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When I think of the human movement system, the words poetry in motion come to mind: the mixture of fluidity and coordination of motion, enhanced by power, speed, and precision. What an awesome and amazing combination!

The definition of poetry in motion:

“Someone or something that moves in a way that is very graceful or beautiful.”

Sports provides a multitude of examples of beauty, intensity control, and precision during movement:

The combination of power and grace during gymnastics (Figure 1) and figure skating performances...

The propulsion of the body through space in diving, pole vault (Figure 2), long jump or high jump...

The reception of a perfectly thrown spiral; fielding a seemingly impossible infield shot, and turning it into a double play...

The end of a race “kick” by a runner (Figure 3)...

Grace and controlled power demonstrated in many forms of the martial arts....

Examples abound. Each reader will summon mental images of what “poetry in motion” means to them and which athletes exemplify this standard of movement. Honestly, I have seldom thought about sport in terms of words or poetry, but who hasn't thought of many parts of sport as art? As sports physical therapists we see poetry in motion or artistry every day, in the movements of our athletes. When the synchrony of body movements is altered, we seek to restore it along a continuum from basic (or fundamental) to extremely high levels of movement.

The movement system has been centrally described and suggested by the American Physical Therapy Association (APTA) as the foundation for the practice of physical therapy. I was an invited participant in the Movement System Summit in 2016 where around 100 physical therapists gathered to discuss many aspects of the movement system (Figure 4). This opportunity provided me with an ongoing sense of investment in and curiosity about the...
movement system and how it could affect physical therapist practice from education to research and clinical practice.

In 2019 the official definition of the human movement system was revised to:

“The integration of body systems that generate and maintain movement at all levels of bodily function.”

I believe that many practicing sports physical therapists have been movement system practitioners for our entire careers, linking functional performance (or lack thereof!) to deficits in the various systems comprising the human movement system. I see the transition to movement system language and thinking as a natural transition for the sports physical therapist from “function” or “functional movement” to a systems-based approach that intentionally encompasses all aspects of the human movement system. Authors of papers in this special issue have endeavored to articulate the links between systems and how these links may impact many aspects of physical therapist practice. It is not a big leap. I have always said that the best sports physical therapists are not only experts in musculoskeletal care, but have in-depth working expertise in the equally important contributory systems: endocrine, neuromuscular, integumentary, and cardiovascular and pulmonary. Without each of the systems, where would our athletes be?

Movement is what we are about, movement analysis it is what we do, in the context of primary prevention, examination, intervention(s), and return to sport decisions. Movement analysis may be visual, use video, or even 3D motion capture, but we commonly tie progress (or lack thereof), changes in intervention(s), and decisions regarding return to play to analysis of the entire movement system. As physical therapists, we are the profession best suited to examine, analyze, and address deficits in movement using all of our senses.1 Visual task analysis (clinical observation),4 feeling movement (tactile analysis),4 and auditory assessment4 are linked to contribute to the appraisal of the overall function of the movement system. The APTA’s proposed movement system screening tool developed in 2018 is intended for use by physical therapists in all areas of practice. This screening tool encompasses performance of several common movement-based tasks and serves to assist the therapist in identifying additional tests and measures to be used during examination and denote symptom provocation, is available as an appendix to Dr. Sahrmann’s paper.

In Sebleski et al,4 I suggested a nomenclature change from “home exercise program (HEP)” to “movement optimization program (MOP),” and that this change in words could better encapsulate the array of interventions that are chosen by a physical therapist that are focused on enhancing movement. A MOP may be more than just “exercise,” and may include many other strategies to enhance movement. Will this label for what we do with patients change? Perhaps other parts of our language will transform as collective understanding of the movement system changes, and we will need to adapt…who knows?

Where are we headed? For many of us it will feel much like it is business as usual. But for those who have not considered all systems contributing to every aspect of human movement, it may be a paradigm shift. The ongoing prioritization and contributions of the APTA in the promotion and adoption of the movement system as a central organizing principle for the profession are currently undefined. I certainly hope that future endeavors include the development of some common movement system diagnoses for all areas of practice which could influence the standardization of practice. My co-authors and I believe that the core documents which guide the profession should continue to evolve to adapt to movement system language, thinking, and expanded clinical reasoning related to movement.4 The Movement System

Figure 4: Movement System Summit attendees, Dr. Michael Voight and Dr. Barb Hoogenboom, editors of the International Journal of Sports Physical Therapy, in Alexandria, Virginia, in 2016.
Special Issue presented by *IJSPT* is a conscious attempt by the editorial staff to illuminate the movement system in the practice of sports physical therapy, and keep the discussion going. I am grateful to each of our contributors for their work regarding movement system concepts, illustration of the use of terminology, and conceptual linking within/among systems, all of which contribute to the evolution of the practice of physical therapy, especially sports physical therapy.

