurance, were assessed. Isometric strength was assessed because data were collected at multiple study sites and the methods used had established reliability.29,46 Other measures of muscle function may have provided additional insight. Second, pain, patient-reported function, and strength changes may have resulted from improved muscle neuromuscular activity in the tested muscles. This determination could not be made since electromyographic data were not collected. Finally, this study did not have a control group to know if subjects would have improved without treatment. Van Linschoten et al47 reported superior short- and long-term outcomes for patients with PFP who participated in supervised exercise compared to patients who received a “wait-and-see” approach of rest and activity modification. Others also have reported both short- and long-term benefits with rehabilitation exercises.17,48 For these reasons, a control group most likely would have provided minimal, if any, additional information.

CONCLUSION
This study was the first to examine between-sex differences for individuals with PFP who participated in either a hip/core or knee rehabilitation program. Nearly 70% of subjects had improved pain, patient-reported function, and strength after completing either program. Responders exhibited lower baseline strength measures for most muscle groups compared to non-responders. This comparison suggested that those with PFP had weakness and responded to either intervention. When prescribing exercises, clinicians should consider that males may benefit more from hip extensor and external rotator exercises and females to hip extensor exercise. It was noteworthy that one-third of subjects did not respond favorably to either intervention. This finding further supported the need to identify subgroups of patients that may benefit from other intervention strategies. While researchers recently have examined this issue,41,42 ongoing studies that consider sex influences are needed to advance the treatment of individuals with PFP.

REFERENCES


ABSTRACT

Background: A variety of risk factors predispose athletes to injury, such as impaired neuromuscular control, insufficient core stability, and muscular imbalances. The goal of assessing functional movement patterns is to detect imbalances and correct them with prevention strategies and thereby decrease injuries, and improve performance and quality of life.

Purpose: The purpose of this study was to generate normative values for the ‘Nine Test Screening Battery’ (9TSB) in a group of recreational athletes. A secondary aim was to study gender differences and differences between subjects with (more than six weeks before test occasion) and without previous injury (regardless of injury location). A third aim was to investigate the psychometric properties of the 9TSB.

Methods: Eighty healthy recreational athletes, (40 men and 40 women) aged 22-58, were included. The subjects were tested according to strict criteria during nine functional movement exercises that comprise the 9TSB; each graded using an ordinal scale of 0-3, at one occasion. The maximum possible score is 27 points.

Results: The median score for the whole group was 18 (Range 12 - 24). A normal distribution of the test scores, with no floor-ceiling effects was found. There was no significant gender difference (p = 0.16) or difference between the group that reported previous injuries (regardless of injury location) and the group that did not (p = 0.65). The internal consistency was 0.41 with Cronbach's alpha.

Conclusion: A normal distribution of test results with no floor-ceiling effect was found. History of previous injury (more than six weeks before testing) or gender did not affect the results. In order to determine and cut scores for what is considered optimal or dysfunctional movement patterns, further cohort studies are required.

Key words: Clinical test, functional movement, movement pattern, screening
INTRODUCTION
Insufficient physical activity and sedentary lifestyles are a major public health problem. Paradoxically, participation in recreational running events has been growing with more than 500,000 Swedes participating in recreational running events annually (and over a million people run without competing). Participating in sporting activities is associated with injury risk among professional as well as recreational athletes. A range of often inter-related risk factors may predispose athletes to injury, such as previous injury, impaired neuromuscular control, insufficient core stability and muscular imbalances. Prevention and rehabilitation of sport-related injuries is continuously evolving and it is an increasing interest among sport medicine professionals, researchers and athletes in prevention strategies focused on improving movement patterns.

Systematic assessment of functional movement patterns was first described in the 1990’s when the Functional Movement Screen (FMS™) was developed. The FMS™ screens athletes for movement competency, and identifies pain during movements as well as musculoskeletal side to side imbalances, enabling correction and thereby reduced injury risk, improved performance and enhanced quality of life, according to the authors. Several research groups have investigated the inter-rater reliability of FMS™ with good results. The FMS™ has been used as the basis for development of the ‘nine test screening battery’ (9TSB). The requirement for evaluating functional movements was spawned in the clinical setting due to the observed lack of mobility and stability among athletes and the concurrent lack of methodology for assessment. This too was the rationale for the development of the 9TSB, which consists of six of seven tests from the FMS™ with modified criteria. Modifications were conducted to make the criteria easier to follow for the testers, but also to make them more stringent. In addition to the FMS™ tests, one test (one-legged squat) was added from the United States Tennis Association (USTA) High-performance profile (HPP) and two tests (straight leg raise and seated rotation) were developed and standardized by the Swedish research team. The rationale for adding the three tests was that the FMS™ lacks screens for vertical rotation and more demanding strength tests. Pictures of the 9TSB tests are available in Appendix 1.

The 9TSB has previously been tested for inter- and intra rater reliability on a group of elite male soccer players with good results (ICC = 0.80). Low scores on the FMS™ has been found to be associated with increased risk of sustaining an injury in female collegiate athletes, professional football players and physically active students. In a study by Letafatkar et al. significant differences were found between pre-season functional movement screening scores in injured compared to non-injured individuals. Kiesel et al. found that those with asymmetries in FMS™ screening had higher risks of sustaining an injury during a professional season compare to those without asymmetries. Asymmetries are defined as a difference in performance on the bilateral tests (left-right extremity). Finally, Kiesel et al. studied soccer players and found that functional movement screening (FMS™) followed by targeted interventions (improve range of motion, core stability, improve quality of movement) addressing the individuals dysfunction, could be used to change fundamental movement patterns evaluated with the same post intervention tests. In addition, they found a current paucity of data linking functional movement and athletes’ injury susceptibility.

To date, only few studies have been published, describing normative values for the FMS™. No data on normative values have been published for the 9TSB, which makes it difficult to interpret raw data. The availability of reference values in healthy populations is vital when studying athletic cohorts at risk of injury.

The purpose of this study was to generate normative values for the 9TSB in a group of recreational athletes. A secondary aim was to study gender differences and differences between subjects with (more than six weeks before test occasion) and without previous injury (regardless of injury location). A third aim was to investigate the psychometric properties of the 9TSB.

METHODS
Subjects
Eighty healthy physically active subjects, (40 men and 40 women) between 22 and 58 years old, were invited to participate (Table 1). Subjects were primarily recruited by direct contact at a single recreational...
The 9TSB was first described by Frohm et al.16 and includes nine different tests: deep squat, one-legged squat, in-line lunge, active hip flexion, straight leg raise, push up, diagonal lift, seated rotation and functional shoulder mobility. The aim of the test is to analyse the quality of functional movement patterns during different tests. All nine tests have standardized starting positions with the quality of movement being graded 0-3. The highest score possible (3), indicates movement without asymmetries and compensatory movements. A score of 2 is recorded if the subject can perform the test but with small compensatory movements. A score of 1 is recorded if the subject cannot perform the test without major compensatory movements. If pain was present during a given test, a score of 0 is registered irrespective of performance.14-15 Thus, the highest possible aggregate score for the nine tests is 27 points (Table 2).

### Nine test screening battery

The 9TSB was first described by Frohm et al.16 and includes nine different tests: deep squat, one-legged squat, in-line lunge, active hip flexion, straight leg raise, push up, diagonal lift, seated rotation and functional shoulder mobility. The aim of the test is to analyse the quality of functional movement patterns during different tests. All nine tests have standardized starting positions with the quality of movement being graded 0-3. The highest score possible (3), indicates movement without asymmetries and compensatory movements. A score of 2 is recorded if the subject can perform the test but with small compensatory movements. A score of 1 is recorded if the subject cannot perform the test without major compensatory movements. If pain was present during a given test, a score of 0 is registered irrespective of performance.14-15 Thus, the highest possible aggregate score for the nine tests is 27 points (Table 2).
<table>
<thead>
<tr>
<th>Tests</th>
<th>3 points (all criteria has to be fulfilled)</th>
<th>2 points</th>
<th>1 points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep squat test</td>
<td>All criteria has to be fulfilled on a 0.02 m board:</td>
<td>Same criteria as for 3 points except the use of a 0.04 m board</td>
<td>One or more of the criteria have to be fulfilled (0.04 m):</td>
</tr>
<tr>
<td></td>
<td>• Straight line hip, knee and foot.</td>
<td></td>
<td>• No straight line hip, knee and foot.</td>
</tr>
<tr>
<td></td>
<td>• Parallel feet and heels kept on the board throughout the motion.</td>
<td></td>
<td>• The feet are not parallel through the motion.</td>
</tr>
<tr>
<td></td>
<td>• Femur below horizontal line.</td>
<td></td>
<td>• Femur is not below horizontal.</td>
</tr>
<tr>
<td></td>
<td>• Arms parallel to ears.</td>
<td></td>
<td>• Arms are not parallel with the ears.</td>
</tr>
<tr>
<td></td>
<td>• The pole is behind the toes.</td>
<td></td>
<td>• The pole is not behind the toes.</td>
</tr>
<tr>
<td>One-legged squat test</td>
<td>• Hip, knee and foot aligned.</td>
<td>One or more of the following criteria:</td>
<td>• Hip, knee and foot is not aligned</td>
</tr>
<tr>
<td></td>
<td>• Pelvis in horizontal line.</td>
<td>• Pelvis is not in horizontal line.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• The upper body is vertical.</td>
<td>• The upper body is not vertical.</td>
<td></td>
</tr>
<tr>
<td>In-line lunge test</td>
<td>• Pole contact with head and sacrum.</td>
<td>One or more of the following criteria:</td>
<td>One or more of the following criteria:</td>
</tr>
<tr>
<td></td>
<td>• The upper elbow pointing 90° to the side.</td>
<td>• No pole contact with head and sacrum.</td>
<td>• Loss of balance</td>
</tr>
<tr>
<td></td>
<td>• No movement of upper body with a pole vertical.</td>
<td>• The upper elbow not pointing 90° to the side.</td>
<td>• Rear knee is not in contact with the plank</td>
</tr>
<tr>
<td></td>
<td>• Contact is kept between knuckle and column.</td>
<td>• Minor movement of upper body, pole is not vertical.</td>
<td>• The anterior heel is not in contact with the plank</td>
</tr>
<tr>
<td></td>
<td>• Both feet in line pointing straight forward</td>
<td>• No contact between knuckle and column.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• The anterior knee is straight over the anterior foot. Anterior heel is kept in the plank.</td>
<td>• Feet is not pointing straight forward</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Rear foot touch the plank</td>
<td>• The anterior knee is not in line over foot.</td>
<td></td>
</tr>
<tr>
<td>Active hip flexion test</td>
<td>• Lateral malleol passes the pole with both knees extended and neck in a neutral position.</td>
<td>The following criteria has to be fulfilled:</td>
<td>Lateral malleol does not pass the given criteria</td>
</tr>
<tr>
<td></td>
<td>• Pole at mid point between ASIS and mid patella.</td>
<td>• Lateral malleol passes the pole between the measurement for 3p and mid</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Both knees extended and neck in a neutral position</td>
<td>patellae</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• The right knee is in contact with the board</td>
<td>• Both knees extended and neck in neutral position</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• The right knee is in contact with the board</td>
<td></td>
</tr>
<tr>
<td>Straight leg raises test</td>
<td>Ability to stabilize trunk with legs together, dorsi flexed feet with, heels touching the floor and back with</td>
<td>Ability to stabilize trunk with legs together to 30°.</td>
<td>No ability to stabilize trunk with 30° hip flexion</td>
</tr>
<tr>
<td></td>
<td>retained position of the lumbar spine L4-L5. Neck in neutral position.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Push up test</td>
<td>• The body is pushed up as a unit facing straight down through the whole motion.</td>
<td>Both criteria have to be fulfilled:</td>
<td>The body is not pushed up as a unit</td>
</tr>
<tr>
<td></td>
<td>• Contact is kept between pole, back of the head as well as between the testers fingers and lumbar spine.</td>
<td>• The body is pushed up as a unit facing straight down through the whole</td>
<td></td>
</tr>
<tr>
<td>Diagonal lift test</td>
<td></td>
<td>motion.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Performs one diagonal lift with the right hand and the opposite foot and knee on a line</td>
<td>All the following criteria have to be fulfilled:</td>
<td>One or more of the following criteria:</td>
</tr>
<tr>
<td></td>
<td>• No visible rotation in the spine</td>
<td>• Performs one diagonal lift with hand and the opposite knee on each side of a line</td>
<td>• Performs one diagonal lift with hand and the opposite knee on each side of a line, with one or of the following compensatory movement pattern</td>
</tr>
<tr>
<td></td>
<td>• Fully extended leg and arm in the horizontal plane</td>
<td>• No visible rotation in the spine</td>
<td>• Visible rotation in the spine</td>
</tr>
<tr>
<td></td>
<td>• No abduction in either leg or arm</td>
<td>• Fully extended leg and arm in the horizontal plane</td>
<td>• Not fully extended leg and arm in the horizontal plane</td>
</tr>
<tr>
<td></td>
<td>• No winging of the scapula</td>
<td>• No abduction in either leg or arm</td>
<td>• Abduction in either leg or arm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• No winging of the scapula</td>
<td>• Winging of the scapula</td>
</tr>
<tr>
<td>Seated rotation test</td>
<td>Performs a slow rotation with the pole in touch with the chest until the poles touch each other</td>
<td>Performs a slow rotation with the pole in touch with the chest more than 45°. The poles are not touching each other</td>
<td>Performs a slow rotation with the pole in touch with the chest less than 45°.</td>
</tr>
<tr>
<td>Functional shoulder mobility test</td>
<td>Less than one hand length between the fists.</td>
<td>Less than one and a half length or more between the fists.</td>
<td>One and a half hand length or more between the fists.</td>
</tr>
</tbody>
</table>
women 18 (14 – 24). The group distributed essentially normally in scoring indicating that no floor or ceiling effects were seen. For distribution of scores, see Figure 1-3.

Gender differences
No significant gender difference in total score was demonstrated ($p = 0.16$). A median (range) total score of 19 (12 – 24) was found for men, and 18 (14 – 24) for women (Figures 2 and 3 demonstrate the distribution). In three of the tests: active hip flexion, straight leg raise and push up, a statistically significant difference ($p = 0.00$) was found between men
and women (Table 3). In the other six tests (Table 3), no gender difference was present. Men obtained higher scores on average in straight leg raise and the push up tests, while the women obtained higher scores in active hip flexion test. Women scored more maximum 3 scores than the men in two tests; active hip flexion (women 63%) and in functional shoulder mobility test (women 63%). In the rest of the tests, the men scored more maximum 3 scores than the women.

**Previous injuries**

No difference ($p = 0.65$) in median total score was determined between the group with a prior history of injury (> 6 weeks before test occasion), median (range) 18 (12 – 24) and the group who had no prior history of injury, 19 (14 – 24). The median (range) total score for the men that reported previous injuries was 18 (12 – 24) and 19 (14 – 22) for the men who did not ($p = 0.96$). The median (range) total score for the women that reported previous injuries was 18 (14 – 21) and 18 (15 – 24) for the women who did not ($p = 0.59$).

**Factor analysis and internal consistency**

The Kaiser-Meyer-Olkin measure of sampling adequacy for this study was marginally acceptable at 0.48, with factor loadings above 0.5 considered strong. The factor analysis suggested that there were four different underlying factors linking performance in the 9TSB tests. The straight leg raise and diagonal lift tests were strongly related to one factor, with loadings of 0.74 and 0.72. The seated rotation and shoulder mobility tests were strongly related to another factor, with loadings of 0.81 and 0.71. The push up, active hip flexion, and deep squat test was also strongly related to a third factor, with loadings of 0.75, -0.68 and 0.52. The In-line lunge was strongly related to a fourth factor with a loading of 0.92 (Table 4). The internal consistency was 0.41.

**DISCUSSION**

The principal finding of this study was that there was no significant difference between men and women in total score on the 9TSB. However, there were significant differences between genders in three specific tests (active hip flexion, straight leg raise, and push up). The nine tests in the screening battery were related to four different factors according to the factor analysis. This indicates that the tests in the 9TSB can identify various dimensions of functional movements that are not necessarily related to one another. This was further confirmed with a Cronbach's alpha of 0.41 indicating that the nine tests reflect different aspects of an individual's movement pattern.

Even though no statistically significant difference was found in the total score between men and women, it is of importance to point out that there were three independent tests (active hip flexion test, straight leg raise test, and push up test) with a statistically significant gender difference. A likely explanation could be a stronger upper body and increased trunk stability in men compared to women. Conversely, women scored higher in active hip flexion, which may be indicative of enhanced hamstring flexibility or hip joint mobility. The straight leg raise test challenges the stability of the trunk, to a larger extent compared to the active

### Table 3. Median (range) for men (n = 40) and women (n = 40) and p-values for gender differences for each included test (n = 9)

<table>
<thead>
<tr>
<th>Test</th>
<th>Men</th>
<th>Women</th>
<th>X²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep squat test</td>
<td>2 (1-3)</td>
<td>2 (1-3)</td>
<td>5.08</td>
<td>0.08</td>
</tr>
<tr>
<td>One-legged squat test</td>
<td>2 (1-3)</td>
<td>2 (1-3)</td>
<td>0.47</td>
<td>0.80</td>
</tr>
<tr>
<td>In-line lunge test</td>
<td>2 (1-3)</td>
<td>2 (0-3)</td>
<td>6.05</td>
<td>0.11</td>
</tr>
<tr>
<td>Active hip flexion test</td>
<td>2 (1-3)</td>
<td>3 (2-3)</td>
<td>26.86</td>
<td>0.00</td>
</tr>
<tr>
<td>Straight leg raises test</td>
<td>2 (1-3)</td>
<td>2 (1-3)</td>
<td>11.02</td>
<td>0.00</td>
</tr>
<tr>
<td>Push up test</td>
<td>3 (0-3)</td>
<td>2 (0-3)</td>
<td>20.74</td>
<td>0.00</td>
</tr>
<tr>
<td>Diagonal lift test</td>
<td>2 (1-3)</td>
<td>2 (1-3)</td>
<td>2.22</td>
<td>0.33</td>
</tr>
<tr>
<td>Seated rotation test</td>
<td>2 (1-3)</td>
<td>2 (1-3)</td>
<td>1.92</td>
<td>0.38</td>
</tr>
<tr>
<td>Functional shoulder mobility test</td>
<td>2 (1-3)</td>
<td>3 (0-3)</td>
<td>4.2</td>
<td>0.25</td>
</tr>
</tbody>
</table>

### Table 4. Factor analysis with varimax rotation for each included test (n = 9)

<table>
<thead>
<tr>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep squat test</td>
<td>0.39</td>
<td>0.52*</td>
<td>0.43</td>
</tr>
<tr>
<td>One-legged squat test</td>
<td>0.65</td>
<td>-0.03</td>
<td>-0.07</td>
</tr>
<tr>
<td>In-line lunge test</td>
<td>0.17</td>
<td>-0.002</td>
<td>-0.01</td>
</tr>
<tr>
<td>Active hip flexion test</td>
<td>0.25</td>
<td>-0.68*</td>
<td>0.29</td>
</tr>
<tr>
<td>Straight leg raises test</td>
<td>0.74*</td>
<td>0.32</td>
<td>-0.08</td>
</tr>
<tr>
<td>Push up test</td>
<td>0.21</td>
<td>0.75*</td>
<td>0.04</td>
</tr>
<tr>
<td>Diagonal lift test</td>
<td>0.72*</td>
<td>-0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Seated rotation test</td>
<td>-0.08</td>
<td>-0.02</td>
<td>0.81*</td>
</tr>
<tr>
<td>Functional shoulder mobility test</td>
<td>-0.05</td>
<td>-0.2</td>
<td>0.71*</td>
</tr>
</tbody>
</table>

* Factor loadings above 0.5
There are several strengths of this study. This is the first study of its kind to provide normative values for the 9TSB in a group of recreational athletes. The 9TSB has been shown to be a standardized and reliable (ICC) tool that has been used for years in a clinical setting to assess functional movements and identify weak physical links during specific movements. This study provides some normative data of use for future studies, which should focus on specific age groups, types of athletes, and varied diagnoses or deficiencies.

Athlete screening followed by individual conditioning may be useful in reducing injury (acute and over-use) and hypothetically also have value in enhancing performance. The use of the 9TSB in this population of recreational middle-aged athletes showed no floor-ceiling effect, which indicates that the test battery was neither too easy nor too hard for this group to perform. A normal distribution of scores in women and men was found, with no clear age difference.

CONCLUSION

No difference in total score on the 9TSB was found between men and women, yet in three different tests (active hip flexion test, straight leg raises test and push up test) significant differences between men and women were found. Further, normally distributed 9TSB scores with no floor-ceiling effect were found, indicating that this test battery can be useful to assess functional movements in recreational athletes. These findings can serve as reference values for healthcare professionals when evaluating physically active individuals. Further cohort studies are required in order to determine cut scores or scores considered to represent optimal or dysfunctional movement.
REFERENCES
Appendix

Deep squat test

One-legged squat test

In-line lunge test

Straight leg raises test

Active hip flexion test

Diagonal lift test

Push-up test

Seated rotation test

Functional shoulder mobility test
ABSTRACT

Background: Although functional tests including the single leg hop (SLH), triple hop (TH), cross over hop (COH) for distance, and the tuck jump assessment (TJA) are used for return to play (RTP) criteria for post anterior cruciate ligament (ACL) injury, sport-specific baseline measurements are limited.

Purpose: The purpose of this study was to examine differences in SLH, TH, and COH distance and limb symmetry index (LSI), as well as total scores, number of jumps, and individual flaws of the TJA in 97 injury-free Division I (DI) collegiate female student athletes participating in ACL injury prone vs. non ACL injury prone sports. The hypothesis was that significant mean differences and asymmetries (LSI) would exist between the two groups in SLH, TH, COH and TJA.

Study Design: Cross sectional.

Methods: Due to research suggesting inherent ACL injury risk associated with specific sport involvement, participants were grouped into high (HR, n=57) and low (LR, n=40) ACL injury risk based on participating in a sport with high or low ACL injury rates. The HR group was composed of athletes participating in soccer, basketball, and volleyball, while the LR group athletes participated in diving, cross country, and track and field. Participants performed all standard functional tests (SFT) and side-to-side differences for each participant as well as between group differences were assessed for the hop tests. The LSI, a ratio frequently used to gauge athletes' readiness for RTP post injury, was also assessed for between group differences. The TJA was compared between the groups on individual flaws, overall scores, and number of jumps performed.

Results: No between group differences for hop distances were found, with medium to large effect sizes for SLH, TH, and COH. The HR group had a higher TJA score, number of jumps, and higher proportion of the flaw of ‘foot placement not shoulder width apart’.

Conclusion: Although most SFT's showed no significant differences between athlete groups, some differences were seen in the TJA; the HR group showed an increase in 'foot placement not shoulder width apart' flaw, higher overall flaw scores, and overall jumped more times compared to the LR group. These results may warrant caution in relying solely on SFT for RTP decisions, due to potential asymmetries seen in an uninjured population with baseline testing.

Level of Evidence: 4

Key Words: Asymmetry, knee, return to play
INTRODUCTION
Anterior cruciate ligament (ACL) injuries are physically, financially, and emotionally devastating sport-related knee trauma, leading to over 134,000 ACL reconstructions per year in the United States. The majority of ACL injuries are due to non-contact mechanisms. There is a substantial difference by sex, with females up to four times more likely to sustain an ACL injury compared to males, depending on sport participation. Sports associated with most ACL injuries often require sidestepping, pivoting, landing, deceleration, and cutting maneuvers, which place the knee in valgus positions under high loads and rotational forces. Furthermore, sports played on courts, such as basketball and volleyball, may have an increased ACL injury occurrence, compared to other types of playing surfaces.

After ACL injury, proper re-introduction to sport is vital to prevent re-injury and long-term consequences. To provide measurements for assessment for safe return to play (RTP) post-ACL injury, standard functional tests (SFT) have been developed. Most SFTs measure distances hopped during complex multi-planar movements as a surrogate for strength and power assessment when evaluating neuromuscular control of athletes. Myer, et al reported that hopping tests could be used to identify female athletes who are at risk for ACL re-injury. Differences between injured and uninjured limbs are one criteria used to assess readiness for RTP and may also be used to document improvements in athletes’ strength symmetries throughout progression of rehabilitation protocols; the Limb Symmetry Index (LSI) is commonly used to measure such differences. LSI is the mean hop test score of one limb divided by the mean score of the contralateral limb, multiplied by 100.

Participating in sports may facilitate pre-programed neuromuscular strategies that are sport-specific, which may predetermine functional asymmetries. Superior motor functioning on dominant limbs, including strength and power, may exist in athletes of various sports. Specifically, lower limb imbalances and asymmetries during cutting and pivoting have been observed in sports such as basketball, soccer, and volleyball. It is important to determine if such potential pre-programmed movement patterns of specific sports influence baseline performance on hop tests and the tuck jump assessment (TJA).

The purpose of this study was to examine differences in single leg hop (SLH), triple hop (TH), and cross over hop (COH) distance and LSI, as well as total scores, number of jumps, and individual flaws of the TJA in 97 injury-free Division I (DI) collegiate female student athletes participating in ACL injury prone vs. non ACL injury prone sports. The hypothesis was that significant mean differences and asymmetries (LSI) would exist between the two groups in SLH, TH, COH and TJA.

METHODS
This cross-sectional study included 97 healthy and injury free Division I (DI) female student athletes (n=97) between 18 and 22 years of age (mean ± standard deviation: 19.3 ± 1.2 years). Athletes participated in soccer, basketball, volleyball, diving, cross-country, and track and field. Potential participants were cleared to play by the team physician during the pre-participation exam prior to being given a health questionnaire. Positive responses on the questionnaire were reviewed by a physical therapist (mw) prior to performance of any of the functional tests. Participants were excluded if they had a history of concussion in the prior six months, any current injury or illnesses that would limit ability to participate in the testing, or if improper attire (i.e., non-athletic shoes) was worn. Data were collected at Northern Arizona University’s athletic facilities throughout the 2014-2016 sport seasons.

Before data collection, participants were given verbal information about the purpose, risks, benefits, and expectations of the study as well a chance to ask questions. All participants signed an informed consent, which was approved by the Institutional Review Board at Northern Arizona University.

Participants were categorized into two groups based on ACL injury risk from sport participation. The high ACL injury risk group (HR) was composed of participants in soccer, basketball, and volleyball (n=57). The low ACL injury risk group (LR) included participants in diving, cross country, and track and field (n=40).

Each participant completed four tests – SLH, TH, and COH for distance, and the TJA. The order of the
tests was randomized for each participant. Protocols as outlined by Noyes, et al27 were used for each hop test, while published guidelines by Myer, et al15 were used to administer and score the TJA. Hop test data from two participants, and all three left hop test data from one participant were not collected due to injury concerns based on health questionnaire responses. TJA data from seven participants were not collected due to camera malfunction.

The SLH, TH, and COH for distance27 are the most frequently reported functional tests used post-ACL reconstruction, thus these were chosen for this study. Literature shows a correlation between hop tests and knee function, as measured by self-reported questionnaires post ACL injury.28 Furthermore, the distance hopped for the SLH test may predict low back pain and lower extremity injuries.29-32 Hop tests can reveal differences between injured and uninjured limbs;27,29,30,33 when determining a measure for safe RTP, the literature supports a LSI threshold of 90%.16,17 Reduced LSI asymmetry is associated with the promotion of improved RTP rates and lower rates of re-injury.34-36 Hop tests have also shown good reliability (intraclass correlation coefficients [ICCs] 0.84 to 0.97).29,37 The SLH, TH, and COH required participants to stand with the tips of one shoe on a piece of tape on the ground. For the SLH, the participant hopped forward in a straight line as far as possible, landing on the same foot. For the TH, the distance measured included three consecutive hops on one leg in a straight line, with no recovery allowed between hops. For the COH, each participant performed three hops, crossing a one-foot wide area marked off with tape with each hop. The distance was measured from the starting tape to the back of the heel upon landing. For each test, participants had to demonstrate no loss of balance at landing before the hop distance was measured and recorded; having to put down the second foot at any time during the hop or landing or any aberrant movement that caused the plant foot to move upon landing was recorded as a failed attempt. Failure to perform the hop properly required repeated attempts until a proper hop was completed. The hops were performed two times per limb with a short rest break between attempts. One practice attempt was allowed before each of the hop tests.

The tuck jump assessment (TJA) has been suggested as a useful tool to identify lower extremity flaws seen with plyometric movements14,38 and can, along with hop tests, document improvements in an athlete’s progression through rehabilitation protocols.8,14,15 With the TJA, clinicians identify movement patterns associated with ACL injury, such as excessive knee valgus,3,5 and target impairments with neuromuscular training to help lower injury risk.13 Good inter- and intrarater reliability for the TJA have been published;39 however, conflicting research exists. Dudley, et al40 found poor interrater reliability and poor to moderate intrarater reliability, and further suggested a possible learning curve to scoring the TJA and resultant improvements with interrater reliability with repeat scoring. To help achieve consistent scoring, two independent assessors were trained and underwent practice sessions before scoring; consensus was achieved between the two independent assessors on videos from 25 athletes not associated with this study. For the TJA, participants stood with feet placed approximately shoulder width apart on pieces of tape and performed tuck jumps for ten seconds, bringing both thighs as close to parallel with the ground as possible, landing in the same footprint, and immediately jumping again upon landing for 10 seconds. The participants were recorded from both the frontal and sagittal view using standard video cameras (Sony Handycam, Sony Corporation San Diego, CA and JVC camcorder, JVC Americas Corporation Wayne, NJ). The videos were reviewed after all testing was completed, and scored on ten different flaws that a participant may have displayed during the jumps.15,38 An overall score of the TJA was the summed total number of flaws observed by an individual scorer. The number of jumps in 10 seconds was also recorded.

STATISTICAL METHODS

Independent t-tests of means were used to compare continuous demographic variables between the two groups. For each hop test (i.e., SLH, TH, COH), the participant's average distance of two hops was normalized to height.17 The LSI was calculated by the ratio of right to left limb, versus injured vs. non-injured, due to the population being healthy. Because there were significant differences in weight between those in high and low ACL risk sports as well as a significant association between hop tests and weight, differences between the groups from
the hop tests were analyzed using linear regression, adjusting for body weight. For the TJA score and number of jumps, between group differences were assessed with independent t-tests. The association of each flaw by group was analyzed using Chi Square. Bonferroni's correction was used to minimize the risk of Type 1 error due to multiple tests; alpha of 0.003 was used for statistical significance. Cohen's d were calculated as effect sizes and categorized (<0.29 = small, 0.3-0.49 = medium, >0.5 = large) to aid in interpretation of clinical relevance of the tests. SAS 9.4 (SAS Institute, Inc., Cary, NC) was used for statistical analysis.

RESULTS
There were 97 participants in this study with 57 in the HR group and 40 in the LR group. The two groups were similar in age (p = 0.95); however, the HR group participants were taller and heavier (p = 0.004 and 0.005, respectively) (Table 1).

Ninety-five (HR = 57, LR = 38) participants completed the right SLH, TH, and COH, while 94 (HR = 56, LR = 38) completed the left SLH, TH, and COH. There were no significant differences in average SLH, TH, COH distances between groups (p-values: SLH R = 0.05 L = 0.02, TH R = 0.05 L = 0.005, COH R = 0.1 L = 0.04) (Figure 1). Effect sizes ranging from 0.35 to 0.62 (RSLH = 0.42, LSLH = 0.49, RTH = 0.43, LTH = 0.62, RCOH = 0.35, LCOH = 0.46) were found for both right and left SLH, TH, and COH, showing a moderate to large clinical relevance, despite lack of statistical significance. In general, the participants hopped equal distances on the right and left leg (LSI close to 100% for all). No between-group differences were found with LSI with any of the hop tests (Table 2).

Ninety-seven participants completed the TJA with 57 in the HR group and 40 in the LR group; however, only data from 90 participants (HR = 50, LR = 40) were analyzed due to video malfunctioning. The HR group had a higher TJA score, (HR: 5.86 ± 1.51 vs. LR: 4.68 ± 1.29, p < 0.001) indicating worse performance, as well as a greater number of jumps (HR: 37.6 ± 20.5 vs. LR: 29.6 ± 15.5, p < 0.001).

Table 1. Demographic Characteristics by Group

<table>
<thead>
<tr>
<th></th>
<th>High Risk ACL, n=57</th>
<th>Low Risk, n=40</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, years (mean ± standard error [SE])</td>
<td>19.3 ± 0.2</td>
<td>19.3 ± 0.2</td>
<td>0.95</td>
</tr>
<tr>
<td>Height, cm (mean ± SE)</td>
<td>170.9 ± 0.01</td>
<td>166.5 ± 0.01</td>
<td>0.004</td>
</tr>
<tr>
<td>Weight, kg (mean ± SE)</td>
<td>68.3 ± 1.2</td>
<td>61.2 ± 2.1</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 2. Average Adjusted Limb Symmetry Index (LSI) by Group

<table>
<thead>
<tr>
<th>Hop Test</th>
<th>High Risk, n = 56</th>
<th>Low Risk, n = 38</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Leg Hop LSI (mean ± standard error [SE])</td>
<td>100.5% ± 0.95%</td>
<td>99.1% ± 1.1%</td>
<td>0.33</td>
</tr>
<tr>
<td>Triple Hop LSI (mean ± SE)</td>
<td>103.3% ± 1.0%</td>
<td>100.3% ± 1.2%</td>
<td>0.006</td>
</tr>
<tr>
<td>Crossover Hop LSI (mean ± SE)</td>
<td>100.8% ± 1.1%</td>
<td>99.6% ± 1.4%</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Figure 1. Average Adjusted* Hop Distances for left (L) and right (R) Single Leg Hop (SLH), Triple Leg Hop (TLH), and Cross Over Hop (COH) Relative to Height Between Groups†
and showed a close relationship with asymmetry measurements (LSI). Above 90% threshold was observed for all participants with the LSI regardless of group. This may suggest that hop tests are not affected by pre-programmed motor programs associated with sport performance and may be used for RTP measurements independent of the participant’s sport. However, this sample may not reveal significant differences between the groups due to post hoc analysis (power = 0.31-0.57) showing some comparisons (hop tests) were underpowered. With medium to large effect sizes, there may be important differences between the two sport groups for the hopping tests that the sample size may have limited the ability to uncover. It would be clinically important to know of such possible discrepancies prior to injury, otherwise it would not be of clinicians’ best interests to use hop tests as RTP criteria.

The TJA showed a significant difference between the two groups on the ‘foot placement not shoulder width apart’ flaw with an increase in the flaw seen in the HR group. Participants in the HR group also performed significantly more jumps and pre-

<table>
<thead>
<tr>
<th>Flaw</th>
<th>% HR (n=50) Displaying Flaw</th>
<th>% LR (n=40) Displaying Flaw</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Extremity Valgus at Landing</td>
<td>64.6</td>
<td>35.4</td>
<td>0.0053</td>
</tr>
<tr>
<td>Thighs Do Not Reach Parallel (Peak of Jump)</td>
<td>59.7</td>
<td>40.3</td>
<td>0.18</td>
</tr>
<tr>
<td>Thighs Not Equal Side-to-Side (During Flight)</td>
<td>65.8</td>
<td>34.2</td>
<td>0.095</td>
</tr>
<tr>
<td>Foot Placement Not Shoulder Width Apart</td>
<td>75.5</td>
<td>24.5</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>Foot Placement Not Parallel (Front to Back)</td>
<td>60.6</td>
<td>39.4</td>
<td>0.11</td>
</tr>
<tr>
<td>Foot Contact Timing Not Equal</td>
<td>87.5</td>
<td>12.5</td>
<td>0.0046</td>
</tr>
<tr>
<td>Excessive Landing Contact Noise</td>
<td>51.5</td>
<td>48.5</td>
<td>0.20</td>
</tr>
<tr>
<td>Pause Between Jumps</td>
<td>42.9</td>
<td>57.1</td>
<td>0.18</td>
</tr>
<tr>
<td>Technique Declines Prior to 10 Seconds</td>
<td>50.0</td>
<td>50.0</td>
<td>0.68</td>
</tr>
<tr>
<td>Does Not Land in Same Footprint (Excessive In-Flight Motion)</td>
<td>57.5</td>
<td>42.5</td>
<td>0.29</td>
</tr>
</tbody>
</table>

* = Significant (p-value < 0.003)
sented with a higher number of total flaws. Linginger et al. and Myer et al. have suggested grouping individual TJA flaws into various categories, with the ‘foot placement not shoulder width apart’ flaw being grouped into the ‘proximal control’ and ‘ligament dominance’ categories, respectively. Ligament dominance refers to difficulty maintaining a stable knee with dynamic tasks due to imbalances found between muscular and ligamentous knee influences, leading to inability to control lower extremities during jumping tasks. Furthermore, hip weakness may result in participants shifting their feet to minimize forces on a weaker limb. If the HR group did have asymmetries in muscle strength, this may be manifested in the TJA performance, which may explain the increased number in the “foot placement not shoulder width apart” flaw. This flaw may represent lack of proximal control due to hip weaknesses. Further, if the HR group demonstrated increased occurrences of hip weakness and lack of proximal control, other flaws will be more likely to be observed in the jumps, especially the ‘excessive knee valgus’ flaw as hip weakness is also associated with increased valgus moments. This may potentially explain the increase number of total flaws seen in this group and may suggest that certain uninjured athletes perform functional tests with increased asymmetry and decreased LE control compared to others, depending on type of sport performed.

It is also possible that the increase in number of flaws seen with the HR group may be due to the increased number of jumps performed and thus increased fatigue that occurred during the 10 second test. Lininger, et al. suggested faster jumping rates lead to increased fatigue, compared to slower jumping rates, where there is increased time spent on the ground and thus potentially less fatigue during the 10 second TJA. Fatigue onset has been shown to occur in male and female track athletes under 10 seconds on the Wingate test with resulting decrease in postural control and hip mechanics. Furthermore, fatigue has been shown to affect quality of jumps. A slower rate of jumps may be witnessed in a population not trained in jumping, and thus taking a longer time to control the new skill. This is consistent with the findings of this study. Since jumping is a frequent activity seen with the HR group sports, it may explain the greater number of jumps recorded. The LR group sports expose athletes to less frequent jumping activities, leading to potential decreased jump rates due to inexperience with the task. This may have caused the discrepancy between jump rates and thus total jumps performed from each group. Therefore it may be beneficial to provide participants with a way to practice the jumps or control jumping rates in the TJA in future studies to help standardize the procedure and minimize possible fatigue discrepancies between athletes.

Because the TJA is often used for RTP progression, as well as for identifying females at risk of injury, understanding performances on this test pre-injury is important for proper analysis of results. The HR group performed worse on the TJA, suggesting that female athletes in soccer, volleyball, and basketball may be at an increased risk of ACL injury compared to female athletes in track and field, cross country, and diving. The results also suggest possible differences in the biomechanical motor programs between the groups. This may be present in a healthy population and be related to their respected sport participation, with HR ACL injury risk sport participants presenting with decreased neuromuscular control and increased asymmetries.

The results of this study show similar performances on hop tests, but significantly different TJA performances between female athletes participating in HR and LR sports; thus, in part rejecting the original hypothesis. Due to some significant differences found, caution is warranted when using the TJA for RTP post injury, due to possible pre-injury differences, which may exist as a result of pre-programmed motor programs. Such differences may be the result of functional asymmetries witnessed due to participation in sports such as soccer, volleyball, and basketball and the biomechanical loads and demands of these sports. Further research investigating such differences among healthy athletes of different sports is needed. Knowledge of pre-injury differences on performances between various sports may lead to development of sport specific RTP protocols.

If rehabilitation clinicians rely on hop tests or the TJA results for RTP decisions, caution is warranted as asymmetry and performance differences may exist.
because of pre-programmed motor programs established through sport participation. Clinicians may want to focus on a multi-planar approach instead and this should be the focus of further research. Furthermore, if differences do exist between athletes of various sports, more specific and, thus, effective interventions and RTP protocols could be developed.

Limitations to this study include a small sample of convenience, with all 97 female participants of this study playing for one Division I university, potentially limiting external validity; practical application to males and different levels of competition cannot be assumed. Also, participants were not screened for a history of previous ACL injuries. This could be a limitation due to research that describes the possibility of long term deficits between involved and uninvolved limbs on strength and functional tests post ACL injury. However, Hartigan et al reported that the mean scores on four hop indices (SLH, TH, COH, and six-meter timed hop) were above 90% in males and females at six months post ACL reconstruction. It also remains unclear whether such post-surgical neuromuscular limitations in hopping tests are purely the result of ACL injury, or if pre-injury asymmetries existed as studies designed to assess field tests in ACL injury have only been retrospective, not prospective, in nature. Despite the limitations, this is the first study that examined differences in functional tests based on type of sport.

Further research should examine performances on SFTs with larger samples and in male athletes to extend findings across sexes and minimize the possibility of type II error. Comparing dominant and non-dominant, versus left and right, limbs between groups in a healthy population may also be of benefit. Further research should also evaluate the ability of functional hop tests and TJA in predicting incidence of ACL injury in female athletes participating in high ACL injury risk sports compared to females participating in low ACL injury risk sports.

CONCLUSION

The results of this study showed no differences between hop test scores in Division I female athletes of high and low ACL risk sports, however differences were observed between groups for the TJA. Due to the differences seen between baseline performance in normal subjects examined in this research, caution should be used when interpreting the TJA for RTP decisions. Due to the medium effect sizes, showing clinically relevant differences for the hop tests, future research with increased sample sizes is warranted to help lower the risk for potentially committing Type II errors. Performances on the TJA might vary due to the inherent nature of different and asymmetrical biomechanical movements associated with specific sports. More research is needed to verify the observed differences of this study.

REFERENCES

10. Lephart SM, Perrin DH, Fu FH, et al Relationship between selected physical characteristics and functional capacity in the anterior cruciate ligament-


ABSTRACT

**Background:** Injuries are inherent in basketball with lower extremity (LE) injury rates reported as high as 11.6 per 1000 athletic exposures (AEs); many of these injuries result in time loss from sport participation. A recent trend in sports medicine research has been the attempt to identify athletes who may be at risk for injury based on measures of pre-season fitness.

**Hypothesis/Purpose:** The purpose of this prospective cohort study was to determine if the standing long jump (SLJ) and/or the single-leg hop (SLH) for distance functional performance tests (FPT) are associated with non-contact time loss lower quadrant (LQ, defined as lower extremities or low back) injury in collegiate male basketball players. It was hypothesized that basketball players with shorter SLJ or SLH measures would be at an increased risk for LQ injury.

**Methods:** Seventy-one male collegiate basketball players from five teams completed a demographic questionnaire and performed three SLJ and six SLH (three per lower extremity) tests. Team athletic trainers tracked non-contact LQ time loss injuries during the season.

**Study Design:** Prospective cohort

**Results:** Mean SLJ distance (normalized to height) was 0.99 (± 0.11) and mean SLH distances for the right and left were 0.85 ± 0.11 and 0.87 ± 0.10, respectively. A total of 29 (18 initial, 11 subsequent) non-contact time loss LQ injuries occurred during the study. At risk athletes (e.g., those with shorter SLJ and/or SLH) were no more likely to experience a non-contact time loss injury than their counterparts [OR associated with each FPT below cut scores = 0.9 (95% CI: 0.2, 4.9)]. The results from this study indicate that preseason performance of the SLJ and the SLH were not associated with future risk of LQ injury in this population.

**Conclusions:** Preseason SLJ and SLH measures were not associated with non-contact time loss injuries in male collegiate basketball players. However, the descriptive data presented in this study can help sports medicine professionals evaluate athletic readiness prior to discharging an athlete back to sport after a LQ injury.

**Level of Evidence:** 2

**Keywords:** College, epidemiology, functional test, single-leg hop, standing long jump

---

**CORRESPONDING AUTHOR**

Jason Brumitt, PT, PhD, ATC, CSCS
Assistant Professor of Physical Therapy
School of Physical Therapy
George Fox University
Newberg, Oregon
Phone: 503-554-2461
E-mail: jbrumitt@georgefox.edu, jbrumitt72@gmail.com

1 George Fox University, Newberg, OR, USA
2 Warner Pacific College, Portland, OR, USA
3 Multnomah University, Portland, OR, USA
4 Spalding University, Louisville, KY, USA
INTRODUCTION
Basketball is a popular sport played worldwide both competitively and recreationally by players of all ages. Injuries are inherent in basketball with the ankle, knee, lumbar spine, and the thigh cited as the most frequently injured regions in the lower quadrant. Lower extremity (LE) injury rates in basketball players have been reported as high as 11.6 per 1000 athletic exposures (AEs); many of these injuries result in time loss from practice and/or competition.

Injury rates (overall, time loss, and non-time loss) have been reported for male basketball players who compete at the NCAA and NAIA collegiate levels. Collegiate male basketball players (consisting of all levels of NCAA and NAIA players) experienced an overall injury rate of 27.8 per 1000 AEs (non-time loss injuries = 21.8 per 1000 AEs; time loss injuries = 6.0 per 1000 AEs). The highest overall (36.6 per 1000 AEs), non-time loss (28.8 per 1000 AEs), and time loss injury (7.8 per 1000 AEs) rates were observed in male basketball players who competed at the NCAA Division I (D I) level. NCAA Division III (D III) male basketball players had the second highest time loss injury rate of 7.0 per 1000 AEs. The overall injury rate for NAIA male basketball players was reported at 18.4 per 1000 AEs with a time loss rate of 4.8 per 1000 AEs. With thousands of male basketball players competing at the NCAA and NAIA collegiate levels there is the potential for time loss injuries impacting team performance and success.

A recent trend in sports medicine research has been the attempt to identify athletes who may be at risk for injury based on measures of preseason fitness. Functional performance tests (FPTs) such as the Star Excursion Balance Test (SEBT), the Functional Movement Screen (FMS)™, the standing long jump (SLJ), and the single-leg hop (SLH) for distance have been administered to basketball players during the preseason to determine if scores are associated with subsequent sports-related injury during the season. Poorer preseason performance on the SEBT has been associated with greater risk of lower extremity injury in high school basketball players and D I athletes (a population that included basketball athletes). Scores on the FMS™, a series of dynamic and static tests, did not discriminate injury risk in National Basketball Association (NBA) basketball players or in a general population of D I athletes (which included basketball players). Preseason performance of the SLJ was not associated with an increased risk of LQ injury in a general population of male D III athletes. Interestingly, greater SLH distances were associated with a greater risk of lower quadrant (LQ) injury in a general population of male D III athletes (a population that included male basketball players).

The aforementioned studies represent FPTs that have been prospectively evaluated for discriminating risk associations in athletes who play basketball (or, in some cases, a general population of athletes that included basketball players). However, the results from these studies leave sports medicine professionals and strength coaches with uncertainty as to which FPT, or combination of FPTs, can best identify male collegiate basketball players who may be at an increased risk for injury. Thus, additional assessment of FPTs in a population of male collegiate basketball players is warranted. The purpose of this prospective cohort study was to determine if the SLJ and/or the SLH for distance FPTs are associated with non-contact time loss lower quadrant (LQ = lower extremities or low back) injury in male collegiate basketball players. It was hypothesized that basketball players with shorter SLJ and/or SLH measures would be at an increased risk for LQ injury.

METHODS
Participants
Seventy-one male collegiate basketball players (20.2 ± 1.9 y) were recruited from two NCAA D III and three NAIA teams. An athlete was excluded from study participation if a) he was under the age of 18 or b) restricted from full sport participation by the team’s physician. The Institutional Review Board of George Fox University approved this study. Informed consent was obtained from each subject prior to participation.

Procedures
Off-season training habits, anthropometric measures, and FPT scores were collected for players at the start of the preseason. Prior to performing...
the FPTs each basketball player completed a short questionnaire collecting the following demographic information: age, years in university/college, age starting their sport, and average time training per week during the six week period prior to the start of the official preseason. The specific off-season training categories included: weightlifting, cardiovascular exercise, plyometric exercise, and scrimmaging. Height and weight measures were also collected using a cloth tape for height (measured to nearest half inch) and standard medical scale for weight (measured to the nearest half pound).

**Dynamic Warm-Up**
Each subject participated in a dynamic warm-up after collecting anthropometric and demographic information and prior to performing the FPTs. The dynamic warm-up consisted of five minutes of active movements across the width of the basketball court: forward walking, backward walking, forward lunging, backward lunging, and high knee marching. After completing the dynamic warm-up each athlete performed three submaximal SLJs.

The FPTs were performed in the following order: a) three SLJ, b) three SLH for distance per LE (total of six hops); alternating between sides with testing order determined by a coin flip.

**Standing Long Jump**
Each basketball player stood with their feet placed shoulder width apart and positioned behind a piece of tape placed on the court. A cloth measuring tape was fixed to the floor to record distance jumped. Each subject performed three maximal effort SLJ with hands clasped behind their back. For a test to count, a basketball player had to maintain hands clasped behind their back and stick the landing holding the position for five seconds. A SLJ trial was repeated if the athlete was unable to stick the landing. The SLJ distance was measured from the rear-most heel to the starting line. The mean score of the three SLJs, normalized to height, was used for statistical analysis.

**Single-Leg Hop for Distance**
After completing the three SLJ trials an athlete performed the three SLH tests (performed bilaterally for a total of six SLH trials). A coin flip determined which leg an athlete hopped with first; each trial alternated between legs. For a test to be recorded subjects had to maintain hands clasped behind their back and stick the landing for five seconds. A trial was repeated if the athlete was unable to land successfully. The distance hopped was measured from the heel to the starting line. The mean score hopped for each leg, normalized to height, was used for statistical analysis.

**Injury Surveillance**
Injury records and daily athletic exposures (one AE = one practice or one game) were collected by each university's/college's athletic training staff. The certified athletic trainers recorded the following features for each injured basketball player: body region, side of the body, and number of days missed from sport participation. The operational definition of an injury was any muscle, joint, or bone problem/injury (mechanism of injury: non-contact) of the low back or the lower extremity (categorized by region: hip, thigh, knee, leg, ankle, or foot) that occurred either during practice or competition that required the athlete to be removed from that day's event or to miss a subsequent practice or competition. The primary investigator (PI) collected and reviewed injury records on a weekly basis to ensure accurate data collection.