**References:**


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Grace and controlled power demonstrated in many forms of the martial arts....

Examples abound. Each reader will summon mental images of what “poetry in motion” means to them and which athletes exemplify this standard of movement. Honestly, I have seldom thought about sport in terms of words or poetry, but who hasn’t thought of many parts of sport as art? As sports physical therapists we see poetry in motion or artistry every day, in the movements of our athletes. When the synchrony of body movements is altered, we seek to restore it along a continuum from basic (or fundamental) to extremely high levels of movement.

The movement system has been centrally described and suggested by the American Physical Therapy Association (APTA) as the foundation for the practice of physical therapy. I was an invited participant in the Movement System Summit in 2016 where around 100 physical therapists gathered to discuss many aspects of the movement system (Figure 4). This opportunity provided me with an ongoing sense of investment in and curiosity about the
movement system and how it could affect physical therapist practice from education to research and clinical practice.

In 2019 the official definition of the human movement system was revised to:

“The integration of body systems that generate and maintain movement at all levels of bodily function.”

I believe that many practicing sports physical therapists have been movement system practitioners for our entire careers, linking functional performance (or lack thereof!) to deficits in the various systems comprising the human movement system. I see the transition to movement system language and thinking as a natural transition for the sports physical therapist from "function" or "functional movement" to a systems-based approach that intentionally encompasses all aspects of the human movement system. Authors of papers in this special issue have endeavored to articulate the links between systems and how these links may impact many aspects of physical therapist practice. It is not a big leap. I have always said that the best sports physical therapists are not only experts in musculoskeletal care, but have in-depth working expertise in the equally important contributory systems: endocrine, neuromuscular, integumentary, and cardiovascular and pulmonary. Without each of the systems, where would our athletes be?

Movement is what we are about, movement analysis it is what we do, in the context of primary prevention, examination, intervention(s), and return to sport decisions. Movement analysis may be visual, use video, or even 3D motion capture, but we commonly tie progress (or lack thereof), changes in intervention(s), and decisions regarding return to play to analysis of the entire movement system. As physical therapists, we are the profession best suited to examine, analyze, and address deficits in movement using all of our senses, visual task analysis (clinical observation), and auditory assessment are linked to contribute to the appraisal of the overall function of the movement system. The APTA's proposed movement system screening tool developed in 2018 is intended for use by physical therapists in all areas of practice. This screening tool encompasses performance of several common movement-based tasks and serves to assist the therapist in identifying additional tests and measures to be used during examination and denote symptom provocation, is available as an appendix to Dr. Sahrmann's paper.

In Sebleski et al, I suggested a nomenclature change from “home exercise program (HEP)” to “movement optimization program (MOP),” and that this change in words could better encapsulate the array of interventions that are chosen by a physical therapist that are focused on enhancing movement. A MOP may be more than just “exercise,” and may include many other strategies to enhance movement. Will this label for what we do with patients change? Perhaps other parts of our language will transform as collective understanding of the movement system changes, and we will need to adapt...who knows?

Where are we headed? For many of us it will feel much like it is business as usual. But for those who have not considered all systems contributing to every aspect of human movement, it may be a paradigm shift. The ongoing prioritization and contributions of the APTA in the promotion and adoption of the movement system as a central organizing principle for the profession are currently undefined. I certainly hope that future endeavors include the development of some common movement system diagnoses for all areas of practice which could influence the standardization of practice. My co-authors and I believe that the core documents which guide the profession should continue to evolve to adapt to movement system language, thinking, and expanded clinical reasoning related to movement. The Movement System

Figure 4: Movement System Summit attendees, Dr. Michael Voight and Dr. Barb Hoogenboom, editors of the International Journal of Sports Physical Therapy, in Alexandria, Virginia, in 2016.
Special Issue presented by IJSPT is a conscious attempt by the editorial staff to illuminate the movement system in the practice of sports physical therapy, and keep the discussion going. I am grateful to each of our contributors for their work regarding movement system concepts, illustration of the use of terminology, and conceptual linking within/among systems, all of which contribute to the evolution of the practice of physical therapy, especially sports physical therapy.