**Statistical Analyses**
A sample size of 67 subjects (based on an a priori calculation) was needed to determine statistically significant associations between LQ injury and functional performance test measures. Descriptive statistics (means ± SD) were calculated for the athlete's demographic characteristics and FPT scores. Mean SLJ and SLH scores were normalized as a percentage of height. Comparison of means between starters/non-starters and forwards/guards were calculated by performing independent t-tests. The PI's test-retest reliability (ICC3,3) has been previously reported for each FPT: SLJ = 0.96 (95% CI = 0.83, 0.97); R SLH = 0.95 (95% CI = 0.89, 0.98); L SLH = 0.96 (95% CI: 0.89, 0.98). Incidence and rate ratios were analyzed based on starter/non-starter status and player positions (forward (including centers)/guard). Injury rates were calculated per 1000 ath-
The purpose of this study was to determine if pre-season performance on the SLJ and/or the SLH FPTs
**Table 1. Demographic Characteristics and Normalized Functional Performance Test Measures (Mean ± SD) of Male Collegiate Basketball Players**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Total (n = 71)</th>
<th>Starters (n = 25)</th>
<th>Non-Starters (n = 46)</th>
<th>p-value*†</th>
<th>Guards (n = 45)</th>
<th>Forwards (n = 26)</th>
<th>p-value‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>20.2 ± 1.9</td>
<td>20.9 ± 1.9</td>
<td>19.9 ± 1.8</td>
<td>0.03</td>
<td>20.2 ± 1.9</td>
<td>20.4 ± 2.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Years in School</td>
<td>2.4 ± 1.2</td>
<td>2.9 ± 1.3</td>
<td>2.1 ± 1.1</td>
<td>0.01</td>
<td>2.4 ± 1.2</td>
<td>2.4 ± 1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Age Starting Sport (y)</td>
<td>8.7 ± 3.1</td>
<td>7.8 ± 3.2</td>
<td>9.1 ± 2.9</td>
<td>0.1</td>
<td>8.7 ± 3.0</td>
<td>8.8 ± 3.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Off-Season Training (hr/wk)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weightlifting</td>
<td>4.8 ± 2.5</td>
<td>4.6 ± 2.3</td>
<td>4.9 ± 2.6</td>
<td>0.7</td>
<td>4.9 ± 2.6</td>
<td>4.6 ± 2.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Cardiovascular Exercise</td>
<td>5.8 ± 4.1</td>
<td>5.6 ± 3.4</td>
<td>5.8 ± 4.4</td>
<td>0.9</td>
<td>5.9 ± 4.4</td>
<td>5.5 ± 3.5</td>
<td>0.7</td>
</tr>
<tr>
<td>Plyometric Exercise</td>
<td>2.3 ± 2.1</td>
<td>2.7 ± 2.6</td>
<td>2.1 ± 1.8</td>
<td>0.2</td>
<td>2.0 ± 1.7</td>
<td>2.9 ± 2.6</td>
<td>0.08</td>
</tr>
<tr>
<td>Scrimmage</td>
<td>5.4 ± 3.2</td>
<td>5.4 ± 3.1</td>
<td>5.4 ± 3.2</td>
<td>0.9</td>
<td>5.4 ± 3.3</td>
<td>5.3 ± 2.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.88 ± .07</td>
<td>1.89 ± .08</td>
<td>1.88 ± .07</td>
<td>0.4</td>
<td>1.84 ± 0.06</td>
<td>1.94 ± 0.04</td>
<td>≤0.0001</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>83.1 ± 9.4</td>
<td>83.1 ± 8.7</td>
<td>83.1 ± 9.9</td>
<td>0.9</td>
<td>78.9 ± 7.1</td>
<td>90.3 ± 8.6</td>
<td>≤0.0001</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>23.5 ± 2.0</td>
<td>23.3 ± 2.1</td>
<td>23.7 ± 2.0</td>
<td>0.5</td>
<td>23.3 ± 1.9</td>
<td>23.9 ± 2.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Functional Performance Test</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standing Long Jump</td>
<td>0.99 ± 0.11</td>
<td>0.99 ± 0.10</td>
<td>0.99 ± 0.11</td>
<td>0.9</td>
<td>1.02 ± 0.08</td>
<td>0.93 ± 0.12</td>
<td>≤0.001</td>
</tr>
<tr>
<td>(R) Single-Leg Hop</td>
<td>0.85 ± 0.11</td>
<td>0.86 ± 0.09</td>
<td>0.85 ± 0.12</td>
<td>0.7</td>
<td>0.88 ± 0.09</td>
<td>0.81 ± 0.13</td>
<td>0.005</td>
</tr>
<tr>
<td>(L) Single-Leg Hop</td>
<td>0.87 ± 0.10</td>
<td>0.89 ± 0.08</td>
<td>0.86 ± 0.12</td>
<td>0.2</td>
<td>0.88 ± 0.09</td>
<td>0.85 ± 0.13</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*Independent t-tests†Comparison of means between starters vs. non-starters‡Comparison of means between guards vs. forwards
p-values in bold illustrate statistically significant differences at the 0.05 level.

**Table 2a. Non-Contact Lower Quadrant Injury Rates in Male Collegiate Basketball Players, Starters vs. Non-Starters.**

<table>
<thead>
<tr>
<th>Injury Category</th>
<th>Total</th>
<th>Starters</th>
<th>Non-Starters</th>
<th>Rate Ratio†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.AEs</td>
<td>Rate</td>
<td>No. AEs</td>
<td>Rate</td>
</tr>
<tr>
<td>Onset Initial</td>
<td>18</td>
<td>6558</td>
<td>2.7 (1.7, 4.3)</td>
<td>8</td>
</tr>
<tr>
<td>Subsequent</td>
<td>11</td>
<td>917</td>
<td>1.2 (0.6, 2.1)</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>29</td>
<td>7475</td>
<td>3.9 (2.6, 5.5)</td>
<td>12</td>
</tr>
</tbody>
</table>

Rate: Injury rate per 1000 AEs† Rate Ratio between starters and non-starters

**Table 2b. Non-Contact Lower Quadrant Injury Rates in Male Collegiate Basketball Players, Guards vs. Forwards.**

<table>
<thead>
<tr>
<th>Injury Category</th>
<th>Guards</th>
<th>Forwards</th>
<th>Rate Ratio††</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. AEs</td>
<td>Rate</td>
<td>No. AEs</td>
</tr>
<tr>
<td>Onset Initial</td>
<td>13</td>
<td>4191</td>
<td>3.1 (1.7, 5.2)</td>
</tr>
<tr>
<td>Subsequent</td>
<td>9</td>
<td>652</td>
<td>1.4 (0.7, 2.5)</td>
</tr>
<tr>
<td>Total</td>
<td>22</td>
<td>4843</td>
<td>4.5 (2.9, 6.8)</td>
</tr>
</tbody>
</table>

Rate: Injury rate per 1000 AEs††Rate Ratio between guards and forwards
The majority of injuries experienced in this population of BB players were at the ankle. Lateral ankle sprains are common in basketball; this finding is consistent with reports from other epidemiologic studies.6-11 However, the overall injury rate in this population was lower than what has been previously reported.6-11 There are three potential reasons for this finding. First, in this study the focus was on injuries to the LQ only. Most studies report injury rates that include musculoskeletal injuries experienced throughout the body. It is possible that the overall time loss injury rate of 3.9 per 1000 AEs observed in this study, which is below previously reported time loss injury rates of 4.8 (NAIA BB players)12 to 7.0 per 1000 AEs (Division III BB players)12, was due to the exclusion of injuries to the head and upper quadrant. Second, many studies present rates that include both contact and non-contact injuries.4,6-11 Deitch et al reported a LE injury rate of 11.6 per 1000 AEs in NBA basketball players; however,
this rate also included all injury mechanisms (e.g., contact and non-contact mechanisms). For the purposes of this study the authors chose to only analyze risk associations between non-contact injury mechanisms and preseason FPT scores. Finally, it is possible that a lower overall rate observed was the result of fewer injuries sustained during the study period.

The descriptive data presented may also help sports medicine professionals appreciate functional performance requirements for injured basketball players. Return to sport clinical guidelines recommend male athletes with a LE injury should be able to jump at least 90 percent of their height and hop for distance at least 80% of their height. Collegiate male BB players jumped on average almost 100 percent of their height (0.99 ± 0.11) and hopped on average over 85 percent of their height (range 0.85 ± 0.11 – 0.87 ± 0.10). Sports medicine professionals should consider requiring injured collegiate male BB players to jump and hop greater distances than those currently recommended before discharging the athlete back to full sport participation.

**Limitations**

A few limitations in this current study are noted. First, even though more basketball players were recruited than necessary based on the a priori power analysis, analysis of risk per body region was limited to “all injuries” and “foot/ankle region”. Analysis of risk was not possible at the “thigh/knee region” due to a lack of total number of reported injuries. Second, athletes were asked to self-report their training habits prior to the start of the season; it is possible that some athletes under or over-reported their weekly training habits (e.g., recall bias).

**CONCLUSION**

Preseason measures on the SLJ and the SLH for distance are not associated with an increased risk for a lower quadrant (e.g., low back or lower extremity) injury in collegiate male BB players. However, the descriptive data presented in this study can help sports medicine professionals evaluate athletic readiness prior to discharging an athlete back to sport after a LQ injury.

**REFERENCES**


ABSTRACT

Objectives: To investigate outcomes after surgical repair of distal biceps tendon rupture and the influence of arm dominance on isokinetic flexion and supination results.

Background/Purpose: While relatively uncommon, rupture of the distal biceps tendon can result in significant strength deficits, for which surgical repair is recommended. The purpose of this study was to assess patient reported functional outcomes and muscle performance following surgery.

Methods: A sample of 23 participants (22 males, 1 female), who had previously undergone surgical repair of the distal biceps tendon, were re-examined at a minimum of one year after surgery. Biodex isokinetic elbow flexion and supination testing was performed to assess strength (as measured by peak torque) and endurance (as measured by total work and work fatigue). The Quick Disabilities of the Arm, Shoulder and Hand (QuickDASH) and Mayo Elbow Performance Scale (MEPS) were used to assess participants’ subjectively reported functional recovery.

Results: At a mean of 7.6 years after surgical repair, there were no differences between the repaired and uninvolved elbows in peak torque (p = 0.47) or total work (p = 0.60) for flexion or supination. There was also no difference in elbow flexion work fatigue (p = 0.22). However, there was significantly less work fatigue in supination, which was likely influenced by arm dominance, as most repairs were to the dominant arm, F(1,22) = 5.67, p = 0.03.

Conclusion: The long-term strength of the repaired elbow was similar to the uninvolved elbow after surgery to the distal biceps tendon. Endurance of the repaired elbow was similar in flexion but greater in supination, probably influenced by arm dominance.

Study design: Retrospective case series

Level of Evidence: Level 4

Key Words: Elbow, endurance testing, flexion, strength testing, supination
INTRODUCTION

Rupture of the distal insertion of the biceps brachii tendon is a relatively uncommon injury,\textsuperscript{1,2} with an reported incidence of 1.2 per 100,000 patients per year.\textsuperscript{3} Most of these injuries occur from an eccentric contraction of the biceps brachii, when the flexed and supinated elbow is abruptly loaded.\textsuperscript{4,5} Most reported cases have involved middle-aged men\textsuperscript{1,2} and the dominant arm is most frequently affected.\textsuperscript{6}

It is commonly accepted that surgical management represents the treatment of choice for avulsion of distal biceps tendon, given the deficits reported in the strength and endurance of both elbow flexion and supination associated with conservative or non-operative management.\textsuperscript{1,2,5,7} Reattachments of the tendon using the Endobutton and Footprint techniques are two common surgical procedures used for repair after this injury. The Endobutton technique has the advantage of using a single incision, has a low complication rate and provides the strength of fixation to enable early active mobilization.\textsuperscript{8,9} The Footprint technique is a new single incision technique, which provides attachment of the tendon to the radial tuberosity.\textsuperscript{10}

It is difficult to clearly establish the functional outcomes following surgical repair of the distal biceps tendon avulsion. This is due in part, to the variety of surgical techniques and rehabilitation, variable outcome measures, and methodological challenges associated with case series and small subject numbers.\textsuperscript{1,2,5,11,12} Recently in a cohort of 17 patients who underwent a double incision surgical repair and standardized post-operative rehabilitation program, deficits of 10-15% in supination strength and endurance were noted at an average follow up of 24 months.\textsuperscript{5} In a review of 26 patients who underwent surgical repair using the Endobutton technique and a standardized post-operative rehabilitation program, ongoing deficits in flexion strength (20%) and supination strength (9%) were noted at a mean of 16 months postoperatively.\textsuperscript{13}

Isokinetic dynamometry has been used to assess muscle function following surgical intervention as it is more sensitive than manual muscle testing and is thought to provide a more comprehensive assessment of muscle performance than isotonic or isometric measures.\textsuperscript{14} The clinical value of isokinetic testing rests on its reliability, which has been well documented in samples reflective of the general population.\textsuperscript{15} The use of isokinetic dynamometry as a measure of post-surgical muscle function has been well established in patients with repaired distal biceps tendons. However, interpreting recovery of muscle function can be complicated by the effect of arm dominance. It is known to have a variable effect, as authors have reported different degrees of dominance, as well as dominance being only evident in specific muscle groups.\textsuperscript{1,5,11-13}

A better understanding of the clinical outcomes following surgical repair of distal biceps tendon avulsion is important for evaluating management options. The purpose of the current study was to assess patient reported functional outcomes and muscle performance following two current operative techniques. A secondary purpose was to investigate whether arm dominance influenced muscle performance.

METHODS

Twenty-three participants who had been managed operatively for acute rupture of the distal biceps brachii tendon were recruited between May and August 2015. In all cases, the distal biceps brachii tendon had been repaired by a single surgeon (GB) using the Endobutton\textsuperscript{8} or Footprint\textsuperscript{10} technique at least one year previously.

Participants self-reported their age, weight, handedness, mechanism of injury, number of days from injury to surgery, and whether they had physical therapy as part of their management. Functional outcomes were measured with the Quick Disabilities of the Arm, Shoulder and Hand (QuickDASH) and Mayo Elbow Performance Score (MEPS) questionnaires. Concentric strength (as measured by peak torque) and endurance (as measured by total work and work fatigue) of the elbow flexors and supinators was tested using an isokinetic dynamometer (Biodex System 4 Dynamometer, Biodex Medical Systems Inc, Shirley, NY). Data were collected using Bioware advantage software (Biodex Applications/operations, Biodex advantage software 4.0) and Spike2 CED software (Cambridge Electronic Design Ltd, Cambridge, England).
The Southern Adelaide Human Research Ethics Committee approved the study (Protocol number 42.15). All participants gave informed consent.

**Testing protocol:** The Biodex was calibrated in accordance with manufacturer’s instructions prior to testing each individual. The system was set-up for testing flexion and supination in the seated position using the manual’s guidelines and adjusted to each individual. The limit to motion was set to stop comfortably before full range in each direction. Testing consisted of two tests on each arm, elbow flexion/extension, and supination/pronation. The uninjured arm was tested before the surgically repaired arm. Participants were familiarized with the angular velocity of the dynamometer and practiced trial repetitions with gradually increasing effort until they were confident with the procedures. A minute’s rest was given before each test was started. Participants were given verbal encouragement to give their maximal effort during each test of 50 maximal repetitions at 120°/s. Three investigators (CO, TZ and CR) performed the testing as described below.16

**Elbow flexion/extension:** The chair and dynamometer were each rotated 15° from the base position, and the dynamometer tilt was maintained at 0°. Participants were seated with their upper arm resting on the limb-support (Figure 1). The height and angle of the limb-support was positioned so that the axis of rotation of elbow flexion, passing through the center of the trochea and capitulum, was aligned with the axis of rotation of the dynamometer arm. Participants were instructed to exert maximal effort in the flexion phase of movement, and to relax during the extension phase. Previous isokinetic testing has involved between three and six repetitions for the evaluation of peak torque1,5,13 and between 15 and 50 repetitions for the evaluation of endurance.5,13,17 Previous testing speeds have varied between 30-150°/s for the evaluation of strength,1,5,13 while testing speeds for endurance have been reported up to 240°/s. This study protocol used 50 repetitions to ensure that fatigue would be experienced during the test and 120°/s was chosen, as it is an intermediate speed, to assess both strength and endurance in a single test.

**Forearm supination/pronation:** The chair was rotated 60° from the base position and the dynamometer was rotated 30° and tilted downward 5°. Participants were seated and the limb support adjusted so that the axis of rotation of the forearm, (center of the head of the radius proximally to center of the ulna head distally), was aligned with the axis of rotation of the dynamometer (Figure 2). Participants were instructed to exert maximal effort...
into the supination phase of movement, and to relax during the pronation phase.

The uninjured contralateral arm was used as a matched control without adjusting for an effect of dominance.18 Strength was evaluated using the value for peak torque in Newton meters (Nm) generated during the 50 repetitions for each test.

Endurance has been evaluated both by total work5 and work fatigue.11,12 Total work is the sum of work (in Joules) for all repetitions performed during the test. Work fatigue, is the ratio of the difference, expressed as a percentage between the work performed in the first third of the test to that performed during the last third of the test, expressed using the formula:

\[
W_{\text{fatigue}} = \frac{W_{\text{first third}} - W_{\text{last third}}}{W_{\text{first third}}} \times 100\%
\]

\[W = \text{work}\]

The manual's guide to interpreting results suggests that a deficit percentage within 1-10% indicates that there is no significant difference between muscle groups in strength and endurance measures and a deficit within 11-25% indicate that rehabilitation is recommended to improve muscle balance between the injured and uninvolved sides.

Data analysis: IBM SPSS Statistics for Macintosh, version 23 was used data analysis (IBM Corp., Armonk, N.Y., USA). Data were summarized descriptively. Variables were expressed as means (95% confidence interval) or median (range), according to their distribution. The biceps function of the repaired and uninvolved arms was compared using paired t-tests. This analysis was for both strength and endurance in flexion and supination. A two-way ANOVA was conducted that examined the effect of surgical repair and arm dominance on muscle function. The probability level of 0.05 was set as the standard of statistical significance for all analyses.

RESULTS

Participants: The median age was 57 years (range 42-79). All participants were male except one. The mechanism of injury involved a sudden eccentric load associated with falls, heavy lifting at work, or during recreational sporting activities. Surgery involved the dominant arm in 70% (16/23) of cases and 65% (15/23) had received physical therapy during their recovery. Isokinetic testing was performed at a mean of 7.6 years after surgical repair, at which stage all participants had achieved good to excellent recovery based on their functional scores. The median QuickDASH score was 2.25, range [0-29.5], where 0 indicates no functional limitations. The median MEPS score was 100, range [80-100] where a score of 100 indicates full function.

The participant characteristics are presented in Table 1.

Isokinetic outcomes

Strength

The mean peak torque (Nm) for elbow flexion in the surgically repaired arm was not significantly different from the uninvolved arm (\(p = 0.47\)). The mean peak torque for supination of the surgically repaired arm was also not significantly different from the uninvolved arm (\(p = 0.75\)).

Endurance

The mean percentage of work fatigue for flexion (49%) for the surgically repaired arm was not significantly different from the uninvolved arm (45%, \(p = 0.22\)). The mean percentage of work fatigue for supination (12%) for the surgically repaired arm was significantly less than for the uninvolved arm (23%, \(p = 0.046\)).

The total work performed (J) over the 50 repetitions by the surgically repaired arm was not significantly different from the uninvolved arm for flexion (\(p = 0.60\)) or for supination (\(p = 0.75\)). The isokinetic results are presented in Table 2.

Figure 3 displays an example torque tracing from the four tests for Subject 8, who was right arm dominant. It illustrates how work fatigue percentages will be reduced if the biceps muscle is sub-maximally activated at the start of a test, or if there are fluctuations in effort during a test. The top two tracings are for the flexion tests and show that the peak torque generated by the repaired dominant right arm occurred later, on repetition 31. The peak torque (N.m), total work (J) and work fatigue (%) were less than for the uninvolved left arm. The lower two tracings are for the supination tests and show that there were
more fluctuations and spikes in the torque generated by the dominant right arm during the trial. This resulted in less peak torque (N.m) and work fatigue (%) but more total work (J) than for the uninvolved left arm.

**Table 1. Participant characteristics and self-assessed outcomes**

| Case | Mechanism of injury                          | Age | Dominance | Injury | Follow-up (years) | Quick DASH | Pain (VAS) | MEPS | Recovery (self-assessed)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fall whilst water skiing</td>
<td>54</td>
<td>Right</td>
<td>Right</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100%</td>
</tr>
<tr>
<td>2</td>
<td>Heavy lifting</td>
<td>56</td>
<td>Right</td>
<td>Right</td>
<td>9</td>
<td>4.5</td>
<td>0.5</td>
<td>100</td>
<td>85%</td>
</tr>
<tr>
<td>3</td>
<td>Heavy lifting - industrial</td>
<td>46</td>
<td>Right</td>
<td>Right</td>
<td>7</td>
<td>4.5</td>
<td>1.5</td>
<td>100</td>
<td>85%</td>
</tr>
<tr>
<td>4</td>
<td>Fall from ladder</td>
<td>79</td>
<td>Left</td>
<td>Left</td>
<td>9</td>
<td>0</td>
<td>0.5</td>
<td>95</td>
<td>75%</td>
</tr>
<tr>
<td>5</td>
<td>Stopping a sheep - farming</td>
<td>75</td>
<td>Right</td>
<td>Left</td>
<td>8</td>
<td>29.5</td>
<td>1.5</td>
<td>100</td>
<td>85%</td>
</tr>
<tr>
<td>6</td>
<td>X Catching a partner – martial arts</td>
<td>43</td>
<td>Right</td>
<td>Left</td>
<td>9</td>
<td>6.9</td>
<td>X</td>
<td>95</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>Golf swing</td>
<td>44</td>
<td>Right</td>
<td>Left</td>
<td>6</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
<td>95%</td>
</tr>
<tr>
<td>8</td>
<td>Heavy lifting – structural steel</td>
<td>72</td>
<td>Right</td>
<td>Right</td>
<td>8</td>
<td>27.3</td>
<td>0.5</td>
<td>80</td>
<td>95%</td>
</tr>
<tr>
<td>9</td>
<td>Heavy lifting – landscaping rocks</td>
<td>68</td>
<td>Right</td>
<td>Right</td>
<td>10</td>
<td>4.5</td>
<td>0</td>
<td>100</td>
<td>100%</td>
</tr>
<tr>
<td>10</td>
<td>Heavy lifting – dancing</td>
<td>65</td>
<td>Right</td>
<td>Right</td>
<td>5</td>
<td>4.5</td>
<td>0</td>
<td>100</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>Catching a partner – dancing</td>
<td>69</td>
<td>Right</td>
<td>Right</td>
<td>8</td>
<td>9.1</td>
<td>0.5</td>
<td>100</td>
<td>95%</td>
</tr>
<tr>
<td>12</td>
<td>Stopping playground equipment</td>
<td>62</td>
<td>Right</td>
<td>Left</td>
<td>8</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
<td>95%</td>
</tr>
<tr>
<td>13</td>
<td>Heavy lifting</td>
<td>48</td>
<td>Right</td>
<td>Right</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>100%</td>
</tr>
<tr>
<td>14</td>
<td>Water skiing take off</td>
<td>59</td>
<td>Right</td>
<td>Right</td>
<td>8</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
<td>95%</td>
</tr>
<tr>
<td>15</td>
<td>Cricket swing</td>
<td>50</td>
<td>Right</td>
<td>Right</td>
<td>10</td>
<td>6.8</td>
<td>0.5</td>
<td>100</td>
<td>85%</td>
</tr>
<tr>
<td>16</td>
<td>Cricket swing</td>
<td>42</td>
<td>Right</td>
<td>Right</td>
<td>5</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
<td>75%</td>
</tr>
<tr>
<td>17</td>
<td>Lifting child</td>
<td>53</td>
<td>Left</td>
<td>Left</td>
<td>5</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
<td>95%</td>
</tr>
<tr>
<td>18</td>
<td>Lifting a heavy lounge</td>
<td>47</td>
<td>Right</td>
<td>Left</td>
<td>6</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
<td>95%</td>
</tr>
<tr>
<td>19</td>
<td>Supporting own body weight</td>
<td>60</td>
<td>Right</td>
<td>Left</td>
<td>6</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
<td>95%</td>
</tr>
<tr>
<td>20</td>
<td>Catching patient – health care</td>
<td>49</td>
<td>Right</td>
<td>Right</td>
<td>6</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
<td>95%</td>
</tr>
<tr>
<td>21</td>
<td>Water skiing take off</td>
<td>63</td>
<td>Right</td>
<td>Right</td>
<td>11</td>
<td>2.3</td>
<td>X</td>
<td>100</td>
<td>X</td>
</tr>
<tr>
<td>22</td>
<td>Preventing a slip / fall</td>
<td>57</td>
<td>Right</td>
<td>Left</td>
<td>7</td>
<td>15.9</td>
<td>2.5</td>
<td>85</td>
<td>55%</td>
</tr>
<tr>
<td>23</td>
<td>Grindering the wrench – sailing</td>
<td>59</td>
<td>Right</td>
<td>Right</td>
<td>5</td>
<td>0</td>
<td>0.5</td>
<td>100</td>
<td>85%</td>
</tr>
</tbody>
</table>

Median (range) 2.25 (0-29.5) 100 (85-100) 95(55 – 100)

Key: DASH Disabilities of the Arm, Shoulder and Hand; VAS Visual Analogue Scale; MEPS Mayo Elbow Performance Scale; X=missing data

**Table 2. Isokinetic results from flexion and supination tests of 50 repetitions at 120°/s (n = 23).**

<table>
<thead>
<tr>
<th>Flexion</th>
<th>Repaired Mean</th>
<th>95% CI</th>
<th>Uninvolved Mean</th>
<th>95% CI</th>
<th>Mean difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak torque (N.m)</td>
<td>40</td>
<td>34.5, 45.5</td>
<td>38.9</td>
<td>34.4, 43.3</td>
<td>1.1</td>
<td>0.47</td>
</tr>
<tr>
<td>Work fatigue (%)</td>
<td>49.4</td>
<td>43.0, 55.7</td>
<td>44.7</td>
<td>38.1, 51.4</td>
<td>4.6</td>
<td>0.22</td>
</tr>
<tr>
<td>Total work (J)</td>
<td>1545</td>
<td>1331, 1760</td>
<td>1516</td>
<td>1308, 1724</td>
<td>29.5</td>
<td>0.60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Supination</th>
<th>Repaired Mean</th>
<th>95% CI</th>
<th>Uninvolved Mean</th>
<th>95% CI</th>
<th>Mean difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak torque (N-M)</td>
<td>8.4</td>
<td>7.4, 9.4</td>
<td>8.6</td>
<td>7.5, 9.6</td>
<td>-0.2</td>
<td>0.75</td>
</tr>
<tr>
<td>Work fatigue (%)</td>
<td>12.1</td>
<td>4.6, 19.6</td>
<td>22.9</td>
<td>14.1, 31.7</td>
<td>-10.8</td>
<td>0.046</td>
</tr>
<tr>
<td>Total work (J)</td>
<td>410</td>
<td>317,502</td>
<td>390</td>
<td>322,459</td>
<td>19.2</td>
<td>0.75</td>
</tr>
</tbody>
</table>

M= mean; CI=confidence interval; Nm= Newton-Meters; J= Joules

Repair of dominant versus non-dominant arm

A two-way analysis of variance examined if the effect of surgical repair of the biceps tendon on strength and endurance varied depending on whether the dominant or non-dominant arm was repaired. Arm dominance
had a statistically significant effect on work fatigue in supination, $F(1,22) = 5.67, p = 0.03$, suggesting that the dominant arm (mean = 12.0%, $SD = 16.0$) fatigued less than the non-dominant arm (mean = 23.0%, $SD = 21.3$%). Partial eta squared = 0.21. This is a moderate effect. The interaction between surgery and arm dominance was not significant.