References:


Invited Clinical Commentary

Doctors of the Movement System – Identity by Choice or Therapists Providing Treatment – Identity by Default

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THE CHRONIC NATURE OF HEALTH CONDITIONS AND THE IMPLICATIONS FOR PHYSICAL THERAPY

Two major developments in the understanding of the nature of health conditions should position physical therapy as a growth profession. One understanding is recognition that many, if not most, health conditions are chronic in nature. Conditions such as diabetes, cardiovascular disease and even some forms of cancer begin insidiously many years before the onset of symptoms and then continue throughout life. Lack of physical activity contributes to these conditions. These systemic conditions as well as musculoskeletal problems have their roots in lifestyle. The second development is the recognition of the importance of movement. As would be expected increased activity or exercise, is an effective intervention for health conditions ranging from cancer to dementia. The physical therapist should be considered as the health professional with the most comprehensive expertise in physical activity. Optimizing physical activity for health is more than just participating in a form of exercise. Physical activity should be focused on optimizing the components of movement, including the musculoskeletal and neuromuscular systems (including alignment and neuromuscular activation patterns) as well as the cardiovascular, pulmonary, and metabolic systems. In other words, optimizing the performance of the movement system. Physical activity including exercise should contribute to prevention or minimization of musculoskeletal problems because the recommended programs incorporate knowledge of structural variations, optimal movement patterns, and appropriate progression. That knowledge should be applied to analysis of specific activities such as running, biking, dance, and various sports.

IS THE PHYSICAL THERAPIST CONSIDERED AS AN EXPERT IN MOVEMENT AND ALL THE COMPONENTS OF EXERCISE?

Currently, the physical therapist is recognized for expertise in the treatment of the patient with a neurological disorder or post-surgery. The profession has not demonstrated its role in physical activity in individuals without an underlying medical or pain condition. The profession has not conveyed the complexity of optimizing physical activity and how individual characteristics including structural variations need to be considered. Embracing the movement system to promote the identity of physical therapy would be a step in demonstrating such expertise. Changing the long-established pattern of a limited number of treatments for an episode of care, for what was considered an acute problem, to an expanded role that includes prevention, program development, and on-going monitoring is challenging but consistent with the chronic nature of health conditions. Such change would substantially increase the demand for physical therapists. The challenges to the current practice and business models indicate that change from the established pattern is not only the right thing but also the necessary thing to do.

One indicator of these challenges is that, instead of strong professional growth, a report from an American Physical Therapy Association (APTA) workforce analysis indicated that there may be a 25,000 oversupply of therapists by 2030. Another indicator is that the profession is being frequently challenged by actions to reduce reimbursement. There are other factors indicating the profession must clarify its identity for long-term viability. Demands for increased productivity is enough of a concern to spur House of Delegates action. In addition, the requirement of doctoral level education has not resulted in recognition commensurate with the title, or of the implied movement or exercise expertise, or a substantial increase in direct access patients/clients. Unwarranted variability in practice compromises the demonstration of value for physical therapy interventions. Why hasn’t the recognition or identity of the profession progressed to take advantage of the new understanding of health conditions and the importance of movement? Have we clarified how the title of doctor is appropriate and how we are movement experts? Transforming our identity from therapists implementing treatment to doctors of an important body system, the movement system, would contribute to recognition and growth.

ACTIONS THAT HAVE BEEN TAKEN AND ACTIONS THAT NEED TO BE TAKEN

In 2013, eight years ago, the APTA initiated activities that could clarify and address the challenges to expanded recognition. These activities, 1) an outward looking vision statement, 2) a movement system identity, 3) a movement screening exam, and 4) development of specific movement
related diagnoses, were to build on the many progressive actions that have taken place since 1979 and that were highlighted in Vision 2020. In 1979 the APTA required the entry professional degree to be beyond the baccalaureate level. Ultimately in 2018, 39 years later, the clinical doctorate became the required educational degree. Many, APTA documents refer to physical therapists being doctors, diagnosticians, movement experts, providing direct access, and using evidence-based practice. But these roles of physical therapists have limited recognition because the expected details and abilities associated with these roles have not been defined.

For example, although most physical therapists are doctors they do not demonstrate characteristics of this level of autonomous practitioners. Doctors are recognized for their expertise in a body system and for making a diagnosis of conditions affecting that system. Though numerous APTA documents state that physical therapists are diagnosticians, there is not one document that provides any examples of the diagnoses that physical therapists make. Without demonstrated expertise in a body system, diagnostic ability, or role as an autonomous practitioner, the implementation of direct access is limited. Currently expertise is based on providing treatment for a condition that another health care practitioner diagnoses. The 2013 vision statement that physical therapy will "transform society by optimizing movement to enhance the human experience" requires recognition of movement expertise. The profession has not officially defined what constitutes movement expertise nor how we can or do optimize movement or even what is meant by optimizing movement.

The insightful members of the APTA committee charged to develop the 2013 Vision statement addressed implementation by designating eight guiding principles accompanying the vision statement. Recognizing the long-standing concerns of professional identity, the first guiding principle is that the movement system is the identity of physical therapy. The importance of this identity is reflected in the accompanying statement:

"Physical therapy will define and promote the movement system as the foundation for optimizing movement. The recognition and validation of the movement system is essential to fully understand the physiological function and potential of the human body."

These are two powerful statements that clearly make the point that professional recognition requires promotion of expertise in the movement system. Our professional expertise should include understanding 1) how movement causes or exacerbates problems, especially musculoskeletal (kinesiopathology), 2) how movement becomes dysfunctional with pathology in component systems (pathokinesiology), 3) how the result is compromised function, health, and/or quality of life, and 4) how movement in the form of activity or exercise is a powerful prevention or moderator of disease. The profession needs to clarify that therapists not only have expertise in dose and type of exercise during rehabilitation but also in prevention and reduction of injury resulting from exercise and activity in individuals without an identified problem.

Recognition and implementation of the profession’s role in healthcare should be achieved in the same way as other health professions have achieved recognition by demonstrating expertise in a body system and using recognized labels for potential or actual diagnoses. Doctors are consulted for a diagnosis or a potential problem, that conveys to the patient and other health professionals, knowledge of dysfunctions of a body system. The diagnosis is also the guide to treatment. The question is whether the profession can take 39 years to implement the actions required for recognition of doctoral level education and practice.

IMPLEMENTATION OF THE MOVEMENT SYSTEM IDENTITY

INITIAL STEPS

In 2013 after acceptance of the vision statement and guidelines, a Board of Directors Work Group was appointment to develop a definition of the Movement System and a Plan of Implementation. The eight members including three individuals from the APTA board of directors, were educators, practitioners, and researchers. A white paper was produced and published in 2015 on the APTA website that included the following definition and statements of physical therapists’ role in the movement system:

“The human movement system (HMS) comprises the anatomic structures and physiologic functions that interact to move the body or its component parts.

PHYSICAL THERAPIST PRACTICE AND THE MOVEMENT SYSTEM

Human movement is a complex behavior within a specific context.

Physical therapists:

- Provide a unique perspective on purposeful, precise, and efficient movement across the lifespan
- Based upon the synthesis of their distinctive knowledge of the movement system and expertise in mobility and locomotion.
- Examine and evaluate the movement system (including diagnosis and prognosis)
- Provide a customized and integrated plan of care
- To achieve the individual’s goal directed outcomes.
- Maximize an individual's ability to engage with and respond to their environment
- Using movement related interventions to optimize functional capacity and performance.

By further defining and articulating PT’s unique role in diagnosing and managing both risk of and intervention for movement system disorders:

- We professionally advance toward standardizing our management methods to reduce unwarranted variations in practice and
- Subsequently enhance our ability to achieve consistent positive outcomes for specific diagnoses and
- Enhance the value of the services we provide.
A DETAILED PLAN FOR ACHIEVING THESE GOALS WAS ALSO DEVELOPED.

The white paper also described 1) the basic requirements for a human movement system practitioner, 2) how the movement system identity can impact practice and education, and 3) implications for research. The impact of identity on practice was stated as: "A movement system practitioner, the PT has the expertise to examine, diagnose, and treat all elements of this system to produce a meaningful change in an individual’s movement behavior and physical function. The PT uses his or her integrative knowledge to establish a plan of care to maximize physical performance of people of all ages, pathologies, or levels of physical function."

The paper further articulates the relevance of the human movement system (HMS) to society and the profession by stating that "...promotion of the physical therapists’ expertise in diagnosing and treating movement impairments will have profound impact on the health of the public" by:

1. Promoting a more active population,
2. Returning patients/clients to participation in life, and
3. Reducing the consumption of unnecessary, high-cost medical procedures.

To make this a reality, the profession must develop a common language to describe our diagnostic process and our management of the HMS. A major impact of a common approach to detailing the HMS is that communities internal and external to the profession will communicate via a common language that accounts for the complexity of optimal movement.

These are insightful and powerful statements that make the case for why promotion of the HMS is important to the recognition and growth of the profession. Unfortunately, the limited distribution and implementation of the recommendations have not had the impact that is necessary for recognition of the HMS and thus have not successfully expanded the role of the profession.