In contrast to the results for work fatigue in supination, the dominant arm did not significantly affect the results from the other strength and endurance measures. The strength of the dominant arm was similar to the non-dominant arm in both flexion and supination and the endurance of the dominant arm was similar to the non-dominant arm in flexion.

**Association between physical therapy and outcomes**

Physical therapy was not associated with isokinetic results for flexion ($p = 0.42$) or supination strength ($p = 0.63$), or MEPS scores ($p = 0.20$) but was associated with better QuickDASH scores ($p = 0.04$).

**DISCUSSION**

The patients in this series who had undergone a surgical repair of the distal biceps tendon had excellent recovery of strength in flexion and supination at a minimum follow up of one year. This compares favorably with deficits in flexion$^{13}$ and supination strength$^{11,13}$ reported in other case series and may

---

**Figure 3.** Graph of torque tracing for Subject 8, which shows greater fluctuations in effort by the repaired dominant right arm (seen as spikes in torque output for right elbow flexion/extension and supination/pronation during the 50-repetitions).
reflect that the follow-up in this case series ranged up to eleven years. As expected, elbow flexion peak torques were observed to be greater than supination peak torques, reflecting differences in leverage and cross-sectional area of the muscles involved, both of which relate to a muscle’s ability to generate torque.19

Two measures were used to assess biceps muscle endurance. These were total work, which is the sum of work from all repetitions performed during the test and work fatigue, which is a measure of the ability to maintain maximal muscular effort over a sustained period. Of the two measures, work fatigue provided interesting results, by revealing a difference that was likely as a result of arm dominance. The authors identified that the rate of fatigue for flexion was similar between the repaired arm (mean, 49%) and uninvolved arm (mean, 45%). In contrast, the work fatigue for supination was different between the repaired arm (mean, 12%) and the uninvolved arm (mean, 23%). This result was affected by whether the dominant arm or non-dominant arm was repaired. Participants who had surgery on their dominant arm demonstrated greater endurance in supination than those who had surgery to their non-dominant arm. Arm dominance had a variable effect, and influenced supination but not flexion, which may reflect differences in the coordination required for these movements, as supination is more of a fine motor skill.

The dominant arm may have greater endurance, or alternatively, fluctuating effort during the 50-repetition trial may have been a factor that contributed to lower rates of fatigue. Fluctuations in effort by the repaired arm during the supination test are illustrated by representative torque data from Subject 8 in Figure 3. This subject was one of the few subjects who had ongoing functional limitations (QuickDASH = 27.3). The torque tracings illustrate intermittent spikes in the amount of torque produced when the repaired arm was tested. Poor motivation or confidence, pain, deficits in neuromuscular control, ineffective stabilization of the arm20 or different characteristics of the muscles involved in flexion and supination5 are all factors that may contribute to fluctuations in performance.

Patient-reported functional outcomes in the current study, assessed by the QuickDASH and MEPS scales, indicated that function was good to excellent in all subjects. These results are consistent with other authors who have reported good to excellent functional outcomes after operative repair.5,13

The difference in work fatigue seen in supination has implications for testing and interpreting supination/pronation movements with isokinetic equipment. If patients feel less confident when the repaired arm is tested, it may be advisable to use repeated measurement, as muscle performance may improve over short periods of time with practice.21 It also has implications for rehabilitation, as muscle is highly adaptable and responds to training through hypertrophy and neural adaptations. Training to improve neuromuscular control should be incorporated into rehabilitation programs, once adequate strength is restored. Neuromuscular control is improved by prescribing exercises that gradually increase the challenge through varying load, repetition and speed for individual strength-endurance needs.22 Neural adaptations include increased neural output from the CNS and improved motor unit recruitment and synchronization.23

The present study has added to the literature by exploring the influence of arm dominance on post-operative measures of strength and endurance. It has previously been suggested that rehabilitation may benefit patients with non-dominant distal bicep tendon repairs, to counteract a preference for using their dominant arms for activities of daily living. Previous case series have found that patients with repairs of the non-dominant arm had long-term deficits in supination strength,11,12 while those who underwent repairs of the dominant arm had deficits in flexion endurance.11 In contrast, we found that the repaired dominant arm had greater endurance in supination but similar results to the repaired non-dominant arm in flexion.

Given that the results from various studies are conflicting, referral to physical therapy should not be based on whether the dominant or non-dominant arm was repaired. In addition, the results from the current and prior studies,5,13 have shown similar long-term recovery of strength, regardless of whether post-operative rehabilitation was provided. However, there is still a need to understand if
rehabilitation benefits recovery in the shorter term. Physical therapy may be indicated when recovery of movement is inhibited by ongoing pain, in order to assist individuals to return to sport or occupations with high demands for physical function, to prescribe specific exercises to enhance neuromuscular control, or to assist patients in regaining confidence to return to normal activities.

Currently there is little information to justify different rehabilitation protocols in the early post-operative period. Protocols for the first few months after surgery are influenced by fixation methods and initially aim to protect the repair. The protocol used with patients in this series was for unsupervised post-operative recovery. This consisted of advice given at one to two weeks postoperatively, to gradually discontinue the sling, begin active range of movement and resume restricted, light activities for a period of three months, before returning to unrestricted activity, including heavy lifting. Although this protocol does not include routine referral to physical therapy, the 65% of the subjects in this case series who accessed physiotherapy services may have been self-referred or referred by the surgeon or other health professionals.

Several limitations may affect this study. Long-term outcomes were examined using a case series, which limits the ability to generalize from the findings. Prospective studies are needed to examine functional recovery in the immediate post-operative period, so physical therapy practice is better informed. In addition, there is a need for further research to determine the reliability of isokinetic testing in clinical populations, and the optimal parameters for measuring endurance.

CONCLUSION
Full recovery of isokinetic flexion and supination strength and good to excellent functional abilities was obtained following distal biceps tendon repair in 23 subjects. Arm dominance had an effect on the results, in that patients who had surgery on their dominant arm demonstrated better endurance in supination than those who had surgery on their non-dominant arm.

Additional research is warranted to study patients who have undergone distal biceps tendon repair that evaluates the expected trajectory for the recovery of strength and endurance and to provide further guidance on the optimal, specific exercise parameters for rehabilitation.

REFERENCES
13. Peeters T, Ching-Soon NG, Jansen N, Sneyers C, Declercq G, Verstreken F. Functional outcome after...


ABSTRACT

Introduction: Breathing pattern disorders (BPDs) are characterized by persistent, suboptimal breathing strategies that may result in additional musculoskeletal pain and/or dysfunction. The purpose of this case series was to examine the effects of Primal Reflex Release Technique (PRRT) and breathing exercise interventions in physically active individuals that presented with a primary complaint of musculoskeletal pain, a BPD, and startle reflexes.

Subjects: The assessment techniques described in Part 1 of this series were used to identify three student athletes (aged 16-22) who presented with musculoskeletal pain of the low back, mid back, and knee, BPDs, and startle reflexes. The subjects were unable to identify an apparent source of their pain.

Intervention: The clinician's classification of the subject's breathing patterns guided intervention(s). Each subject was treated once with PRRT and/or a breathing reflex triggering exercise.

Results: Each of the three subjects demonstrated clinically important improvements on the numerical pain rating scale specific to their tender areas and/or with their primary musculoskeletal complaint.

Discussion: These findings suggest that it may be useful to assess for a BPD and startle reflexes along with a standard orthopedic evaluation in the physically active athlete. Treatment of BPD's may positively impact musculoskeletal pain and/or dysfunction. Further research is needed to understand the effects of treatment of BPD's and how these effects relate to musculoskeletal dysfunction.

Summary: The prevalence of BPD with startle reflexes is unknown and implications regarding the assessment for and treatment of BPD has limited research; however, positive results were demonstrated for the three subjects after normalizing breathing patterns.

Level of Evidence: 4

Key Words: Primal Reflex Release Technique, musculoskeletal pain, startle reflex
INTRODUCTION
Musculoskeletal injury incidence is high among the physically active population; Hootman et al. reported an average rate of injury of 13.79 per 1000 athlete-exposures in collegiate athletics during games. Physical activity increases the respiratory, cardiovascular, and musculoskeletal demands on the body and simultaneously the body adapts to chemical, psychological, and biomechanical changes through the breath. Respiration and breathing patterns play a vital role in maintaining allostatic stability and biomechanical stability and mobility of the trunk and spine.

Therefore, breathing pattern disorders (BPDs) may cause or contribute to a variety of general health and musculoskeletal conditions (e.g., inappropriate motor control patterns and/or compromised trunk stability). An optimal breathing pattern is typically defined as a three-dimensional abdominal breath resulting in expansion of the lower ribs and has been suggested as an essential component for maintenance of allostatic stability, posture, and spinal stability.

The autonomic nervous system (ANS) plays an essential role in maintaining allostatic stability and balancing several involuntary systems in the body (e.g., endocrine, respiratory, circulatory, lymphatic, and muscular) by altering breathing, blood pressure, heart rate, muscle tone, and hormones. The sympathetic nervous system (SNS) and parasympathetic nervous system (PNS), branches of the ANS, respond to experiences (e.g., emotions, pain, fear, or stressors) and adjust breathing, blood pressure, and heart rate. A change or dysfunction in the ANS, operating mainly (i.e., biased) through the SNS is also considered “up-regulation,” a continuous period of heightened arousal of the nervous system. "Up-regulation" could alter breathing patterns in order to attempt to maintain allostatic stability, and change the recruitment of respiratory muscles and alter motor control patterns, potentially causing acute or chronic musculoskeletal pain.

When the body functions with an “up-regulated” nervous system, there is an increased sensitivity to touch and increased pain perception to various tender areas in the body. Hallman et al. found that patients in chronic pain presented with an “up-regulated” nervous system and suggested that patients with chronic neck-shoulder musculoskeletal pain may benefit from treating the ANS. The “up-regulated” nervous system can also be present in conjunction with a startle or withdrawal reflex. A startle reflex is an abnormal response to normal palpation/stimulus causing the body to withdraw from an area or move in a pattern to protect itself (e.g., head jolting forward, shoulders flexing, or other reflex reactions of the body). The presence of startle reflexes may be relevant to the ANS, theoretically explaining the cause and perpetuation of BPDs in patients reporting musculoskeletal pain without a pathoanatomic cause. Further, abnormal sensitivity to pressure (e.g., palpation) and temperature is theorized to be caused by hypersensitivity of the CNS and is thought to contribute to chronic musculoskeletal pain.

Palpation bilaterally of the 1st/2nd, 7th/8th, and 11th/12th ribs may be associated with BPDs and a startle reflex. Through palpation of the ribs, as described in Part 1, the clinician can identify if a startle reflex is present during the breathing pattern assessment. While the Numerical Pain Rating Scale (NPRS) may be variable between subjects (e.g. minimal to very painful), but most importantly the patient reacts abnormally to normal palpation. It should be noted that following the initial trigger that initiated the SNS response, the dysfunctional movement patterns and BPDs may continue even after the stimulus has been eliminated. The inclusion of the one-minute nociceptive exam™ assists the clinician to establish whether the ANS plays a role in changes in breathing patterns and consequently in global movement patterns.

Many factors influence breathing patterns, therefore it is essential to have a multifaceted assessment. Part 1 of this series presented techniques for observation, palpation for the presence of startle reflexes, and orthopedic tests to assess local and global motor control patterns. The causes of BPDs are typically compensatory for biochemical, biomechanical, psychosocial, and/or psychological factors, varying widely between individuals. Therefore, the assessment and intervention strategies presented in this case series could be helpful in improving primary musculoskeletal complaints and/or overall health of patients. The purpose of this case series was to examine the effects of Primal Reflex Release Technique (PRRT) and breathing exercises in physically
active individuals that presented with a primary complaint of musculoskeletal pain, a BPD, and startle reflexes.

**SUBJECT DESCRIPTIONS**

**Initial Examination**
The evaluating clinician performed a breathing pattern assessment prior to determining the source of a potential subject's primary complaint of musculoskeletal pain. Two different clinicians at their respective work locations examined patients in order to identify subjects appropriate for the case series. The clinicians had over four years of professional experience, with one year of focused experience evaluating and treating BPDs in the physically active population. Inclusion criteria included patients that presented with musculoskeletal pain and a startle reflex to palpation at the 1st/2nd, 7th/8th, and/or 11th/12th ribs; if the patient presented with a startle reflex at any of the tender points they were then evaluated for a BPD via the physical assessment described in Part 1 of this series. Eight individuals who were examined presented with a BPD without a startle reflex, and were therefore excluded. All included subjects provided written informed consent for participation in the case series.

The observation of the subjects breathing pattern began prior to the formal assessment, thus allowing the clinician to observe unaltered breathing patterns. Mentioning to a patient that their breathing is being observed has been noted to significantly alter their natural pattern.8 Bilateral palpations assessed startle reflexes at 1st/2nd, 7th/8th, and/or 11th/12th ribs tender areas using the NPRS scale. The assessment of breathing patterns occurred in two positions: seated and supine. In a seated position, the clinician performed a modified version of the Manual Assessment Respiratory Movement (MARM)2,31 and a Hi Lo assessment in a supine position,2,5,8,31 both as described in Part 1. For the purposes of this case series, the MARM was recorded only as positive (apical) or negative (abdominal) perceived motions rather than the calculations. The results were utilized in addition to the Hi Lo assessment in order to classify respiratory motion. The examiner observed and noted where the respiratory movement initiated in each of the patients’ (e.g., paradoxical, apical, or abdominal) as described in Part 1. The clinician then determined the subjects breathing patterns, normal or dysfunctional, from the outcomes of the modified MARM and Hi Lo assessment. The outcomes from the assessments above might provide varying degrees to further classify each subject's breathing pattern.

**HISTORY AND EXAMINATION**
A summary of each subject's history is provided in Table 1. Each subject denied any history of a traumatic event or spinal pathology. Orthopedic special tests, specific to each subjects musculoskeletal injury were negative, manual muscle testing of the involved muscles were completed, and no weakness or pain was noted, therefore the authors performed the Selective Functional Movement Assessment32 to identify muscle imbalances and motor control dysfunctions.

Subject #1 had been experiencing low back pain for over a year without resolution despite participating in a therapy routine including, interferential current electrical stimulation and a core stabilization program. The subject reported an increase in pain and discomfort following a long travel day (i.e., bus and airplane ride). The subject's NPRS was a 2/10 for her

<table>
<thead>
<tr>
<th>Table 1.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>PATIENT HISTORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient Number</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>
primary complaint of low back pain during daily and physical activities. Upon entry to the clinic, the subject exhibited excessive chest movement upon inhalation. The Hi Lo assessment revealed the subject’s breathing pattern as an apical breathing pattern with limited movement of the abdomen. Startle reflexes were elicited upon palpation bilaterally at the 11th/12th ribs (Left-3/10 NPRS, Right-2/10 NPRS). A positive modified MARM confirmed the apical breathing pattern with minimal lateral and no back breath at rest (Table 2).

Subject #2 had been experiencing a sharp pain in the middle back for a period of five years without resolution. During initial examination, the 5th rib ring was determined to be laterally positioned to the right at rest, as assessed by the Thoracic Ring Approach™ developed by Linda Joy Lee. The subject's NPRS was a 6/10 for her primary complaints (i.e., pain during inhalation or physical activity). The Hi Lo assessment revealed the subject's breathing pattern as an apical breathing pattern with limited movement of the abdomen. The subject also presented with bilateral startle reflex response upon palpation of the 11th/12th ribs (Left-3/10 NPRS, Right-4/10 NPRS) and 1st/2nd ribs (Left-5/10 NPRS, Right-6/10 NPRS). A positive modified MARM confirmed that the breathing pattern was apical with a rigid abdomen and limited anterior, lateral, and back movement at rest (Table 2).

Subject #3 had been experiencing intermittent, throbbing pain in her left knee for a period of two years. During evaluation, the subject presented with muscle pain and a tender point on her left medial knee proximal to the joint line. The subject's NPRS was a 6/10 for her primary complaint of muscle pain at insertion of gracilis. The Hi Lo assessment revealed a paradoxical breathing pattern with minimal abdominal movement. Upon palpation, the subject also presented with a startle reflex at the left 11/12th ribs (8/10 NPRS). A positive modified MARM confirmed that the breathing pattern was paradoxical with minimal abdominal movement (Table 2).

**INTERVENTION**

The exercises used in this case series have been beneficial in the authors' clinical setting to address various BPDs (e.g., paradoxical, apical, and breathing lacking lateral or back motion). The “clamshell” and/or PRRT were used to address BPDs in all three subjects in order to reset and re-establish motor control dysfunctions. While the concept of resetting a BPD is fairly uncommon, a reflex triggering exercise, the “clamshell” is a modified exercise proposed by the authors from Michael Grant White’s “Optimal Reflex Triggering Ankle Raise” exercise. The reflex triggering exercise elicits the subject’s need to breathe by altering the intra-abdominal pressure at the end of a natural exhalation. The subject was side-lying and instructed to complete a full natural exhalation, (not a forced exhalation), then hold their breath. While holding their breath, the subject abducted the top knee, keeping their heels together for a count of three for abduction and count of three for abduction movements of the leg (Figure 1). When the limb returns to the resting position, the subject relaxes the body and inhales normally. If the “clamshell” reset is needed, and done correctly, the subject will demonstrate a deep and normal (e.g., a three-dimensional abdominal) breath, or at least significant progress in that direction as compared to a “normal” breathing pattern. A common mistake is to either force the exhalation or to not follow all of the breath out, both would not trigger the need to breathe reflexively. The process can be

---

**Table 2.**

<table>
<thead>
<tr>
<th>Patient Number</th>
<th>BPD</th>
<th>Startle Reflex</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chest/lateral breath</td>
<td>11th/12th rib</td>
<td>PRRT/McGill Side Bridge</td>
</tr>
<tr>
<td>2</td>
<td>Chest breath</td>
<td>1st/2nd rib 11th/12th rib</td>
<td>PRRT/Clam Shell</td>
</tr>
<tr>
<td>3</td>
<td>Paradoxical</td>
<td>11th/12th rib</td>
<td>PRRT/Clam Shell</td>
</tr>
</tbody>
</table>

PRRT - Primal reflex release technique
The subject should monitor a few breaths between each “clamshell” repetition in order to create awareness of the changes in their breathing pattern.

The PRRT developed by John Iams, utilizes the one-minute nociceptive exam™ as a global assessment to identify startle reflexes and quick movements with specific body positioning for treatment.16,17 The PRRT treatment technique utilizes coughing in certain positions in order to eliminate startle reflexes and decrease pain upon palpation of the 1st/2nd and 11th/12th ribs. The PRRT technique for the 7th/8th ribs utilizes applying pressure with two fingers just below the costochondral cartilage angle during the pause between the exhalation and inhalation.34

RESULTS

Subject #1: PRRT was used to correct the startle reflex and BPD. PRRT performed (2x) bilaterally to the 11th/12th ribs as a means to reduce the tender areas that elicited a startle reflex upon palpation. Following the intervention, the clinician reassessed the subject's breathing pattern using the MARM and Hi Lo assessment and identified a normal abdominal breath (abdominal, lateral and back breath). The startle reflexes were re-evaluated using the one-minute nociceptive exam™ and determined that the startle reflexes dissipated and tender areas all had an NPRS of 0/10 bilaterally; however following re-assessment using the MARM and Hi Lo, the BPD was still present. The BPD was therefore treated using the “clamshell” exercise (5x) and following the exercise the subject was able to establish an abdominal breath with anterior and lateral movement, but still lacked back movement. The subject’s primary musculoskeletal complaint of low back pain was 1/10 NPRS following a single treatment session.

Subject #2: PRRT was used to correct the startle reflex and BPD. The PRRT was performed (1x) bilaterally to the 1st/2nd and 11th/12th ribs. Re-evaluation using the one-minute nociceptive exam™ determined that the startle reflexes dissipated and tender areas all had an NPRS of 0/10 bilaterally; however following re-assessment using the MARM and Hi Lo, the BPD was still present. The BPD was therefore treated using the “clamshell” exercise (5x) and following the exercise the subject was able to establish an abdominal breath with anterior and lateral movement, but still lacked back movement. The subject’s primary musculoskeletal complaint of sharp pain in the middle of the back was 0/10 NPRS following a single treatment session.

Subject #3: PRRT was used to correct the startle reflex and BPD. The PRRT was performed (1x) to the left 11th/12th ribs. Re-evaluation using the one-minute nociceptive exam™ determined that the startle reflex dissipated, but the subject was still tender (NPRS score of 7/10) upon palpation at the left 11th/12th ribs. The MARM and Hi Lo assessment indicated that the BPD was still present. The BPD was then treated with the “clamshell” exercise (5x) and following the exercise the subject had established an abdominal breath with anterior movement, but still had limited lateral and back movement. The subject’s primary musculoskeletal complaint of left knee pain was 4/10 NPRS following a single treatment session.

The outcomes of this case series demonstrate that subjects #1 and #2 presented a change on the NPRS35 achieving the minimal clinically important difference (MCID) in the affected areas after treatment of the startle reflex using PRRT (Table 3). All three subjects reported a change on the NPRS related to their primary complaint of musculoskeletal pain (consistent with the MCID) after the breathing pattern interventions (Table 4). Subject #1 was the only participant to exhibit a normalized breathing pattern following the PRRT treatment of the 11th/12th startle reflex. Whereas subjects #2 and #3 needed the addition of the clamshell exercise to initiate the ideal abdominal breath.
DISCUSSION

The assessment and treatment of BPDs in three physically active subjects presented in this case series was beneficial in decreasing pain and improving breathing patterns prior to a clinical orthopedic evaluation and subsequent interventions. Breathing pattern disorders can produce inappropriate motor control patterns and compromised trunk stability resulting in musculoskeletal pain.5-7 Janda’s approach to pain and dysfunction focuses on finding the cause of signs and symptoms, which is typically away from the site of the patient’s primary complaint.36 The Central Nervous System (CNS) and musculoskeletal system work together to create movement; pathology to one system may be reflected by adaptation of another.36 The diaphragm is crucial to structural posture and core stabilization.37 Elevation of the lower rib cage (caudally) during inspiration may be a result of a weak diaphragm or poor recruitment of deep spinal stabilizers that can contribute to musculoskeletal pain or dysfunction of the cervical, thoracic, or lumbar segments.36,38 The diaphragm is responsible for initiating core stability by regulating intra-abdominal pressure37 and works collaboratively with the transversus abdominis, multifidus, and pelvic floor to provide support.5,38 If breathing is dysfunctional this may predispose the patient to muscular adaptations and/or musculoskeletal pain in various other regions. For example, the most extreme BPD, a paradoxical pattern, is often accompanied with cervical spine pain, muscle imbalances, and/or dysfunction.2,8 Alterations or weakness of the pelvic floor muscles have been associated with low back pain, groin strains, iliotibial band syndrome, anterior knee pain, anterior cruciate ligament tears, and lateral ankle sprains.36,38-41 In this case series, the focus was on treating the diaphragm, often overlooked as a contributing factor to core stability, in order to decrease the subject’s musculoskeletal pain through reflexive exercises targeting the CNS and ANS. The variety of musculoskeletal pain complaints in this case series may be related to global muscle imbalances, motor control adaptations, and trigger points within the kinetic chain.

The decrease in pain may have been due to improvement in diaphragmatic function, and/or the ability to initiate core stabilization, restore movement patterns, and diminish tender areas associated with BPDs. The exact mechanism for positive effects in these three subjects is unknown. Lucas et al42 determined that altered muscle patterns within the kinetic chain had trigger points that may be associated with changes to breathing patterns or posture. Mehling et al43

| Table 3. | STARTLE REFLEX PRE/POST NPRS |
| --- | --- | --- |
| Patient Number | Startle Reflex Palpation Location | Pre NPRS | Post NPRS |
| 1 | 11/12th Left | 3/10 | 0* |
| 11/12th Right | 2/10 | 0* |
| 2 | 1/2nd Left | 5/10 | 0* |
| 1/2nd Right | 6/10 | 0* |
| 11/12th Left | 3/10 | 0* |
| 11/12th Right | 4/10 | 0* |
| 3 | 11/12th Left | 8/10 | 7/10 |

* = achieved MCID, NPRS = numerical pain rating scale

| Table 4. | PATIENT PRIMARY COMPLAINT PRE/POST NPRS |
| --- | --- | --- |
| Patient Number | Primary Complaint Pre NPRS | Primary Complaint Post NPRS |
| 1 | 2 | 1 |
| 2 | 6 | 0* |
| 3 | 6 | 4* |

* = MCID, NPRS = numerical pain rating scale
compared the effects of physical therapy (e.g., soft-tissue mobilization; joint mobilization; and exercises for postural righting, flexibility, pain relief, stabilization, strengthening, functional task performance, and back-related education) and breathing therapy (e.g., verbal intervention and tactile cueing for proper breathing mechanics) on patients presenting with chronic low back pain and found that patients undergoing breathing therapy had similar improvements in pain, function, and physical and emotional role as the physical therapy group even though breathing therapy or exercises are typically not viewed as effective as physical therapy. The results of this case series determined that early inclusion of breathing exercises were beneficial in decreasing musculoskeletal pain in three physically active individuals.

Breathing is influenced by emotional and psychological input, yet it is difficult to identify if these sources contribute to BPDs. McNulty et al reported that EMG activity increased over trigger points when a patient was placed in a stressful situation. Untreated trigger points could result in continuous disruption of motor patterns that can be “reset” and re-established through appropriate interventions, such as muscle re-education. If trigger points increase during stressful circumstances, it may explain the startle reflex response and decreased tolerance to palpation, as seen in this case series. The PRRT used in this study are proposed to address the startle reflexes associated with BPD by addressing the nervous system through “resetting” primal reflexes. Theoretically, by stimulating the reflexes through a cough or quick palpation, neural input being sent to the spinal cord and brain and is temporarily overloaded and/or “reset,” which restores normal neural input to the muscles being treated. The inclusion of evaluating startle reflexes in primary and accessory respiratory muscles could assist in directing treatment intervention and explain how BPDs have an intimate connection to stress, emotions, and musculoskeletal pain.

Stress has been identified as a risk factor and contributor to musculoskeletal injuries and chronic pain. Hallman et al monitored participants with chronic neck and shoulder pain and found that during rest there was a decrease in PNS activation and increased SNS activation suggesting a mild ANS imbalance, when compared to the healthy control group. Mehling et al suggested that the breath therapy might teach coping skills and provide insight regarding the effect of stress on the body and chronic low back pain. It has been theorized that the presence of startle reflexes provides information regarding the state of the ANS, specifically an ANS imbalance, or “up-regulated” nervous system, however this supposition has not been studied. If restoration of an ideal breathing pattern and treatment using breathing exercises and PRRT created changes in the ANS, specifically an increase in PNS activation, such a change could provide an explanation for the decrease in musculoskeletal pain seen in these subjects. The authors hypothesize that the ANS, specifically an “up-regulated” nervous system contributes to the presence and perpetuation of BPDs in patients that present with a startle reflex.

Breathing pattern disorders in the general population are theorized to be more common than reported and if prevalence is similar in the physically active population, the effects of BPDs could be multiplied due to the increased physiological and biomechanical demands during exercise. If the body is not able to appropriately recruit muscles then compensatory motor patterns may ensue. Therefore, it is the opinion of the authors that breathing should be assessed in all patients due to the bidirectional influence of the psychological, chemical, and biomechanical systems. The limitations of the present case series include the small number of subjects treated, the absence of a control group, and the clinicians only present the initial assessment and treatment of BPDs outcomes, which do not allow for the generalization of the results. Additionally, the clinician's reliability of assessing BPDs was not tested and only used two treatment techniques to improve breathing patterns out of several simple techniques that have been suggested in the literature. Research on the long-term effects of assessing and treating BPDs is necessary to see if patients maintain improvements in diaphragm function and musculoskeletal pain. Further research using a larger sample with a control group is needed to recognize if changes in breathing patterns actually occur and are due to interventions, and whether the changes alter motor control patterns sustain long-term improvements in pain and function throughout the body. Analyzing the connection between the
ANS, startle reflex, breathing patterns and motor control is essential to understanding how these treatments impact a patient's well-being.

**SUMMARY**

In this case series, following the PRRT and/or “clamshell” exercise, each subject presented with a clinically important change in NPRS scores in regards to their primary musculoskeletal complaint. In addition, all subjects displayed a change in their breathing pattern as well as a diminished or eliminated presence of a startle reflex. The current findings suggest that the occurrence of a startle reflex upon palpation may be a contributing factor associated with a BPD and musculoskeletal pain. Using PRRT and/or the “clamshell” exercise facilitated reestablishment of an optimal breathing pattern and theoretically, global motor control, contributing to the why the participants primary complaint of pain decreased. No previous research has indicated that the presence of a startle reflex is a common occurrence in an athletic population with disordered breathing. Therefore, the assessment and treatment of BPDs and startle reflexes might be an essential component to determine a potential cause or contributors to musculoskeletal pain.

**REFERENCES**


ABSTRACT

Introduction: Breathing pattern disorders (BPDs) are characterized by persistent, suboptimal breathing strategies that may result in additional musculoskeletal pain and/or dysfunction. The purpose of this case series was to examine the effects of Primal Reflex Release Technique (PRRT) and breathing exercise interventions in physically active individuals that presented with a primary complaint of musculoskeletal pain, a BPD, and startle reflexes.

Subjects: The assessment techniques described in Part 1 of this series were used to identify three student athletes (aged 16-22) who presented with musculoskeletal pain of the low back, mid back, and knee, BPDs, and startle reflexes. The subjects were unable to identify an apparent source of their pain.

Intervention: The clinician's classification of the subject's breathing patterns guided intervention(s). Each subject was treated once with PRRT and/or a breathing reflex triggering exercise.

Results: Each of the three subjects demonstrated clinically important improvements on the numerical pain rating scale specific to their tender areas and/or with their primary musculoskeletal complaint.

Discussion: These findings suggest that it may be useful to assess for a BPD and startle reflexes along with a standard orthopedic evaluation in the physically active athlete. Treatment of BPD's may positively impact musculoskeletal pain and/or dysfunction. Further research is needed to understand the effects of treatment of BPD's and how these effects relate to musculoskeletal dysfunction.

Summary: The prevalence of BPD with startle reflexes is unknown and implications regarding the assessment for and treatment of BPD has limited research; however, positive results were demonstrated for the three subjects after normalizing breathing patterns.

Level of Evidence: 4

Key Words: Primal Reflex Release Technique, musculoskeletal pain, startle reflex
INTRODUCTION
Musculoskeletal injury incidence is high among the physically active population; Hootman et al. reported an average rate of injury of 13.79 per 1000 athlete-exposures in collegiate athletics during games. Physical activity increases the respiratory, cardiovascular, and musculoskeletal demands on the body and simultaneously the body adapts to chemical, psychological, and biomechanical changes through the breath. Respiration and breathing patterns play a vital role in maintaining allostatic and biomechanical stability and mobility of trunk and spine. Therefore, breathing pattern disorders (BPDs) may cause or contribute to a variety of general health and musculoskeletal conditions (e.g. inappropriate motor control patterns and/or compromised trunk stability). An optimal breathing pattern is typically defined as a three-dimensional abdominal breath resulting in expansion of the lower ribs and has been suggested as an essential component for maintenance of allostatic, posture, and spinal stability.

The autonomic nervous system (ANS) plays an essential role in maintaining allostatic and balancing several involuntary systems in the body (e.g., endocrine, respiratory, circulatory, lymphatic, and muscular) by altering breathing, blood pressure, heart rate, muscle tone, and hormones. The sympathetic nervous system (SNS) and parasympathetic nervous system (PNS), branches of the ANS, respond to experiences (e.g., emotions, pain, fear, or stressors) and adjust breathing, blood pressure, and heart rate. A change or dysfunction in the ANS, operating mainly (i.e., biased) through the SNS is also considered “up-regulation,” a continuous period of heightened arousal of the nervous system. “Up-regulation” could alter breathing patterns in order to attempt to maintain allostatic, and change the recruitment of respiratory muscles and alter motor control patterns, potentially causing acute or chronic musculoskeletal pain.

When the body functions with an “up-regulated” nervous system, there is an increased sensitivity to touch and increased pain perception to various tender areas in the body. Hallman et al. found that patients in chronic pain presented with an “up-regulated” nervous system and suggested that patients with chronic neck-shoulder musculoskeletal pain may benefit from treating the ANS. The “up-regulated” nervous system can also be present in conjunction with a startle or withdrawal reflex. A startle reflex is an abnormal response to normal palpation/stimulus causing the body to withdraw from an area or move in a pattern to protect itself (e.g., head jolting forward, shoulders flexing, or other reflex reactions of the body). The presence of startle reflexes may be relevant to the ANS, theoretically explaining the cause and perpetuation of BPDs in patients reporting musculoskeletal pain without a pathoanatomic cause. Further, abnormal sensitivity to pressure (e.g., palpation) and temperature is theorized to be caused by hypersensitivity of the CNS and is thought to contribute to chronic musculoskeletal pain.

Palpation bilaterally of the 1st/2nd, 7th/8th, and 11th/12th ribs may be associated with BPDs and a startle reflex. Through palpation of the ribs, as described in Part 1, the clinician can identify if a startle reflex is present during the breathing pattern assessment. While the Numerical Pain Rating Scale (NPRS) may be variable between subjects (e.g. minimal to very painful), but most importantly the patient reacts abnormally to normal palpation. It should be noted that following the initial trigger that initiated the SNS response, the dysfunctional movement patterns and BPDs may continue even after the stimulus has been eliminated. The inclusion of the one-minute nociceptive exam™ assists the clinician to establish whether the ANS plays a role in changes in breathing patterns and consequently in global movement patterns.

Many factors influence breathing patterns, therefore it is essential to have a multifaceted assessment. Part 1 of this series presented techniques for observation, palpation for the presence of startle reflexes, and orthopedic tests to assess local and global motor control patterns. The causes of BPDs are typically compensatory for biochemical, biomechanical, psychosocial, and/or psychological factors, varying widely between individuals. Therefore, the assessment and intervention strategies presented in this case series could be helpful in improving primary musculoskeletal complaints and/or overall health of patients. The purpose of this case series was to examine the effects of Primal Reflex Release Technique (PRRT) and breathing exercises in physically

The International Journal of Sports Physical Therapy | Volume 11, Number 6 | December 2016 | Page 972
active individuals that presented with a primary complaint of musculoskeletal pain, a BPD, and startle reflexes.

SUBJECT DESCRIPTIONS

Initial Examination

The evaluating clinician performed a breathing pattern assessment prior to determining the source of a potential subject's primary complaint of musculoskeletal pain. Two different clinicians at their respective work locations examined patients in order to identify subjects appropriate for the case series. The clinicians had over four years of professional experience, with one year of focused experience evaluating and treating BPDs in the physically active population. Inclusion criteria included patients that presented with musculoskeletal pain and a startle reflex to palpation at the 1st/2nd, 7th/8th, and/or 11th/12th ribs; if the patient presented with a startle reflex at any of the tender points they were then evaluated for a BPD via the physical assessment described in Part 1 of this series. Eight individuals who were examined presented with a BPD without a startle reflex, and were therefore excluded. All included subjects provided written informed consent for participation in the case series.

The observation of the subjects breathing pattern began prior to the formal assessment, thus allowing the clinician to observe unaltered breathing patterns. Mentioning to a patient that their breathing is being observed has been noted to significantly alter their natural pattern.8 Bilateral palpations assessed startle reflexes at 1st/2nd, 7th/8th, and/or 11th/12th ribs tender areas using the NPRS scale. The assessment of breathing patterns occurred in two positions: seated and supine. In a seated position, the clinician performed a modified version of the Manual Assessment Respiratory Movement (MARM)2,31 and a Hi Lo assessment in a supine position,2,5,8,31 both as described in Part 1. For the purposes of this case series, the MARM was recorded only as positive (apical) or negative (abdominal) perceived motions rather than the calculations. The results were utilized in addition to the Hi Lo assessment in order to classify respiratory motion. The examiner observed and noted where the respiratory movement initiated in each of the patients’ (e.g., paradoxical, apical, or abdominal) as described in Part 1. The clinician then determined the subjects breathing patterns, normal or dysfunctional, from the outcomes of the modified MARM and Hi Lo assessment. The outcomes from the assessments above might provide varying degrees to further classify each subject's breathing pattern.

HISTORY AND EXAMINATION

A summary of each subject's history is provided in Table 1. Each subject denied any history of a traumatic event or spinal pathology. Orthopedic special tests, specific to each subject's musculoskeletal injury were negative, manual muscle testing of the involved muscles were completed, and no weakness or pain was noted, therefore the authors performed the Selective Functional Movement Assessment32 to identify muscle imbalances and motor control dysfunctions.

Subject #1 had been experiencing low back pain for over a year without resolution despite participating in a therapy routine including, interferential current electrical stimulation and a core stabilization program. The subject reported an increase in pain and discomfort following a long travel day (i.e., bus and airplane ride). The subject's NPRS was a 2/10 for her

<table>
<thead>
<tr>
<th>Patient Number</th>
<th>Age</th>
<th>Sex</th>
<th>Onset of Pain</th>
<th>Occupation/Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>F</td>
<td>1 year</td>
<td>Student/Collegiate Softball Participant</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>F</td>
<td>5 years</td>
<td>Student/Track Participant</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>F</td>
<td>2 years</td>
<td>Student/High School Softball Participant</td>
</tr>
</tbody>
</table>
primary complaint of low back pain during daily and physical activities. Upon entry to the clinic, the subject exhibited excessive chest movement upon inhalation. The Hi Lo assessment revealed the subject’s breathing pattern as an apical breathing pattern with limited movement of the abdomen. Startle reflexes were elicited upon palpation bilaterally at the 11th/12th ribs (Left-3/10 NPRS, Right-2/10 NPRS). A positive modified MARM confirmed the apical breathing pattern with minimal lateral and no back breath at rest (Table 2).

Subject #2 had been experiencing a sharp pain in the middle back for a period of five years without resolution. During initial examination, the 5th rib ring was determined to be laterally positioned to the right at rest, as assessed by the Thoracic Ring Approach™ developed by Linda Joy Lee.33 The subject’s NPRS was a 6/10 for her primary complaints (i.e., pain during inhalation or physical activity). The Hi Lo assessment revealed the subject’s breathing pattern as an apical breathing pattern with limited movement of the abdomen. The subject also presented with bilateral startle reflex response upon palpation of the 11th/12th ribs (Left-3/10 NPRS, Right-4/10 NPRS) and 1st/2nd ribs (Left-5/10 NPRS, Right-6/10 NPRS). A positive modified MARM confirmed that the breathing pattern was apical with a rigid abdomen and limited anterior, lateral, and back movement at rest (Table 2).

Subject #3 had been experiencing intermittent, throbbing pain in her left knee for a period of two years. During evaluation, the subject presented with muscle pain and a tender point on her left medial knee proximal to the joint line. The subject’s NPRS was a 6/10 for her primary complaint of muscle pain at insertion of gracilis. The Hi Lo assessment revealed a paradoxical breathing pattern with minimal abdominal movement. Upon palpation, the subject also presented with a startle reflex at the left 11/12th ribs (8/10 NPRS). A positive modified MARM confirmed that the breathing pattern was paradoxical with minimal abdominal movement (Table 2).

**INTERVENTION**

The exercises used in this case series have been beneficial in the authors’ clinical setting to address various BPDs (e.g., paradoxical, apical, and breathing lacking lateral or back motion).21 The “clamshell” and/or PRRT were used to address BPDs in all three subjects in order to reset and re-establish motor control dysfunctions. While the concept of resetting a BPD is fairly uncommon, a reflex triggering exercise, the “clamshell” is a modified exercise proposed by the authors from Michael Grant White’s “Optimal Reflex Triggering Ankle Raise” exercise.21 The reflex triggering exercise elicits the subject’s need to breathe by altering the intra-abdominal pressure at the end of a natural exhalation.21 The subject was side-lying and instructed to complete a full natural exhalation, (not a forced exhalation), then hold their breath. While holding their breath, the subject abducted the top knee, keeping their heels together for a count of three for abduction and count of three for adduction movements of the leg (Figure 1). When the limb returns to the resting position, the subject relaxes the body and inhales normally. If the “clamshell” reset is needed, and done correctly, the subject will demonstrate a deep and normal (e.g., a three-dimensional abdominal) breath, or at least significant progress in that direction as compared to a “normal” breathing pattern. A common mistake is to either force the exhalation or to not follow all of the breath out, both would not trigger the need to breathe reflexively. The process can be

<table>
<thead>
<tr>
<th>Patient Number</th>
<th>BPD</th>
<th>Startle Reflex</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chest/lateral breath</td>
<td>11th/12th rib</td>
<td>PRRT/McGill Side Bridge</td>
</tr>
<tr>
<td>2</td>
<td>Chest breath</td>
<td>1st/2nd rib</td>
<td>PRRT/Clam Shell</td>
</tr>
<tr>
<td>3</td>
<td>Paradoxical</td>
<td>11th/12th rib</td>
<td>PRRT/Clam Shell</td>
</tr>
</tbody>
</table>

PRRT- Primal reflex release technique
repeated until normal breathing is established, but the subject should monitor a few breaths between each “clamshell” repetition in order to create awareness of the changes in their breathing pattern.

The PRRT developed by John Iams, utilizes the one-minute nociceptive exam™ as a global assessment to identify startle reflexes and quick movements with specific body positioning for treatment.16,17 The PRRT treatment technique utilizes coughing in certain positions in order to eliminate startle reflexes and decrease pain upon palpation of the 1st/2nd and 11th/12th ribs. The PRRT technique for the 7th/8th ribs utilizes applying pressure with two fingers just below the costochondral cartilage angle during the pause between the exhalation and inhalation.34

RESULTS

Subject #1: PRRT was used to correct the startle reflex and BPD. PRRT performed (2x) bilaterally to the 11th/12th ribs as a means to reduce the tender areas that elicited a startle reflex upon palpation. Following the intervention, the clinician reassessed the subject’s breathing pattern using the MARM and Hi Lo assessment and identified a normal abdominal breath (abdominal, lateral and back breath). The startle reflexes were re-evaluated using the one-minute nociceptive exam™ determined that the startle reflexes dissipated and tender areas all had an NPRS of 0/10 bilaterally; however, following re-assessment using the MARM and Hi Lo, the BPD was still present. The BPD was therefore treated using the “clamshell” exercise (5x) and following the exercise the subject was able to establish an abdominal breath with anterior and lateral movement, but still lacked back movement. The subject’s primary musculoskeletal complaint of low back pain was 1/10 NPRS following a single treatment session.

Subject #2: PRRT was used to correct the startle reflex and BPD. The PRRT was performed (1x) bilaterally to the 1st/2nd and 11th/12th ribs. Re-evaluation using the one-minute nociceptive exam™ determined that the startle reflexes dissipated and tender areas all had an NPRS of 0/10 bilaterally; however following re-assessment using the MARM and Hi Lo, the BPD was still present. The BPD was therefore treated using the “clamshell” exercise (5x) and following the exercise the subject was able to establish an abdominal breath with anterior and lateral movement, but still lacked back movement. The subject’s primary musculoskeletal complaint of sharp pain in the middle of the back was 0/10 NPRS following a single treatment session.

Subject #3: PRRT was used to correct the startle reflex and BPD. The PRRT was performed (1x) to the left 11th/12th ribs. Re-evaluation using the one-minute nociceptive exam™ determined that the startle reflex dissipated, but the subject was still tender (NPRS score of 7/10) upon palpation at the left 11th/12th ribs. The MARM and Hi Lo assessment indicated that the BPD was still present. The BPD was then treated with the “clamshell” exercise (5x) and following the exercise the subject had established an abdominal breath with anterior movement, but still had limited lateral and back movement. The subject’s primary musculoskeletal complaint of left knee pain was 4/10 NPRS following a single treatment session.

The outcomes of this case series demonstrate that subjects #1 and #2 presented a change on the NPRS35 achieving the minimal clinically important difference (MCID) in the affected areas after treatment of the startle reflex using PRRT (Table 3). All three subjects reported a change on the NPRS related to their primary complaint of musculoskeletal pain (consistent with the MCID) after the breathing pattern interventions (Table 4). Subject #1 was the only participant to exhibit a normalized breathing pattern following the PRRT treatment of the 11th/12th startle reflex. Whereas subjects #2 and #3 needed the addition of the clamshell exercise to initiate the ideal abdominal breath.
DISCUSSION

The assessment and treatment of BPDs in three physically active subjects presented in this case series was beneficial in decreasing pain and improving breathing patterns prior to a clinical orthopedic evaluation and subsequent interventions. Breathing pattern disorders can produce inappropriate motor control patterns and compromised trunk stability resulting in musculoskeletal pain.\textsuperscript{5-7} Janda’s approach to pain and dysfunction focuses on finding the cause of signs and symptoms, which is typically away from the site of the patient’s primary complaint.\textsuperscript{36} The Central Nervous System (CNS) and musculoskeletal system work together to create movement; pathology to one system may be reflected by adaptation of another.\textsuperscript{36} The diaphragm is crucial to structural posture and core stabilization.\textsuperscript{37} Elevation of the lower rib cage (caudally) during inspiration may be a result of a weak diaphragm or poor recruitment of deep spinal stabilizers that can contribute to musculoskeletal pain or dysfunction of the cervical, thoracic, or lumbar segments.\textsuperscript{36,38} The diaphragm is responsible for initiating core stability by regulating intra-abdominal pressure\textsuperscript{37} and works collaboratively with the transversus abdominis, multifidus, and pelvic floor to provide support.\textsuperscript{5,38} If breathing is dysfunctional this may predispose the patient to muscular adaptations and/or musculoskeletal pain in various other regions. For example, the most extreme BPD, a paradoxical pattern, is often accompanied with cervical spine pain, muscle imbalances, and/or dysfunction.\textsuperscript{2,8} Alterations or weakness of the pelvic floor muscles have been associated with low back pain, groin strains, iliotibial band syndrome, anterior knee pain, anterior cruciate ligament tears, and lateral ankle sprains.\textsuperscript{36,38-41} In this case series, the focus was on treating the diaphragm, often overlooked as a contributing factor to core stability, in order to decrease the subject’s musculoskeletal pain through reflexive exercises targeting the CNS and ANS. The variety of musculoskeletal pain complaints in this case series may be related to global muscle imbalances, motor control adaptations, and trigger points within the kinetic chain.

The decrease in pain may have been due to improvement in diaphragmatic function, and/or the ability to initiate core stabilization, restore movement patterns, and diminish tender areas associated with BPDs. The exact mechanism for positive effects in these three subjects is unknown. Lucas et al\textsuperscript{42} determined that altered muscle patterns within the kinetic chain had trigger points that may be associated with changes to breathing patterns or posture. Mehling et al\textsuperscript{43}
compared the effects of physical therapy (e.g., soft-tissue mobilization; joint mobilization; and exercises for postural righting, flexibility, pain relief, stabilization, strengthening, functional task performance, and back-related education) and breathing therapy (e.g., verbal intervention and tactile cueing for proper breathing mechanics) on patients presenting with chronic low back pain and found that patients undergoing breathing therapy had similar improvements in pain, function, and physical and emotional role as the physical therapy group even though breathing therapy or exercises are typically not viewed as effective as physical therapy. The results of this case series determined that early inclusion of breathing exercises were beneficial in decreasing musculoskeletal pain in three physically active individuals.

Breathing is influenced by emotional and psychological input, yet it is difficult to identify if these sources contribute to BPDs. McNulty et al reported that EMG activity increased over trigger points when a patient was placed in a stressful situation. Untreated trigger points could result in continuous disruption of motor patterns that can be “reset” and re-established through appropriate interventions, such as muscle re-education. If trigger points increase during stressful circumstances, it may explain the startle reflex response and decreased tolerance to palpation, as seen in this case series. The PRRT used in this study are proposed to address the startle reflexes associated with BPD by addressing the nervous system through “resetting” primal reflexes. Theoretically, by stimulating the reflexes through a cough or quick palpation, neural input being sent to the spinal cord and brain and is temporarily overloaded and/or “reset,” which restores normal neural input to the muscles being treated. The inclusion of evaluating startle reflexes in primary and accessory respiratory muscles could assist in directing treatment intervention and explain how BPDs have an intimate connection to stress, emotions, and musculoskeletal pain.

Stress has been identified as a risk factor and contributor to musculoskeletal injuries and chronic pain. Hallman et al monitored participants with chronic neck and shoulder pain and found that during rest there was a decrease in PNS activation and increased SNS activation suggesting a mild ANS imbalance, when compared to the healthy control group. Mehling et al suggested that the breath therapy might teach coping skills and provide insight regarding the effect of stress on the body and chronic low back pain. It has been theorized that the presence of startle reflexes provides information regarding the state of the ANS, specifically an ANS imbalance, or “up-regulated” nervous system, however this supposition has not been studied. If restoration of an ideal breathing pattern and treatment using breathing exercises and PRRT created changes in the ANS, specifically an increase in PNS activation, such a change could provide an explanation for the decrease in musculoskeletal pain seen in these subjects. The authors hypothesize that the ANS, specifically an “up-regulated” nervous system contributes to the presence and perpetuation of BPDs in patients that present with a startle reflex.

Breathing pattern disorders in the general population are theorized to be more common than reported and if prevalence is similar in the physically active population, the effects of BPDs could be multiplied due to the increased physiological and biomechanical demands during exercise. If the body is not able to appropriately recruit muscles then compensatory motor patterns may ensue. Therefore, it is the opinion of the authors that breathing should be assessed in all patients due to the bidirectional influence of the psychological, chemical, and biomechanical systems.

The limitations of the present case series include the small number of subjects treated, the absence of a control group, and the clinicians only present the initial assessment and treatment of BPD outcomes, which do not allow for the generalization of the results. Additionally, the clinician’s reliability of assessing BPDs was not tested and only used two treatment techniques to improve breathing patterns out of several simple techniques that have been suggested in the literature. Research on the long-term effects of assessing and treating BPDs is necessary to see if patients maintain improvements in diaphragm function and musculoskeletal pain. Further research using a larger sample with a control group is needed to recognize if changes in breathing patterns actually occur and are due to interventions, and whether the changes alter motor control patterns sustain long-term improvements in pain and function throughout the body. Analyzing the connection between the
ANS, startle reflex, breathing patterns and motor control is essential to understanding how these treatments impact a patient's well-being.

SUMMARY
In this case series, following the PRRT and/or “clamshell” exercise, each subject presented with a clinically important change in NPRS scores in regards to their primary musculoskeletal complaint. In addition, all subjects displayed a change in their breathing pattern as well as a diminished or eliminated presence of a startle reflex. The current findings suggest that the occurrence of a startle reflex upon palpation may be a contributing factor associated with a BPD and musculoskeletal pain. Using PRRT and/or the “clamshell” exercise facilitated reestablishment of an optimal breathing pattern and theoretically, global motor control, contributing to the why the participants primary complaint of pain decreased. No previous research has indicated that the presence of a startle reflex is a common occurrence in an athletic population with disordered breathing. Therefore, the assessment and treatment of BPDs and startle reflexes might be an essential component to determine a potential cause or contributors to musculoskeletal pain.

REFERENCES


ABSTRACT

Background: Subacromial impingement is a common condition among overhead athletes. The cause of subacromial impingement can be multifactorial and often involves impaired rotator cuff function.

Case Description: The following cases outline the presentation, examination and intervention of two overhead athletes, a high school football quarterback and a collegiate swimmer, each presenting with signs and symptoms of subacromial impingement. The unique feature in each case was the manifestation of the cervical spine as the apparent source of rotator cuff weakness, which contributed to functional subacromial impingement although other overt signs of cervical or associated nerve root involvement were absent.

Outcome: Subsequent to this finding, the athletes demonstrated a rapid recovery of rotator cuff strength and resolution of impingement symptoms in response to cervical retraction and retraction with extension range of motion exercises along with posture correction. They both returned to unrestricted sporting activities within a week, with maintenance of strength and without reoccurrence of symptoms.

Discussion: The signs of functional subacromial impingement often include weakness of the supraspinatus and infraspinatus. The cause of the weakness in the two cases appeared to be the result of stresses associated with forward head posture contributing to a possible intermittent C5 nerve root compression. The findings in the two cases would suggest the cervical spine should be considered as a potential cause of rotator cuff weakness in individuals presenting with subacromial impingement. Future research should examine the influence of cervical postures and shoulder muscle strength.

Level of Evidence: 4

Keywords: Cervical posture, functional subacromial impingement, rotator cuff strength

CORRESPONDING AUTHOR

Steven Pheasant, PT, PhD
Misericordia University
Physical Therapy Department
301 Lake Street
Dallas, PA 18612-1090
(570) 674-6765
E-mail: spheasan@misericordia.edu

Acknowledgement: Tom Karmazyn PT, CertMDT for sharing his clinical expertise.
BACKGROUND AND PURPOSE
Subacromial impingement (SAI) and shoulder pain are common in those who participate in overhead sporting activities. Pitchers, quarterbacks and swimmers are particularly vulnerable to SAI due to the repetition and velocity of the overhead motions inherent to participation in their respective sports. Impaired shoulder mechanics can lead to the approximation of the humeral head and coracoacromial arch, thereby encroaching upon the intervening structures, resulting in tissue injury. The subacromial bursa, the rotator cuff tendons and the long head of the biceps brachii are often injured due to their occupation of the subacromial space.

Extrinsic and intrinsic factors have been identified as contributing to the development of SAI. Bigliani and Levine report extrinsic factors as those extratendinous conditions that compromise the subacromial space. Extrinsic factors may include space occupying bony anomalies, such as a hooked (Type III) acromion or eburnation and bone spur formation at the distal clavicle, projecting into the subacromial space. Glenohumeral joint capsular influences offer potential extrinsic SAI factors through either posterior capsular tightness or general capsular laxity. Posterior capsular tightness may contribute to impingement by encouraging anterior humeral head translation toward the coracoacromial arch during shoulder elevation. On the other hand, general capsular laxity, particularly in the overhead athlete, may result in altered mechanics and subacromial impingement to compensate for subtle subluxations. Lastly, enlargement of the coracoclavicular ligament may compromise the subacromial space, thus providing an additional extrinsic factor, which may contribute to SAI.

Intrinsic factors have been described as those that are intratendinous in nature and may be the result of rotator cuff weakness or fatigue. The repeated exposure of the rotator cuff tendons to high velocity shoulder movements, such as those accompanying throwing and swimming, may lead to overuse strain or tear due to frank tendon overload. Impaired rotator cuff function as a result of strength deficits, endurance limitations, or injury may permit excessive superior humeral head translation during shoulder elevation, resulting in SAI. SAI resulting from the intrinsic factors of deficient rotator cuff strength, endurance or control, resulting in impaired dynamic stability at the glenohumeral joint and excessive superior migration of the humeral head into the coracoacromial arch has been described by Janda as functional impingement. Functional SAI is delineated from structural impingement which is the result of the physical narrowing of the subacromial space due to extrinsic factors.

The symptoms associated with functional SAI often readily resolve once the rotator cuff strength deficit has been addressed and normal dynamic stability has been restored to the glenohumeral joint. The symptoms associated with functional SAI often readily resolve once the rotator cuff strength deficit has been addressed and normal dynamic stability has been restored to the glenohumeral joint.

The causes of rotator cuff weakness in the overhead throwing athlete may include: rotator cuff fatigue secondary to overuse, rotator cuff inhibition due to pain, muscle strain associated with frank tissue overload, and/or periscapular muscle dysfunction, resulting in rotator cuff length-tension issues. The author contends that cervical nerve root compression should also be considered as a potential contributor to rotator cuff weakness and, therefore, to functional SAI in the overhead throwing athlete. This will be discussed later in greater detail.

Regardless of the cause of the rotator cuff weakness, the clinical manifestation of functional SAI is often shoulder pain made worse with overhead use, passive shoulder range of motion (ROM) within normal limits, a painful arc of active abduction between 60-120°, and pain and weakness with isometric testing of shoulder abduction and/or external rotation. Suspicion of functional SAI is often confirmed with a painful response to a battery of special tests, including Neer’s impingement maneuver, the Hawkins-Kennedy test and Empty Can (Jobe) test. This cluster of symptoms often leads to the clinical diagnosis of functional SAI and the clinician would expect to see impairments of rotator cuff strength, painful range of motion and functional limitations, including compromised performance of overhead movements, particularly throwing and swimming.

The conservative clinical management of functional SAI often involves protection of symptomatic tissues from pain provoking activity, maintenance of shoulder passive ROM and gradual restoration of rotator cuff strength and endurance, while attempting to
address any observed possible contributing factors such as muscle length imbalances, impaired scapular muscle control, posterior capsular tightness, poor postural habits or faulty throwing mechanics.\textsuperscript{5,12,15}

The following are two cases in which athletes involved in overhead sporting activities presented with symptoms and signs consistent with functional SAI in which the cause for the muscle weakness appeared to be cervical in origin. The unique feature in both cases was that the only apparent sign of cervical involvement was that of weakness throughout the C5 myotome without complaints of radiculopathy, paresthesia, overt pain or restriction of cervical motions.\textsuperscript{21,22} Therefore, the purpose of these two case reports is to discuss the presentation, diagnostic process, intervention and outcome of the two cases of functional SAI attributable to cervical dysfunction.

**CASE DESCRIPTIONS**

**Case One**
A 5'9”, 165 pound, 16 year-old, left-handed, high school varsity quarterback, who was also a pitcher on the varsity baseball team, presented with left shoulder soreness and complaints of a “dead-arm” after participating in routine pre-season passing drills 24 hours earlier. He recalled his shoulder becoming progressively fatigued and sore after making 10-15 medium to maximum velocity throws of 10-20 yards. He did not recall a specific throw or incident leading to his symptoms nor did he experience sensations of sudden or sharp pain, tearing, popping, catching, instability or parasthesias. He denied a history of significant left shoulder symptoms prior to the onset of his current episode. He had not received prior imaging studies or diagnostic testing. His general health was unremarkable. He noted a history of recurrent episodes of cervical stiffness and acknowledged being a habitual cervical “self-manipulator” in that he would manually with overpressure rotate his cervical spine to end range in a rapid and forceful manner.

He also reported having been involved in an extensive off-season conditioning program that had included core, rotator cuff and scapular stabilizing muscle strengthening exercises. Additionally, he had participated in a progressive football throwing program in preparation for the pre-season. He also acknowledged having donned his football helmet for the first time of the season during practice that day.

**Observation**
The subject was of a mesomorphic build with evidence of left latissimus dorsi and pectoralis major hypertrophy, not uncommon in the dominant side of a throwing athlete.\textsuperscript{8} He also presented with mild scapular abduction, suggestive of pectoralis minor/major tightness and a moderate forward head, suggestive of possible suboccipital and upper trapezius tightness.\textsuperscript{8} No gross asymmetries were noted with regard to his sagittal spinal alignment.

**Physical Examination**
The initial physical examination consisted of active ROM with passive overpressure of the cervical spine and shoulders performed in standing.\textsuperscript{19} This was followed by shoulder, elbow and wrist resisted isometric strength testing per Cyriax.\textsuperscript{19} Active cervical range of motion was within normal limits in all planes of motion with the exception of retraction and retraction with extension, which were both mildly limited. Active cervical motions and active cervical motions with passive overpressure failed to produce symptom complaints. He demonstrated active left shoulder abduction that was visually estimated at 0-175° with a painful arc from 85-95° during both concentric raising and eccentric lowering. Passive left shoulder range of motion (ROM) was visually estimated to be abduction 0-180°, flexion 0-180°, external rotation 0-115° and internal rotation 0-60° all with capsular end feels. Resisted isometric strength testing with his shoulder in neutral tested weak and mildly painful for both the left shoulder external rotators (infraspinatus/teres minor) and abductors (deltoid/supraspinatus). All other left shoulder isometric strength tests were strong and painless. The neutral position of the shoulder is advocated by Cyriax in an attempt to selectively tension the potential contractile tissues at fault without placing the tendons of the rotator cuff in a compromising position or placing undo tension on other inert structures.\textsuperscript{19} No left shoulder glenohumeral joint symptoms, asymmetry or instability were noted with ligamentous testing. Ligamentous examination included Load and Shift testing for anterior and posterior glenohumeral joint translation and Sulcus sign testing for inferior glenohumeral
joint translation. Ligamentous testing was followed by confirmatory special testing including the Empty Can (Jobe) test, Hawkins-Kennedy test and Neer’s impingement sign, each of which was positive for symptom reproduction.14,15 (Tables 1 and 2)

The cluster of positive clinical findings, including a painful arc of active abduction, weakness and pain with resisted external rotation and a positive empty can (Jobe) test strongly suggest the likelihood of SAI.14 This conclusion was further supported by the positive findings with the Hawkins-Kennedy and Neer tests.15 The painful arc, Hawkins-Kennedy and Neer tests are intended to compress subacromial tissues, while resisted external rotation and the Empty Can (Jobe) test tension the rotator cuff tendons with emphasis to the infraspinatus and supraspinatus, respectively.

**Clinical Impression #1**

Preliminary clinical diagnosis was of left shoulder symptoms associated with impaired rotator cuff strength (supraspinatus/infraspinatus), resulting in functional subacromial impingement with overhead activities, most notably repeated throwing motions.

Having identified a clinical cluster of symptoms consistent with SAI associated with rotator cuff weakness, further investigation was indicated to search for factors which may have contributed to the impingement beyond the apparent obvious factor of rotator cuff overuse secondary to throwing a football. The patient’s comments regarding donning his helmet for the initial time in the season supported the idea that further examination of the cervical spine was warranted, in spite of the lack of apparent significant findings with the initial cervical scan of active motions and overpressures.

The continuation of the cervical examination proceeded with repeated cervical motion testing per McKenzie with the intent to discern the influence that repeated cervical motions may have had on the baseline signs and symptoms previously estab-

### Table 1. Common Responses to Resisted Isometrics (RI) and Interpretation19

<table>
<thead>
<tr>
<th>Common Responses to Resisted Isometrics</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong and Painless</td>
<td>No lesion to contractile unit</td>
</tr>
<tr>
<td>Strong and Painful</td>
<td>Minor lesion of muscle or tendon</td>
</tr>
<tr>
<td>Weak and Painless</td>
<td>Musculotendinous rupture (3rd degree) or peripheral nerve or nerve root involvement</td>
</tr>
<tr>
<td>Weak and Painful</td>
<td>Severe soft tissue lesion or fracture with pain induced inhibition</td>
</tr>
</tbody>
</table>

### Table 2. Testing Results Pre-Post Repeated Cervical Motion Interventions*

<table>
<thead>
<tr>
<th>Examination Test</th>
<th>Pre-Testing Case One</th>
<th>Pre-Testing Case Two</th>
<th>Post-Testing Case One</th>
<th>Post-Testing Case Two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Painful Arc</td>
<td>Positive</td>
<td>Positive</td>
<td>Negative</td>
<td>Negative</td>
</tr>
<tr>
<td>Isometric Shoulder External Rotation</td>
<td>Weak and (mild) painful</td>
<td>weak and (mild) painful</td>
<td>Strong and painless</td>
<td>Strong and painless</td>
</tr>
<tr>
<td>Isometric Shoulder Abduction</td>
<td>Weak and (mild) painful</td>
<td>Weak and painful</td>
<td>Strong and painless</td>
<td>Strong and painless</td>
</tr>
<tr>
<td>Empty Can Test (Jobe)</td>
<td>Positive</td>
<td>Positive</td>
<td>Negative</td>
<td>Negative</td>
</tr>
</tbody>
</table>

*Repeated cervical motion testing: Case One= retraction 3x10 reps; retraction with extension 2x 10 reps Case Two= retraction 2x10 reps; retraction with extension 2x 10 reps
lished. Because no acute distress was noted with initial retraction testing, repeated end range cervical retraction (chin tuck) for three sets of ten was performed since the retraction movements were accompanied with end range tightness that lessened with repetition. Cervical repeated motion testing for retraction ceased at this point due to the resolution of the complaint of end range cervical tightness. This was followed by repeated end range cervical retraction with extension that also demonstrated end range tightness, which lessened with repetition of two sets of ten. Testing for cervical retraction with extension was also discontinued at this point due to the resolution of the complaints of end range tightness with the movement. Repeated cervical motion testing was performed in the standing position.

At this point a re-examination of his left shoulder strength and motion was performed to determine if the repeated cervical movements had influenced the patient’s symptoms and signs. Upon re-examination, active left shoulder abduction was performed through full ROM with no painful arc. Resisted isometric testing for left shoulder abduction and external rotation each re-tested as strong and painless. The Empty Can (Jobe) test also re-tested strong and painless.

**Clinical Impression #2**

It was concluded that the cervical spine had contributed to the patient’s left shoulder strength deficits, resulting in a functional SAI. Consequently, both the cervical retraction (chin tuck) and cervical retraction with extension movements would play a major role in the rehabilitative process of this patient.

**Intervention**

Initial intervention included instruction to avoid head forward postures as much as possible for the ensuing 24 hours. This was implemented due to the acknowledged favorable response the repeated cervical retraction movements had on the patient’s symptoms and strength. Accordingly, modifications were made in his standing, sitting and sleeping postures to promote a more neutral position of his cervical spine. Similarly, he was also instructed to perform end range cervical retraction and retraction with extension (10 times each) on an every one to two hour basis in order to reinforce the favorable response demonstrated in the clinic. (Figures 1 and 2).

He was seen for follow up within 24 hours, and it was noted that his improvement with regard to symptom-free left shoulder motion and normal strength had been maintained. He resumed full participation.
in football practice, including throwing drills without event that day. A follow up one week after the initial examination revealed that he had maintained his improvement, and he continued with full participation in pre-season football practices without event. He acknowledged ongoing compliance with his prescribed active cervical ROM exercises and posture modifications.

Clinical Diagnosis
Left shoulder symptoms with impaired rotator cuff strength, resulting in functional SAI with overhead activities, most notably throwing, likely due to faulty cervical postures and excessive lower cervical flexion stresses.

Case Two
A 6’- 4”, 185 lb, 22 year old collegiate swimmer presented with bilateral shoulder pain and dysfunction that he associated with a weight lifting session he had performed the previous day as part of his off-season conditioning program. He reported having performed intense straight bar squats, in addition to a series of upper extremity strength training exercises. He denied a specific exercise or movement that led to his symptoms, but believed his symptoms were, in fact, related to the above activities. He denied a significant history with regards to his shoulders. He had no complaints of joint instability or upper extremity parasthesias. He had not received prior imaging studies or diagnostic testing. His general health was unremarkable.

Observation
The subject presented with a mesomorphic build. His standing posture was characterized by a marked forward head, moderately rounded shoulders and a moderate thoracic kyphosis. No deviations were noted with regards to his sagittal spinal alignment.

Physical Examination
Examination of the cervical spine and upper quarter was performed as described by Cyriax with additional cervical examination proceeding with repeated motion testing as described by McKenzie. Active cervical range of motion was within normal limits in all planes of motion with the exception of retraction and retraction with extension, which were both mildly limited. Active cervical motions and active cervical motions with passive over-pressure failed to produce symptom complaints. He demonstrated active bilateral shoulder abduction that was visually estimated to be 0-180° with bilateral painful arcs between 80-100° during concentric raising and eccentric lowering. Passive shoulder ROM was full with capsular end feels. Excessive external rotation was noted bilaterally. Resisted isometric strength testing, with his shoulder in neutral, tested weak and painful for bilateral shoulder abductors. Bilateral shoulder external rotators were also weak and mildly painful. All other shoulder isometric strength tests were strong and painless. There were no apparent glenohumeral joint instability issues with ligamentous testing of his shoulders bilaterally. Ligamentous testing included Load and Shift testing for both anterior and posterior joint capsules. Inferior translation of the glenohumeral joint was assessed using the Sulcus sign. The Empty Can (Jobe), Hawkins-Kennedy, as well as Neer’s Impingement tests were all positive bilaterally.

Clinical Impression #1
Preliminary clinical diagnosis was: bilateral shoulder symptoms associated with impaired rotator cuff strength (supraspinatus greater than infraspinatus), resulting in functional SAI with overhead activities, most notably weight lifting.

Having arrived at an initial physical therapy diagnosis, the examination proceeded in an attempt to identify additional contributing factors to the previously stated impairments. Given his noted postural faults, additional examination of the cervical spine was warranted, in spite of a lack of significant symptom production or apparent associated symptoms with the initial cervical scan. End range cervical retraction was accompanied with end range tightness, which lessened with 20 repetitions. This was followed by end range cervical retraction with extension that was also accompanied with end range tightness that lessened with 20 repetitions. Examination of both cervical retraction and retraction with extension ceased once end range was attained and reports of tightness ceased.

Re-examination of bilateral active shoulder abduction was performed with a noted absence of a painful arc. The Empty Can (Jobe) test, Hawkins-Kennedy
and Neer's tests were each now noted to be negative bilaterally. Resisted isometrics for bilateral shoulder abductors and external rotators each were strong and painless on re-examination. (Table 2) The patient was asked to perform repeated end range active cervical protrusion times twenty repetitions in an attempt to reproduce the patient's strength deficits and associated symptoms. Protrusion is a cervical movement that accentuates the forward head posture to end range followed by a return to the neutral position. This was done in a slow, repetitious fashion to assess the effect of the cervical motion opposite to that which was found to have a favorable impact on his symptoms and strength, namely cervical retraction. No cervical discomfort was reported during the performance of the repeated active cervical protrusion, however, upon completion, the bilateral painful arc returned, the Empty Can (Jobe) test was once again positive and resisted isometrics for the shoulder abductors and external rotators were again found to be weak and painful.

The performance of an additional twenty end range cervical retraction movements and twenty end range cervical retraction with extension movements resulted in the abolishment of the bilateral painful arc, the return of normalcy for the Empty Can (Jobe) test and a return of abductor and external rotator strength that was strong and painless.

**Intervention**

In a manner similar to the intervention described in Case One, the patient was instructed to sit, stand and sleep in postures that reinforced a more neutral cervical position as opposed to his habitual head forward posture. He was encouraged to use a lumbar roll to assist in the maintenance of his lumbar lordosis when sitting. He was also asked to perform end range cervical retraction and end range cervical retraction with extension exercises for ten repetitions each on an hourly basis throughout the day. He was seen for follow up within 24 hours, and his improvement for symptom reduction and rotator cuff strength was maintained. Subsequent follow up one week later revealed that he had maintained his improvement and had stated ongoing compliance with his prescribed cervical active ROM exercises and posture modifications.

**Clinical Diagnosis**

Final clinical diagnosis for this subject was bilateral shoulder symptoms associated with impaired rotator cuff strength, resulting in functional SAI with overhead activities, most notably recreational weightlifting, likely due to faulty cervical postures and excessive lower cervical flexion stresses.

**DISCUSSION**

The observation that movements of the cervical spine influence upper quarter signs and symptoms and function is not novel. A number of authors have described characteristic patterns of symptoms, myotomal strength deficits, and hypotonic reflex changes which affect the upper extremity to varying degrees when a cervical nerve root has been irritated.21-23. The characteristics of the symptoms and signs present in the upper quarter are dictated by the cervical nerve root level that is involved. Typically, cervical active movements are restricted and produce symptoms of pain and/or paresthesia that may extend or radiate into the upper extremity. Cervical extension and both cervical lateral bending and rotation to the side of the irritated nerve root are likely to produce or increase symptoms due to the narrowing of the intervertebral foramen which accompanies each movement.26 The most common cervical nerve root levels involved in radiculopathy are C6 and C7, followed by C5.22,27 Consequently, the characteristic symptoms and signs associated with involvement of the C6 nerve root may include pain over the lateral forearm into the thumb and 2nd digit, sensory changes over the thumb and 2nd digit, strength deficits in the biceps brachii and wrist extensors, and reflex changes of the biceps brachii.22,27 Characteristics of C7 nerve root irritation may include pain that may extend into the medial scapular region, dorsum of the forearm and 3rd digit, sensory changes that extend over the dorsum of the forearm and 3rd digit, potential strength deficits of triceps brachii and wrist flexors, and reflex changes of the triceps brachii.22,27 Characteristic of C5 nerve root involvement symptoms and signs may include pain over the medial scapula and lateral aspect of the arm, sensory changes present over the lateral aspect of the arm, strength deficits of the deltoid, supraspinatus and infraspinatus, and reflex changes of the supinator.22,27
nerve root is the cause of the rotator cuff weakness in the above cases, it is surmised that the compression was of a magnitude sufficient to impair nerve function, yet not to cause nerve damage.

Periods of accentuated forward head postures and mild limitations in cervical retraction and retraction with extension AROM were common to the subjects in both cases and may suggest that each was vulnerable to a form of cervical nerve root compression. The cause of the compression is open to debate, particularly given the proposed involvement of the C5 nerve root and the paucity of information regarding segmental vertebral kinematics involving the cervical spine in either the protruded (forward head) or retracted (chin tuck) positions.

The literature suggests the most common causes of cervical nerve root compression are from either posterior bulging of an intervertebral disc or by intervertebral foraminal stenosis. 22-24,27 The following discusses the plausibility of the C5 nerve root being compromised under either condition.

Considering that the C5 nerve root exits the spinal column superior to the C5 vertebra, a disc bulge would likely occur at the C4-C5 level in order to compromise the C5 nerve root. Although the C5-C6 and C6-C7 levels are more likely to demonstrate posterior disc protrusion, resulting in nerve root compression on the C6 and C7 nerve roots respectively, a number of studies indicated the C4-C5 disc level is subject to degeneration and protrusion, and therefore, a potential source of compression to the C5 nerve root.25,27,29,30 Matusmato et al30 in an MRI study of asymptomatic subjects noted that 15% of the subjects demonstrated posterior disc protrusions at the C4-5 level. Okada et al29 in a 10-year longitudinal study, using MRI, reported that 25% of the C4-C5 posterior disc protrusions, originally identified, progressed in severity over the course of the study. Wainner et al27 in their study reported that 2 of the 20 cervical radiculopathies identified likely involved the C5 nerve root. Furthermore, Kim et al’s28 study of 1,305 consecutive patients undergoing primary cervical surgery reported 16.6% of those subjects under the age of 40 had C5 nerve root involvement. In the same study, 39.4% of patients between ages 40-60 and 48.1% of those over 60 had procedures for C5 nerve root involvement.

What is of particular interest to the author in the two described cases is the clinical expression of the apparent cervical involvement. The cervical motions themselves were not particularly limited and failed to demonstrate aberrant results that would have initially suggested the cervical spine was involved or at fault. Nor were the cervical motions accompanied by pain during the movement or at end range of any particular movement that would have indicated involvement. Additionally, the cervical movements failed to be accompanied with any of the characteristic upper extremity symptoms indicative of cervical nerve root involvement, namely, pain or parasthesia in the noted distributions.22,27 Admittedly, reflex testing was omitted from the exam for expediency, and extensive sensory testing was not performed due to each patient’s subjective report of normalcy. The primary clinical sign that appeared to be associated with the cervical spine was that of shoulder muscle weakness that appeared to dominate the C5 myotome (deltoid, supraspinatus, infraspinatus). It was, in turn, surmised that the noted strength deficit had compromised normal shoulder mechanics, resulting in a functional SAI. The clinical sign of shoulder muscle weakness of a cervical origin without cervical pain or reports of associated sensory impairment is the unique feature in these cases, and this warrants discussion.

The rather immediate improvement in rotator cuff strength and normalization of shoulder function in response to repeated end range cervical retraction followed by end range cervical retraction with extension range of motion exercises is in need of an explanation. The author contends a plausible explanation is that muscle weakness was produced through an intermittent C5 nerve root compromise induced by forward head postures, resulting in a possible transient conduction block to the C5 myotome. Compressive forces between 20-30 mm Hg can impair neural blood flow, and subsequently, may result in compromised nerve function.28 The reduction in blood flow is believed to reverse once the compression is removed without apparent residual nerve damage.28 However, compressive forces of 50 mm Hg, for periods as little as two minutes duration, have been shown to result in damage to the myelin and axon.28 Therefore, if an intermittent compromise of the C5 nerve root is the cause of the rotator cuff weakness in the above cases, it is surmised that the compression was of a magnitude sufficient to impair nerve function, yet not to cause nerve damage.
A disc bulge, resulting in nerve root compression, would likely be due to flexion at the C4-C5 motion segment, causing the annulus to deform and bulge posteriorly. A radiographic study by Orway et al, analyzing the segmental vertebral kinematics of the cervical spine in the protruded (head forward) position, suggests that the C4 vertebra is in a position of relative flexion to the C5 vertebra of $6.3 \pm 4.1^\circ$. The flexed position places an offset flexion load on the C4-C5 disc level, thus creating a potential mechanism for the nucleus pulposus of the disc to migrate, possibly contributing to a posterior disc bulge. Cervical retraction, in the same study, was demonstrated to begin to extend C4 relative to C5, however, the study suggests the motion segment remains flexed $4.5 \pm 4.4^\circ$.

Orway et al demonstrated that the cervical motion of retraction followed by extension results in extension of C4 relative to C5 of $9.5 \pm 3.9^\circ$. This provides additional theoretical evidence for decreasing a potential C5 nerve root compression (caused by a mildly bulging disc) by encouraging the extension of C4 on C5.

Stenosis of the intervertebral foramen has also been presented as a potential source of cervical nerve root irritation, and is typically thought of in an aging population. Although stenosis is generally associated with degenerative changes that accompany aging, and the two cases involved young adult males, a study by Anderst et al offers information that may shed insight on a potential explanation for C5 nerve root compression through an intervertebral foraminal stenosis mechanism. Their study evaluated segmental cervical kinematics during active flexion and extension in asymptomatic subjects (46±9 yrs) using a bi-planar X-ray system. An anterior shear of C4 on C5, on the magnitude of 33%, was reported to occur preceding end range cervical flexion. This anterior shear is likely to result in a narrowing of the anterior/posterior dimension of the intervertebral foramen as the inferior articular process of C4 moves toward the posterior aspect of the C5 uncovertebral joint as the C4 body shears anteriorly. Cervical flexion is not identical to the protrusion, which accompanies the head forward posture, but similarities do exist in the lower cervical spine. Ordway et al demonstrated C4 to flex on C5 $9.5 \pm 3.1^\circ$ during full flexion, while C4 flexed on C5 $6.3 \pm 4.1^\circ$ during full protrusion in their kinematic study. It is reasonable to assume that an anterior shear of C4 on C5 would also occur during the lower cervical flexion that accompanies protrusion and the forward head posture, however, to a lesser degree than observed during full flexion. Consequently, a foraminal stenosis at C4-C5 may be created by end range lower cervical flexion resulting from time spent in a head forward posture, which, in turn, may be a potential source of C5 nerve root compression.

The potential for the cervical retraction movement to reduce a C5 nerve root compression due to stenosis is supported by Lentell et al, who suggested an increase in both the vertical and transverse dimensions of the C4-C5 intervertebral foramen after moving from the neutral to the retracted cervical posture. Cervical retraction resulted in an 11% increase in foramenal area compared to the neutral cervical position. Their study examined the cervical spines of 20 healthy, asymptomatic 22-25 year old subjects, using MR imaging in the supine position. Cervical retraction, according to data provided by Lentell et al, increases the space available for the C5 nerve root to exit the spinal column, possibly reducing compression of a compromised nerve root in a young adult population.

Evidence has been provided supporting the incidence of the C5 nerve root being involved in cervical pathology. Evidence has also been presented in an attempt to explain the unique findings of the two case reports. The author of this case series has proposed that either a mildly bulging cervical intervertebral disc encroaching on the C5 nerve root or a temporary, mild intervertebral canal stenosis is the potential mechanism of C5 nerve root compression. Nerve root compression from either source could potentially result in the supraspinatus and infraspinatus muscle weakness, as was seen in these two cases, and can help explain the changes in the shoulder symptoms and signs previously reported.

Therefore, both retraction and retraction with extension are cervical movements that could potentially reduce irritation to a mildly compressed nerve root, regardless of etiology. Retraction has two potential mechanisms by which this may occur, first, with cervical retraction, C4 begins to extend on C5. This cervical extension, though limited in magnitude and
The age of the subjects in the current cases should be discussed. The subjects were age 16 and 22. The typical ages of those diagnosed with cervical radiculopathy have been reported to be in their 30’s and 40’s, with incidence peaking in their early 50’s.\textsuperscript{22,37} However, Matsumoto, in a MRI evaluation of asymptomatic cervical intervertebral discs, reported posterior disc protrusions in 17\% of male subjects in their twenties. The most common cervical level to demonstrate protrusion was C5-C6 and C6-C7, followed by C4-C5.\textsuperscript{30} If muscle weakness in the associated myotome is the only sign of nerve compression, as suggested in these cases, it is difficult to determine what the actual incidence of occurrence is or at what age the weakness or other symptoms commence.

An acknowledged factor that should be mentioned, which may have influenced the outcome in the current cases, is the effect of posture on the subacromial space. Borstad and Ludewig\textsuperscript{38} reported a reduction in subacromial space in the presence of pectoralis minor tightness. In both cases, pectoralis minor tightness was suspected, due to the varying degree of rounded shoulder posture observed during the initial examination. Posture instruction, in the form of attempting to maintain an erect cervical posture as much as possible, was part of the intervention in each case. Seitz et al\textsuperscript{39} reported an increase in subacromial space during active upper extremity elevation, in response to a scapular repositioning maneuver. Lewis et al\textsuperscript{40} reported an increase in active forward flexion and abduction ROM in both asymptomatic and symptomatic shoulders, in response to taping and posture correction. Consequently, the posture correction that accompanies cervical retraction, which was prescribed as a part of the exercise plan in these two current cases, could have played a role in shoulder posture thereby affecting the painful arc.

The explanation for the clinical observation of improved rotator cuff strength and shoulder function in apparent response to the performance of repeated cervical retraction and retraction with extension range of motion movements warrants further investigation. If, in fact, a nerve root conduction block resulted in the sole neurologic sign of rotator cuff weakness leading to functional SAI, as suggested by the author, clinicians should be mind-
ful to thoroughly examine the cervical spine and look for cause and effect on shoulder strength and function, even though the cervical movements may not be associated with cervical pain or marked cervical ROM impairments. Otherwise, the impairment of rotator cuff weakness becomes a principle focus of the rehabilitation, while the underlying contribution of the cervical spine may go undetected, making reoccurrence of functional SAI likely.

Additionally, since these patients, once identified, respond in a rapid fashion, the benefits from both outcome and economic perspectives are important.

CONCLUSION
Although weakness of the rotator cuff has long been associated with SAI and has been the direct focus of intervention, the cause for the weakness and the remedy in a number of cases may, in fact, be found by looking more closely at the cervical spine, even when outward symptoms and signs may suggest otherwise. The author contends a population exists that experiences a significant loss of rotator cuff strength following periods in protruded cervical (forward head) postures. Similarly, the author suggests research focusing directly on the effect of various cervical postures on rotator cuff strength be conducted to shed further light on the relationship between the cervical spine and shoulder function.

REFERENCES
ABSTRACT

The modern human foot is the culmination of more than five million years of evolution. The ankle-foot complex absorbs forces during loading, accommodates uneven surfaces, and acts as a lever for efficient propulsion. The ankle-foot complex has six independent functional segments that should be understood for proper assessment and treatment of foot and ankle injuries: the shank, rearfoot, midfoot, lateral forefoot, and the medial forefoot. The compliance of the individual segments of the foot is dependent on velocity, task, and active and passive coupling mechanisms within each of the foot segments. It is also important to understand the passive, active, and neural subsystems that are functionally intertwined to provide structure and control to the multisegmented foot. The purpose of the first part of this clinical commentary and current concepts review was to examine foot and ankle anatomy, detail the roles of the intrinsic and extrinsic foot and ankle musculature from a multisegmented foot perspective, and discuss the biomechanics of the ankle-foot complex during function. The interplay of segmental joint mobility, afferent and efferent sensorimotor function, and movement and stabilization provided by the extrinsic and intrinsic musculature is required to coordinate and execute the complex kinematic movements in the ankle-foot complex during propulsion.

Key Words: intrinsic foot muscles, gait, joint mobility, kinematics, ambulation

Level of Evidence: 5
BACKGROUND AND PURPOSE
The modern human foot is the culmination of more than 5-million years of evolution.1 Our ancient hominine ancestors evolved from arboreal to terrestrial living and the morphology and function of the foot adapted accordingly and transitioned from primarily climbing tasks to bipedal locomotion.1-5 The ankle-foot complex absorbs forces during loading, accommodates uneven surfaces, and acts as a lever for efficient propulsion.6 The six independent functional segments that comprise the ankle-foot complex should be understood for proper assessment and treatment of foot and ankle injuries: the shank, rearfoot, midfoot, lateral forefoot, and the medial forefoot (first ray and hallux).7 Compliance of the individual segments of the foot is dependent on velocity, task, and active and passive coupling mechanisms within each of the foot segments. It is also important to understand the passive, active, and neural subsystems that are functionally intertwined to provide structure and control to the multisegmented foot.8,9

The purpose of the first part of this clinical commentary and current concepts review was to examine foot and ankle anatomy, detail the roles of the intrinsic and extrinsic foot and ankle musculature from a multisegmented foot perspective, and discuss the biomechanics of the ankle-foot complex during function. The companion paper to this commentary will examine the contribution of midfoot and forefoot impairment in lateral ankle sprains and chronic ankle instability in order to increase clinician’s awareness and to facilitate future research in this area.10 The importance of multisegmented foot and ankle assessment will also be discussed from a clinical and research perspective.

ANATOMY AND FUNCTION OF THE ANKLE–FOOT COMPLEX

Shank
The shank (tibia and fibula) begins at the knee where the tibia articulates with the distal femur and the fibular head articulates with the lateral tibial condyle. The tibia and fibula are supported by the anterior and posterior ligaments of the fibula head proximally, by the interosseous ligament along the diaphysis, and the anterior and posterior tibiofibular ligaments distally. The shank forms a distal mortise joint that serves as the proximal segment of the talocrural articulation. During gait, the shank functions like the distal aspect of a pendulum during swing phase and fulcrums over the talus during periods of single support.11 In stance, the fibula shares approximately 10% to 30% of the burden during axial loading of the shank.12 The shank is coupled to ankle motion with tibial internal rotation coupled to rearfoot pronation13,14 and talocural dorsiflexion/plantarflexion coupled to fibular translation and rotation in all cardinal planes.15

Talocrural Articulation
The talocrural articulation is a “mortise and tenon” joint comprised of the shank proximally and the talus distally. Dorsiflexion and plantarflexion are the primary osteokinematic motions of the talocrural joint, with an oblique axis of rotation that travels through the medial malleolus, the talar head, and the lateral malleolus.16-18 The oblique axis of rotation results in component eversion and adduction accompanying dorsiflexion and inversion and abduction accompanying plantarflexion.16,18 The talocural joint is statically supported by the joint capsule, the deltoid ligament (medially), and the anterior talofibular, calcaneofibular, and posterior talofibular ligaments (laterally).

Rearfoot and Subtalar Joint
The rearfoot, also known as the hindfoot, is comprised of the talus (proximally), the subtalar joint, and the calcaneus (distally). The subtalar joint is comprised of anterior (talocalcaneonavicular) and posterior (talocalcaneal) articulations that are separated by the tarsal canal. The joint capsules and the cervical, interosseous talocalcaneal, posterior talocalcaneal, lateral talocalcaneal, calcaneofibular, and fibular-talocalcaneal ligaments support the subtalar joint. The axis of rotation is oriented anterior-superomedial to posterior-inferolateral and transects the three cardinal planes. Primary osteokinematic motions of the subtalar joint are supination and pronation. Similar to what is observed with the oblique axis of rotation in the talocrural joint, subtalar pronation is accompanied by dorsiflexion and abduction and subtalar inversion is accompanied by plantarflexion and adduction.16,16,19 The subtalar joint is
often described as a “mitered hinge” and its triplanar orientation allows for the coupling of shank rotation and rearfoot supination/pronation.

Transverse Tarsal (Chopart or Midtarsal) Articulation

The transverse tarsal articulation is comprised of the talus and navicular (medially) and the calcaneus and cuboid (laterally). The bifurcate (calcaneocuboid and calcaneonavicular ligaments), dorsal calcaneocuboid, dorsal talonavicular, interosseous talocalcaneal, deltoid (tibionavicular part), spring, and plantar cuboideonavicular ligaments statically support the transverse tarsal joint.

Motion between the forefoot and rearfoot occurs in the transverse tarsal joint through two separate axes of rotation; one being supination and pronation of the cuboid on the calcaneus about the longitudinal axis and the other being oblique to the foot as the cuboid translates on the calcaneus.20 The axes vary by task and change based on the congruency of the calcaneocuboid joint.21 The longitudinal axis of the transverse tarsal joint allows for the forefoot to rotate opposite of the midfoot in the transverse plane.20 Arthrokinematic movement about the oblique axis plus dorsiflexion and plantarflexion of the transverse tarsal produces deformation of the longitudinal arches.20 The review conducted by Tweed and colleagues22 is recommended for additional information on the function of the transverse tarsal joint.

Midfoot

The midfoot is comprised of the navicular, medial, intermediate, and lateral cuneiforms, and the cuboid. The bones of the midfoot form the medial longitudinal (Figure 1), the lateral longitudinal, (Figure 2) and the transverse arches (Figure 3), which together comprise a half dome.23 The function of the midfoot is to transmit and attenuate force and allow the foot to accommodate to the variable surface of the ground.23 The arches are supported and controlled by a combination of bony congruency and static and dynamic extrinsic and intrinsic stabilizers.24,25 The primary stabilizers of the midfoot are evolutionary adaptations favorable for bipedal locomotion and consist of the osseous, muscular, and ligamentous structures that support the longitudinal arches, calcaneocuboid, and tarsometatarsal articulations.2–5 The adaptations found in the human foot allow for various degrees of mechanical coupling of the forefoot to the rearfoot during gait (midtarsal locking) and control of dorsiflexion of the lateral tarsometatarsal joints (midtarsal break) during the stance phase.4,5,26,27 Table 1 provides a comprehensive overview of the stance phase of gait and details the multisegmented ankle-foot motions and the relevant muscle actions that occur from initial contact to pre-swing. During lower velocity locomotion, the foot is lengthened and the medial longitudinal arch is flattened, increasing the compliance of the foot.
Table 1. Summary of multisegmented foot and ankle kinematics and muscle actions during stance phases of gait. L = Lateral, M = Medial, FHL = Flexor Hallucis Longus, FDL = Flexor Digitorum Longus.

<table>
<thead>
<tr>
<th>Goal of Phase</th>
<th>Initial Contact</th>
<th>Loading</th>
<th>Midstance</th>
<th>Terminal Stance (heel off)</th>
<th>Pre-swing (toe off)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begin lowering forefoot to ground while maintaining proper frontal plane alignment</td>
<td>Dissipate ground reaction forces while accommodating terrain</td>
<td>Transfer momentum over foot and ankle complex with efficient transfer from deceleration to acceleration</td>
<td>Accelerate mass for forward propulsion</td>
<td>Finish forward propulsion into initial swing</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Relevant Ankle-Foot Muscle Actions</td>
<td>Tibialis Anterior: Maintains frontal plane alignment and eccentrically dorsiflexes foot</td>
<td>Tibialis Anterior: Maintains frontal plane alignment and eccentrically dorsiflexes foot</td>
<td>Tibialis Anterior: Plantarflexes 1st ray</td>
<td>Fibularis Longus: Isometrically stabilizes longitudinal and transverse arches</td>
<td>Fibularis Longus: Maintains 1st ray on ground during propulsion</td>
</tr>
<tr>
<td></td>
<td>Fibularis Longus: Maintains frontal plane alignment prior to initial contact</td>
<td>FHL/FLD: Isometrically stabilizes longitudinal arch</td>
<td></td>
<td>Triceps Surae: Generates plantarflexion propulsion force</td>
<td>Triceps Surae: Generates plantarflexion propulsion force</td>
</tr>
<tr>
<td></td>
<td>Tibialis Posterior: Stabilizes rearfoot</td>
<td>Tibialis Posterior: Isometrically stabilizes medial longitudinal arch</td>
<td>Plantar Intrinsics: Accommodates terrain, stabilizes midfoot, and attenuates force</td>
<td>Fibularis Longus: Generates plantarflexion propulsion force</td>
<td>Fibularis Longus: Generates plantarflexion propulsion force</td>
</tr>
<tr>
<td></td>
<td>Fibularis Longus: Stabilizes rearfoot</td>
<td>Triceps Surae: Tenses plantar aponeurosis</td>
<td>Plantar Intrinsics: Accommodates terrain, stabilizes midfoot, and attenuates force</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Morphology and Dynamic Support of the Longitudinal and Transverse Arches (Plantar Aspect). 1 = Flexor Digitorum Longus, 2 = Flexor Hallucis Longus, 3 = Quadratus Plantae, 4 = Adductor Hallucis, 5 = Abductor Hallucis, 6 = Fibularis Longus, 7 = Tibialis Posterior, 8 = Abductor Digiti Minimi, MLA = Medial Longitudinal Arches, MetA = Metatarsal Arches, LLA = Lateral Longitudinal Arches, TrvA = Transverse Arch.
for accommodation of uneven terrain and to maximize balance control. During higher velocity locomotion, the medial longitudinal arch angle increases and the foot shortens as a means of optimizing the lever arm during pushoff.

**Tarsometatarsal (Lisfranc) Joint**

The tarsometatarsal (TMT) joint is the articulation between mid and forefoot segments and consists of the medial and lateral columns of the foot. The medial column is formed by the articulation of the medial, middle, and lateral cuneiforms with the proximal first, second, and third metatarsals, respectively (Fig 1). Within the medial column, the first cuneiform, metatarsal, and the first TMT articulation form the first ray. The lateral column is comprised of the cuboid, the proximal fourth and fifth metatarsals and the lateral aspect of the TMT (Figure 2). The TMT joint complex is structurally stabilized morphologically in a “Roman Arch” configuration and supported by extensive dorsal, plantar, and interosseous ligamentous network. During locomotion, the degree in which the forefoot couples with the rearfoot varies dependent on velocity and the cardinal plane in which forefoot motion occurs.

**First Ray & Hallux**

The first ray, also referred to as the medial forefoot, is comprised of the first metatarsal, cuneiform, and the TMT joint. The first ray functions as a pillar and forms the distal truss of the medial longitudinal arch. The joint capsule and the dorsal tarsometatarsal, plantar tarsometatarsal, and plantar metatarsal ligaments provide passive stability to the TMT articulation. The hallux is comprised of the first proximal and distal phalanx and the interphalangeal joint. The medial collateral, lateral collateral, and plantar ligaments and the joint capsules provide stability to the first metatarsophalangeal and interphalangeal joints.

**Lateral Forefoot**

The lateral forefoot is comprised of the metatarsals and phalanges of the lateral four digits. The joint capsules and the medial collateral, and lateral collateral ligaments provide stability for each of the metatarsophalangeal and interphalangeal joints. A deep transverse and plantar metatarsal ligament supports the intermetatarsal articulations. Together with the first ray, the metatarsals of the lateral forefoot form a metatarsal arch (Figure 3).

**Extrinsic Control of the Ankle – Foot Complex**

Traditionally, the extrinsic foot and ankle muscles are described as ‘prime movers’ based on the osteokinematic motion they cause when the foot is treated as a rigid segment. However, the authors aim to describe the functional roles of the extrinsic foot and ankle muscles in the context of a multisegmented foot and ankle complex. Collectively, the extrinsic and intrinsic foot and ankle musculature support, stabilize, dissipate force, and move the multiple articulations of the ankle and foot. Please refer to Figures 1-4 for illustrations of the extrinsic muscle tendons and their insertions.

**LATERAL COMPARTMENT**

The lateral compartment contains the fibularis longus and brevis, both of which are innervated by the superficial fibular nerve. The fibularis longus plays an important role in stabilization of the lateral midfoot and the first ray and is the primary evertor of the forefoot. Originating in the lateral compartment, the tendon courses around a series of pulleys formed by the lateral malleolus, the peroneal tubercle, and the cuboid. The tendon exerts a compressive stabilizing force on the cuboid and contributes to midtarsal locking and prevention of midtarsal break. The tendon continues from the cuboid in an anteromedial direction to the lateral plantar base of the first metatarsal. Functionally during stance, the fibularis longus stabilizes the medial column by evertting the first ray and mechanically coupling the tarsometatarsal and naviculocuneiform joints through a torsion of the articular ligamentous and capsular tissues. The fibularis longus is the primary plantarflexor of the first ray and assists in the support of the medial longitudinal arch. The fibularis longus contributes important afferent feedback in regards to ankle position. In a study investigating proprioception, balance, and reaction time in individuals who received a regional nerve block to the foot and ankle, it was concluded that the fibularis longus is a primary afferent input to the brain in maintaining balance even more so than the ligamentous structures of the...
ankle. The fibularis longus, tibialis posterior, and the flexor digitorum longus tendons are oriented in a cross configuration and may contribute to the support and function of the longitudinal and transverse arches. Each tendon courses the span of both arches, with the fibularis longus traversing posterolateral to anteromedial and the flexor digitorum and posterior tibialis coursing posteromedial to anterolateral. It is plausible that synergistic concentric contraction of these muscles would contribute to approximation of opposing voussoirs and increase the rise of the longitudinal and transverse arches. It is also conceivable that like the long toe flexors, isometric or eccentric co-contraction of these muscles may contribute to stabilization and force attenuation of the foot arches.

The fibularis brevis originates in the lateral compartment of the leg and inserts on the styloid process of the fifth metatarsal. The fibularis longus is the primary evertor of the forefoot and similarly, the fibularis brevis and fibularis tertius (of the anterior compartment) are the primary evertors of the rearfoot and midfoot. In a study investigating the contribution of the fibularis longus and brevis to ankle and foot movement during a simulated early heel rise during the stance phase of gait, the fibularis brevis was found to be more effective in everting the talonavicular and subtalar joints than the fibularis longus.

**ANTERIOR COMPARTMENT**

The fibularis tertius, tibialis anterior, extensor digitorum longus, and extensor hallucis longus originate in the anterior compartment and are innervated by the deep fibular nerve. The fibularis tertius, which
functions synergistically with the two lateral compartment muscles and was discussed in the previous section, inserts on the dorsal base of the fifth metatarsal. The tibialis anterior, extensor hallucis longus and the extensor digitorum longus course from the anterior compartment distally to the extensor retinaculum. The tibialis anterior tendon continues and inserts on the inferomedial aspect of medial cuneiform and the base of first metatarsal. During gait, the tibialis anterior is thought to have an important function in maintaining balance during the first quarter of stance. The extensor hallucis and digitorum longus insert into the extensor apparatus of the great toe and the second through fifth toes, respectively. The toe extensors, with the anterior tibialis, activate to lift the toes from the ground at terminal stance of gait. They also assist in the stabilization of the talocrural and the tarsal bones during loading of the foot. Afferent information provided from the muscles of the anterior compartment, in conjunction with lateral compartment muscles and cutaneous receptors, have been suggested to have an important role in ankle kinesthesia and modulation of the soleus during the stance phase of gait.

SUPERFICIAL POSTERIOR COMPARTMENT

The gastrocnemius and soleus, collectively known as the triceps surae, innervated by the tibial nerve, originate in the posterior compartment and insert on the calcaneal tuberosity. During stance phase, the triceps surae controls the forward progression of the shank on the talus and assists in providing a flexion moment at the knee. Additionally, the triceps surae is able to mechanically influence the rearfoot, midfoot, and forefoot through its insertion on the calcaneus and ability to tension the plantar aponeurosis (PA), otherwise known as the plantar fascia (Figure 5). During gait, the PA is tensioned at 30% of stance until midstance, when elongation increases sharply. Peak elongation of the PA occurs at 80% of stance when the triceps surae exerts a plantarflexion moment on the calcaneus and the metatarsophalangeal joints of the toes are extended. The elongation of the PA elevates the medial longitudinal arch and inverts the midfoot and rearfoot via a shift in the calcaneal tendon medial to the axis of rotation of the subtalar joint. Contraction of the triceps surae during weight bearing creates a plantarflexion moment in the rearfoot, tensions the PA, and increases the dorsiflexion moment and ground reaction force and in the midtarsal, cuneonavicular, and tarsometatarsal articulations. An analysis using computer 3-D modeling of forefoot force transmission in the presence of impaired triceps surae strength found that contact area increased in the midfoot and plantar pressures.

Figure 5. The windlass mechanism. The triceps surae forms a coupled relationship with the plantar fascia through the proximal attachment on the calcaneus and action on the rearfoot. Adapted from McKeon PO, Hertel J, Bramble D, Davis I. The foot core system: a new paradigm for understanding intrinsic foot muscle function. Br J Sports Med. 2014. Used with permission of the publisher.
decreased in the forefoot during terminal stance.\textsuperscript{45} The triceps surae also has an important function as a proximal stabilizer of the calcaneus and in intrinsic foot muscle function. This was shown in patients with poliomyelitis who had impaired plantar flexor strength and unopposed intrinsic foot flexor function.\textsuperscript{46} A foot deformity, coined the “calcaneus foot,” was a sequela of triceps surae strength impairment and was characterized by rearfoot dorsiflexion, forefoot plantarflexion, and clawing of the toes.\textsuperscript{46}

**DEEP POSTERIOR COMPARTMENT**

The flexor hallucis longus (FHL) and the flexor digitorum longus (FDL) tendons are innervated by the tibial nerve and traverse from the deep posterior compartment, through the flexor retinaculum, into the plantar aspect of the foot. The FHL is oriented longitudinally along the medial aspect of the foot. The FDL has a more oblique orientation from posteromedial to anterolateral. The FDL tendon is the proximal attachment for the lumbricals and the distal attachment for the quadratus plantae (flexor digitorum accessorius). While inserting distally and causing toe flexion, the FHL and FDL tendons also cross the transverse tarsal and TMT joints. During stance, the long toe flexors have been shown to contract isometrically to support and stabilize the longitudinal arches,\textsuperscript{33,47} provide afferent feedback,\textsuperscript{47} and dissipate force during loading.\textsuperscript{47,48}

The tibialis posterior originates in the deep posterior compartment and courses deep to the flexor retinaculum.\textsuperscript{49} It supports the medial longitudinal arch through its multiple insertions to the navicular tubercle, each tarsal bone, metatarsals two through four, and the flexor hallucis brevis muscle.\textsuperscript{49} During barefoot walking, the tibialis posterior contracts to resist eversion and peroneal contraction and assists in stabilization of the rearfoot during initial contact (IC) and midstance.\textsuperscript{50}

**Intrinsic Control of the Ankle – Foot Complex**

Ten muscles in the plantar foot and two in the dorsal foot provide intrinsic control of the foot (Figure 6). The plantar intrinsic muscles are organized into four layers and are innervated by the medial and lateral plantar nerves, which branch from the tibial nerve. The dorsal intrinsic muscles are innervated by the deep fibular nerve (extensor digitorum brevis) and the lateral plantar nerve (dorsal interossei muscles). During gait, the intrinsic foot muscles function both in open kinetic chain to shape the foot and toes in preparation for contact with the ground and in closed kinetic chain to accommodate the terrain and during force attenuation and transmission.

**FIRST PLANTAR LAYER**

The superficial layer is comprised of the abductor hallucis, flexor digitorum brevis, and the abductor digiti minimi. The abductor hallucis inserts proximally on the medial tubercle of the calcaneus, courses proximal to distal on the medial foot, and inserts distally on the medial base of the first proximal phalanx. The flexor digitorum brevis inserts proximally on the medial tubercle of the calcaneus, courses proximal to distal in the center of the plantar foot, and inserts distally on the middle phalanx of digits 2-5. The abductor digiti minimi inserts proximally on the medial and lateral tubercles of the calcaneus, courses proximal to distal on the lateral foot, and inserts distally on the lateral base of the fifth proximal phalanx. These muscles abduct the hallux, flex toes 2-5, and abduct the little toe when functioning in open kinetic chain, respectfully. During the stance phase of gait, the orientation and location of the abductor hallucis and abductor digiti minimi in relation to the medial and lateral longitudinal arches position these muscles to contribute to stabilization and eccentric control of arch descent during loading. The flexor digitorum brevis is analogous to the flexor digitorum profundus in the upper extremity based on morphology, insertion, and relationship to the long digit flexor. While speculative, it is likely that the flexor digitorum brevis contributes to eccentric control of metatarsophalangeal extension from mid-stance to pre-swing phase of gait.

**SECOND PLANTAR LAYER**

The second layer is comprised of the quadratus plantae (flexor digitorum accessorius) and the lumbrical muscles, all of which attach to and function with the flexor digitorum longus. The quadratus plantae originates on the plantar calcaneus and courses proximal to distal on the flexor digitorum longus tendon. The four lumbrical muscles originate on the flexor digitorum longus tendon proximally and course
distally to insert on the digital extensor expansions. In open kinetic chain, the quadratus plantae assists in long toe flexion and the lumbricals perform metatarsophalangeal flexion and interphalangeal extension. The proximodistal orientation of the quadratus plantae in relationship to the flexor digitorum longus allows for a change in force vectoring of the long toe flexor tendon from a proximomedial-distolateral angle to a more longitudinal vector. During gait, the lumbricals likely contribute to eccentric control of metatarsophalangeal extension while extending the interphalangeal joints during toe-break. It is also plausible that the lumbricals function by pulling the flexor digitorum longus tendons distally when the ankle is plantarflexed to optimize length-tension and prevent active insufficiency during toe flexion.

**THIRD PLANTAR LAYER**

The third plantar layer is comprised of the flexor digiti minimi, the adductor hallucis, and the flexor hallucis brevis. The flexor digiti minimi inserts proximally on the base of the fifth metatarsal and travels distally to insert on the base of the fifth proximal phalanx. The adductor hallucis has two heads, an oblique and transverse head. The oblique head inserts proximally on the base of the second through
fourth metatarsals and traverses distal medial to insert on the base of the first proximal phalanx. The transverse head inserts laterally on the plantar metatarsophalangeal ligaments and travels medially to insert with the oblique head on the base of the first proximal phalanx. The flexor hallucis brevis inserts proximally on the cuboid, lateral cuneiform, and the middle and medial cuneiform by way of the tibialis posterior tendon and travels distally to insert on the base of the first proximal phalanx. In open kinetic chain, these muscles flex the little toe, adduct the hallux, and flex the hallux, respectively. During the stance phase of gait, the flexor hallucis brevis and the flexor digiti minimi likely contribute to eccentric control of toe extension from midstance to pre-swing. The adductor hallucis likely contributes to stabilization of the first ray during forefoot loading in the latter half of stance.

**FOURTH PLANTAR LAYER**

The fourth and deepest plantar layer is comprised of the three plantar interossei. The interossei insert proximally on the medial shafts of metatarsals 3-5 and traverses distally to insert on the bases of the proximal phalanges. These muscles adduct the toes in open kinetic chain and likely provide isometric or eccentric control of toe splay during forefoot loading in pre-swing phase of gait. It has also been speculated that these muscles stabilize the tarsometatarsal joints in conjunction with the dorsal interossei during late stance phase of gait.51

**Dorsal Intrinsic Muscles**

The two intrinsic muscles on the dorsal foot are the extensor digitorum brevis and the four dorsal interossei muscles. The medial head of the extensor digitorum brevis is sometimes treated as a separate muscle, the extensor hallucis brevis. For the purpose of this manuscript, the extensor hallucis brevis will be treated as integral with the extensor digitorum brevis. The extensor digitorum brevis inserts proximally on the calcaneus and courses distally to insert on the tendons of the extensor digitorum longus (toes 2-4) and the base of the first proximal phalanx. The dorsal interossei insert proximally on the shafts of the metatarsals one through five and traverse distally to insert on the proximal phalanges. In open kinetic chain, these muscles abduct and extend toes two through four, respectfully. The dorsal interossei also function with the palmar interossei to stabilize the forefoot in pre-swing phase of gait.51

In the sentinel study performed by Mann and Inman,52 the intrinsic foot muscles were found to work synergistically as a functional unit during gait to provide stabilization of the midfoot, and that greater muscular activity was required to stabilize the foot in individuals who had excessive pronation observed during static standing. More recently, McKeon and colleagues8 described a “foot core” system that is analogous to the lumbopelvic complex and comprised of active, passive, and neural subsystems. The intrinsic muscles play an important direct role in both active and neural subsystems and indirectly to the passive subsystem.8 The flexor digitorum brevis, flexor hallucis brevis, oblique head of the adductor hallucis, and abductor digiti minimi are orientated longitudinally and run perpendicular to the transverse tarsal joint surface, making them prime stabilizers for this articulation and for the longitudinal arch.52 The intrinsic muscles are stretched with deformation of the medial longitudinal arch during loading.25 It is reasonable to assume that the stretch of the musculotendinous sensory organs provide afferent feedback during foot deformation, shaping, and force attenuation. Conversely, concentric contraction of the plantar intrinsic foot muscles produces calcaneal and metatarsal displacement resulting in decreased arch length and increased arch height.25 This alteration of medial longitudinal arch morphology during IFM contraction forms the basis of the short foot exercise, an intervention utilized clinically to strengthen the foot core in the treatment of ankle-foot impairment.8,9 It is thought that the intrinsic muscles, when functioning in conjunction with active extrinsic muscle contraction and the PA, contribute to buttressing of the foot during force attenuation and transmission.25 Electromyographic analysis of muscle function during gait demonstrated coordinated activation of extrinsic and intrinsic toe flexors activity in the mid to terminal stance, sequentially followed by extrinsic and intrinsic toe extension activity in terminal stance to early swing phase.53 The coordinated extrinsic and intrinsic activity observed in this study provides further evidence of the role of the intrinsic foot muscles during force attenuation and transmission in gait.
MULTISEGMENTED ANKLE-FOOT COMPLEX KINEMATICS DURING GAIT

Rearfoot
When referenced to the shank, the rearfoot is in a neutral sagittal, pronated, and adducted position at IC and transitions to a plantarflexed, pronated, and adducted position during early stance phase. During midstance, the rearfoot is dorsiflexed, pronated, and abducted until 70% of stance when the rearfoot becomes plantarflexed and supinated at 90% of stance. Total magnitude of rearfoot excursion is 10-15° in all three planes.

Midfoot
When referenced to the rearfoot, the midfoot is supinated at IC and moves to a dorsiflexed, pronated, and adducted position post IC. From 15% to 80% of stance, the midfoot is maintained in neutral in the sagittal plane, pronation, and abduction. The midfoot is plantarflexed, supinated, and continues into abduction in the last 20% of stance. Total magnitude of midfoot range of motion is 5-8° in all three planes.

Mann described a coupling of the rearfoot and forefoot by way of the midfoot during mid to terminal stance when shank external rotation and rearfoot supination causes the longitudinal axes of talonavicular and calcaneocuboid to diverge, creating a more rigid lever for push off. Position and control of the medial longitudinal arch has been found to be contributory to rearfoot to forefoot coupling. The transverse tarsal joint has been described to have two different modes of function which are dependent on mechanical demands of walking and running at various speeds, with different loads, on various surfaces, and whether the cuboid is locked by the fibularis longus. The individual axes of the transverse tarsal joint have a corresponding parallel axis at the metatarsophalangeal joints. During pushoff, the lever arm of the foot changes dependent on which axis the foot is functioning about. In “low gear” dominated activity such as uphill walking with a load or the first steps of a sprint, pushoff occurs with the rearfoot adducted and plantarflexed while cuboid rotation occurs about the oblique axis in the transverse tarsal joint. Plantar pressure progression is shifted to the lateral forefoot and results in a functionally shortened lever arm as toe break occurs about the axis formed by the lesser metatarsophalangeal joints. With the foot adducted, ground contact during low gear push off is transmitted from the lateral heel to the lateral aspect of the first metatarsal head. During pushoff in “high gear” dominated activity such as fast level walking and sprinting, the plantar aponeurosis (PA) is tensioned and the fibularis longus compresses and everts the calcaneocuboid joint to a closed pack position, mechanically coupling the rearfoot to forefoot to prevent midtarsal break. With the foot neutral in the transverse plane, force is transmitted through the medial border of the first metatarsal head and hallux as push off occurs about the transverse metatarsophalangeal axis. The ability of the foot to pushoff about two axes may contribute to balance and negotiation of uneven ground by allowing for alteration of forward progression in response to perturbation. More recent kinematic studies using multisegmented foot models have found that individual foot segments remain compliant during ambulation. During gait, forefoot inversion and eversion motion remains relatively uncoupled and independent from frontal plane motion in the rearfoot. However, a coupling relationship has been found between rearfoot pronation and forefoot dorsiflexion in the first half of stance and forefoot plantarflexion and rearfoot supination in the latter half of stance, with vector coded mean excursions of 41-43°. Additionally, there is a high degree of coupling (mean excursions 24-32°) between rearfoot frontal plane motion and forefoot transverse motion during walking in the first 20% of stance and again from midstance to preswing.

Lateral Forefoot
The lateral forefoot is plantarflexed, slightly supinated, and abducted at IC, followed by plantarflexion, pronation, and abduction post IC relative to the midfoot. Lateral forefoot pronation occurs in the latter half of IC until the forefoot contacts the ground. The metatarsal arch deforms and widens in a metatarsal forming phase, with loading incurred in the lateral aspect of the forefoot. From 15% to 70% of stance, the lateral forefoot remains dorsiflexed while slightly supinated. Force distribution across the forefoot becomes more uniform during mid stance as the medial forefoot is progressively...
loaded. From 70% to 90% of stance, the lateral forefoot supinates and the metatarsal arch increases to its maximal height. Despite direct loading of the metatarsal arch in the last 25% of stance, forefoot width decreases and tightens as the foot prepares to pushoff. It is speculated that the paradoxical increase in metatarsal arch height during maximal loading is resultant from the engagement of connective tissues (such as the PA) and contractile support mechanisms of the arch. Total lateral forefoot excursion is approximately 10° in each plane.

There are two axes of rotation formed by the metatarsal heads that parallel the axes of transverse tarsal joint. The axis that the body employs during propulsion is dependent on requirements of force generation or balance requirements and is dictated by midfoot function. The three major functions for the metatarsal heads include adaptation to changing gravitational axes in balance, transfer of weight from rearfoot to the forefoot prior to terminal stance, and function as a lever for propulsion in terminal stance. Of these functions, the role of the metatarsal heads in providing fine adjusting movements of the foot has been described as the most important in maintaining balance during standing and walking. Impaired ability of the metatarsals to perform fine adjusting movements would shift the burden of balance to the subtalar joint and result in maximal impairment, a scenario likely to be observed clinically when tarsometatarsal hypomobility or impaired neuromotor function is a consequence post injury. During ambulation that occurs at lower velocity, is balance intensive, involves negotiating inclines, or includes carrying loads, the foot is adducted so pushoff may occur about the oblique axis that transects metatarsal heads 2-5 in the lateral forefoot.

**First Ray & Hallux (Medial Forefoot)**

In relation to the midfoot, the first ray dorsiflexes, everts, and adducts at IC, abducts during early stance phase post IC, and remains dorsiflexed and everted until 75% of stance. During the last quarter of stance, the first ray dorsiflexes, inverts, and adducts. Total excursion in the first ray is 6-16° in all planes. When referenced to the first ray, the hallux is dorsiflexed, supinated, and abducted at IC followed by slight pronation at 15% of stance that persists until the last quarter of stance. The hallux dorsiflexes and abducts during the last 25% of stance. Total hallux excursion is 55°, 50°, and 18° in the sagittal, transverse, and frontal planes, respectively.

During higher velocity ambulation, running, and sprinting, the foot is neutral in the transverse plane so that pushoff may occur about the transverse metatarsal axis. The transverse axis transects the metatarsal heads of digits 1 and 2 and parallels the transverse axis of the midtarsal joint. When the forefoot is coupled to the rearfoot and the transverse metatarsal axis employed during pushoff, the moment arm is functionally lengthened by 20%.

**CONCLUSIONS**

In summary, the multiple segments that comprise the ankle-foot complex function synergistically to transmit and attenuate force during propulsion, accommodate and conform with uneven terrain, and provide important afferent information and motor adjustment to maintain balance during standing and ambulation. The interplay of segmental joint mobility, sensorimotor function, and movement and stabilization provided by the extrinsic and intrinsic musculature is required to coordinate and execute the complex kinematics observed in the ankle-foot complex during propulsion. In part two of this clinical commentary, alterations in kinematics secondary to joint and neuromotor impairment incurred following lateral ankle sprain and in chronic ankle instability will be discussed. Clinical assessment and treatment techniques for the ankle-foot complex will also be addressed.

**REFERENCES**


Dear Editor

We would like to congratulate Dr. Augustsson for his publication in IJSPT in August 2016, on his new clinical test for hip strength. After reading the article, we would like to make several comments pertinent to the interpretation of his results.

The ‘clam’ movement used in this assessment is a popular exercise for hip rehabilitation. The movement tested should not be considered pure hip external rotation; rather, the ‘clam’ exercise movement used in the study is a compound movement including hip external rotation, abduction, and extension to some degree. We’re not aware of any specific measurement of femoral external rotation range of motion during this movement; however, we assume it’s less than pure hip external rotation at 90 degrees of hip flexion, which is the traditional testing position of hip external rotation strength.

Most importantly, however, the amount range of motion of each individual, which didn't appear to be measured or controlled, limits the validity of this measurement. This study did not measure the strength of an individual; rather, it measured the linear distance of excursion in a compound movement that was then interpolated for ‘strength.’ The individual’s flexibility likely had a significant impact on the outcome measure. This would be a major factor in patient populations.

The author neglected to provide detailed data or regression lines of the ‘load-versus-displacement plot’ that was used to ‘interpolate’ the strength values utilized in this study. Furthermore, the regression equation mentioned in the paper was not provided. It’s critical that the author provides the regression equation, as it was the primary source of data used in the analysis. Doing so would also provide others in the field the ability to reproduce this study in other populations for reliability and validity of patient populations.

The internal and external validity of the findings are suspect due to a number of statistical choices the authors committed. The author did not provide any information to support the power of the statistical tests they employed in the analysis, including the effect size in order to address clinical relevance of the findings. The authors did not adequately justify employing an ICC rather than a Pearson's r when assessing consistency of the measure over two data collection points. Finally, the authors did not address the potential for an artificially inflated type I error rate in the study as the result of conducting multiple tests.

Dr. Augustsson did a good job in noting that the reliability of the measurement only applies to healthy individuals with assumed ‘normal’ hip strength. Reliability in a variety of patient populations should be assessed before recommending its use as an indicator of hip external rotation strength in a clinical population. We believe the author the author has prematurely recommended that this test may assess “hip strength in the etiology of ACL injuries” or before return to sport.
While the author accurately described the need to validate this test, his argument against doing so without the presence of a ‘gold standard’ isotonic test should not dismiss the ability to validate this test. Isokinetic and isometric tests of hip external rotation strength remain the gold standard in assessing hip strength and should, therefore, be appropriate to validate the strength of hip external rotation. Furthermore, the author referred to EMG studies of the clam exercise that “validates this test of hip strength in that it actually measures the strength of hip muscles.” The author cannot draw this conclusion because no measurement of hip strength was made in these EMG studies. Without validation, the Augustsson Strength Test is simply a repeatable measurement of a subject's ability to perform the clam exercise against resistance.

We encourage further investigation of this novel clinically based strength test, particularly in patient populations.

Respectfully,

Phil Page, PT, PhD, ATC, CSCS, FASM
Robert Topp, PhD, RN
REPLY TO THE LETTER TO THE EDITOR REGARDING MY ARTICLE


I would like to thank Doctor Page and Doctor Topp for their concern in this paper. I have read their comments with interest.

To begin with, the “Clam” movement (the position in which the subjects were tested) is dominantly an external rotation movement. As the feet stays together (as shown in Figure 3 in the paper) and as the hips and feet are aligned (as shown in Figure 2) the movement takes place in the transverse anatomical plane where the movement axis passes vertically from superior to inferior (hips and feet). Had the feet not stayed together such as when performing, for example, the seated abduction machine exercise then the movement had involved abduction of the hip. The movement of the test does not involve hip extension. Moreover, it would be possible to have the test device assess hip abduction strength, using the same side lying position, simply by letting the subjects extend their hips and knee fully and then have them abduct the upper leg.

It is correct that if the resistance provided from test device is not sufficient then at some point a subject’s hip range of motion (ROM) rather than hip muscle strength will limit any further distance achieved by the subject. This is a valid point that could have been mentioned more clearly in the article. It is mentioned in the article, however, that the rubber band, doubled and of a heavy-duty type, was only moderately stretched during testing (see Figure 3, end position) which meant that full ROM was not reached for any of the subjects in the study. If a very powerful individual is to be tested, however, then an even heavier, larger sized elastic resistance band must be used in order to avoid that hip ROM rather than muscle strength is the limiting factor. The issue of hip ROM is also important, as noted by Doctor Page and Doctor Topp, when testing patient populations. Prior to testing, the ROM of each patient for the test movement should be investigated to make sure that hip flexibility is not the limiting factor during testing. Even a patient with very limited hip ROM (or even the strongest athlete), however, can be tested for muscle strength just as long as the resistance provided from test device is adjusted to avoid full ROM.

When it comes to the conversion of elastic resistance band displacement to force, the procedure was clearly stated in the article. The increase in length corresponded to a progressive increase in the elastic resistance which enabled a plot to be generated. The plot was then used to interpolate results for any given test value. No regression equation was necessary to use when generating the plot. As every elastic resistance band most probably has unique material properties the load-versus-displacement plot will likely differ. It is therefore important (especially in research) to generate a specific plot for a particular resistance band.

The main purpose of the article was to develop a dynamic clinical test of hip strength. A secondary aim was to investigate gender differences in hip strength using this test. No power calculations were performed when it came to the question of gender differences in hip strength. The subjects (34 women and 19 men) were however probably sufficiently many to answer the question on gender differences in hip strength. Effects size is normally calculated to determine the magnitude of treatment effects and was thus not used in the present study. Doctor Page and Doctor Topp mention “the potential for an artificially inflated type I error rate in the study as the result of conducting multiple t tests”. Relatively few t tests (four), however, were performed in this study so the risk of mass significance and thus the incorrect rejection of a true null hypothesis (a “false positive”) was therefore probably rather low. Lastly, the intra class correlation coefficient (ICC) is the gold standard test when it comes to measures of reliability in research and was therefore preferred over Pearson’s r in the present study.
The Pearson r was often used in the past to quantify reliability, but the use of the Pearson r is typically discouraged for assessing test-retest reliability. The primary, although not exclusive, weakness of the Pearson r is that it cannot detect systematic error (Weir 2005).

It is clearly stated in the article that the generalizability of the study is limited to healthy, active young adults. For ACL injured or reconstructed people that has no history of hip disorder, however, the test probably can be used to assess hip muscle strength quite well since it does not involve any movement across the knee. In the Discussion section of the article the use of this test is not “recommended” but rather discussed as a test that could be used as a complement to the common strength tests performed before return to sport after ACL reconstruction.

When it comes to the question of validity: It is stated in the article that “when it comes to clinical tests of hip strength, no particular type of test could be considered as the gold standard measure.” Isokinetic tests are not clinical tests. And isometric tests using isokinetic dynamometry are not clinical tests either. Of the existing clinical tests no one particular could be considered the gold standard measure. It is agreed, however, that a comparison with an isokinetic test of hip external rotation or an isometric test using isokinetic dynamometry would be interesting from a validation standpoint.

Lastly, in the study by Selkowitz et al (2013) a measurement of hip strength (maximum voluntary isometric contraction, MVIC) was indeed made as the subjects, lying in the “Clam” position exerted the MVIC against a strap positioned across the distal thigh, during which time the EMG signal was collected.

REFERENCES


Sincerely,

Jesper Augustsson, PhD, PT
LEARN FROM THE BEST ON YOUR SCHEDULE WITH SPTS HOME STUDY COURSES

Earning CEUs with a busy career can be a challenge. And you don’t want to sacrifice quality for speed! The SPTS Home Study Courses are the perfect answer. Created by the best in the sports physical therapy business, you can obtain quality education while living your life.

Offered in a convenient downloadable format, each Home Study Course (HSC) consists of five or more chapters, along with a final examination.

To receive continuing education credit, HSC participants complete the final examination online through the SPTS Learning Management System. Certification of successful completion and award of CEUs are downloadable immediately.

As always, SPTS members receive deep discounts on Home Study Courses!

Get more information online at www.spts.org/education/study-courses/courses. Start learning and earning today!

AVAILABLE COURSES
• The Sports Certified Specialist Exam Preparatory Course
• Management of the Golfing Athlete throughout the Lifespan
• Imaging for Athletic Injuries and Conditions
• The Knee: Adolescence through the Active Adult
• The Female Athlete
• Current Concepts in Shoulder Rehabilitation
• Running
• Pediatric and Adolescent Sports Medicine
• Current Concepts in Evaluation, Examination and Rehabilitation of the Knee
• Rehabilitation of the Hip
• Rehabilitation of the Articular Cartilage of the Knee
• The Spine in Sports
• Injury Prevention in Sports Medicine
• Rehabilitation of the Aging Athlete

WWW.SPTS.ORG | 877.732.5009 FIND US ON FACEBOOK AND TWITTER
WebExercises® Features:

- Email exercise programs
- Patient mobile app
- Real time patient feedback
- PC, Mac, and Mobile Devices
- Expanded 3,000+ exercise library
- Print exercise handouts with company logo
- Add your own exercises

- Calendar to keep patients on track
- Customize exercise text instructions
- Create your own template protocols
- Posture Screen Mobile sync
- 3D Condition Library Module Available
- Volume License available for group practices
TheraBand® is breaking ground with the new non-latex®, patented CLX-Consecutive Loops, delivering versatility and ease of use that may increase exercise compliance to improve patient outcomes.

“The CLX is the next big thing in sports and orthopedic rehab...”

- 4 products in one – band, loop, tubing with handles & anchor
- Durable non-latex construction
- Easy Grip Loops™ provide multiple unique grip options

FREE App Included

Available in bulk roll and pre-cuts. Follows the authentic TheraBand Trusted Progression

Yellow 3.0 Lbs  Red 3.7 Lbs  Green 4.6 Lbs  Blue 5.8 Lbs  Black 7.3 Lbs  Silver 10.2 Lbs  Gold 14.2 Lbs

Represents typical values at 100% elongation.

Kevin E. Wilk, PT, DPT
Champion Sports Medicine
A Physiotherapy Associates Facility
Birmingham, AL

* not made with natural rubber latex

TheraBand®, the Color Pyramid Design™ and Associated Colors™, and CLX™ trademarks are property of Performance Health and/or its subsidiaries and may be registered in the United States and other countries. Unauthorized use is strictly prohibited. ©2015 Performance Health and Wellness Holdings, All rights reserved.