Another important action reinforced the recommendations of the work group. In 2015 the House of Delegates adopted the motion, "Resolved, [the] APTA endorses the development of diagnostic labels and/or classification systems that reflect and contribute to the physical therapists’ ability to properly and effectively manage disorders of the movement system."16

After completion of their charges by the work group, a movement system task force was appointed to further develop and implement the recommendations. The nine members included two individuals from the Board of Directors. These members were also educators and practitioners. One of the actions recommended by the task force was to conduct a Movement System Summit. One hundred individuals were invited to participate in the summit including a representative from all of the academies and sections. The major goals of the summit, held in 2016, were to discuss 1) what is our understanding of the movement system, 2) what essential components should be included in our examination, and 3) what is a movement system diagnosis?

THE HUMAN MOVEMENT SYSTEM

A graphic depicting the major systems composing the movement system was developed. Though other physiological systems can affect movement, these systems were considered to have the major effects on movement.

A revised definition of the movement system was adopted by the House of Delegates in 2019.10

The official definition is “The integration of body systems that generate and maintain movement at all levels of bodily function.”

MOVEMENT SCREENING EXAM

There was consistent agreement at the summit that assessment of basic body movements and mobility tasks should comprise the examination across settings and practice areas of physical therapy. The purpose of this screen is to be a tool designed to detect movement impairments observed during functional task/activities that will help therapists decide which additional tests and measures to include in the patient examination.” Subsequently meetings with representatives of the Academies and Sections of the APTA were held to further develop and implement the screening examination. The content of the screening examination was considered complete enough to develop a form and general instructions that could be distributed for piloted use. A form with instructions has been appended to this commentary (Appendix A). This screen can provide some commonality to a basic physical therapy assessment that would inform other health care practitioners of our expertise as well as baseline information about the patient. Consistent intake information would convey to others how physical therapists assess the major aspects of movement performance. Additional guidelines regarding decisions related to what is considered impaired depending upon the complaint and severity of the patient’s condition would be useful. In other words, impaired performance of a patient with a muscu-
loskeletal problem would likely be more subtle than the impairment of a patient with a neurological disorder.

MOVEMENT SYSTEM DIAGNOSES

In 2017, the APTA Board of Directors adopted a set of criteria to be used by any stakeholder groups developing diagnostic systems/labels that had been discussed and recommended at the summit. The recommended criteria are:

1. Use recognized movement-related terms to describe the condition or syndrome of the movement system.
2. Include, if necessary, the name of the pathology, disease, disorder, anatomical or physiological terms, and stage of recovery associated with the movement diagnosis.
3. Be as succinct and direct as possible to improve clinical usefulness.
4. Strive for movement system diagnoses that span all populations, health conditions, and the lifespan. Whenever possible, use similar movement-related terms to describe similar movements, regardless of pathology or other characteristics of the patient or client.

At a subsequent meeting with representatives of the academies and sections designed to further identify criteria for developing diagnoses, the decision was made to solicit diagnoses from the membership and a form for that purpose was developed (Appendix A). Ninety suggested diagnoses were received from the membership. There was also a recommendation for the academies and sections to continue with the work of developing diagnoses.

CURRENT STATUS AS OF NOVEMBER 2021

Additional implementation of the movement screen and diagnosis development was assigned to the APTA practice and science committee. The process has stalled. No additional information about the movement system, the movement screen, or movement-related diagnoses has been provided by the APTA. It would seem that this is an opportune time as we as a profession consider how physical therapy will be positioned for the next 100 years.

Early in the process the former Section on Women’s Health developed diagnoses but after the publication of the initial work, nothing additional has been published. The Academy of Neurological Physical Therapy has made major efforts to develop and promote movement system diagnoses. The Academy of Neurological Physical Therapy has formed several task forces and a white paper has been published. A recent publication detailed the diagnoses that have been developed for balance and a document to guide task analysis has also been published. The Academy of Pediatric Physical Therapy has joined with the Academy of Neurologic Physical Therapy to continue the development of diagnoses.

The International Journal of Sports Physical Therapy once again has committed to publishing a special issue on the Movement System. The initial publication on the topic in 2017 contained many key articles and offered insightful perspectives. The topic is an important one. In this era where distribution of ideas and actions can be spread widely and rapidly, the APTA membership can play a significant role in implementing change. The membership will be affected in the long run by how the profession is recognized for its value to health care. There is every reason to promote the movement system in conversations with both patients and other health care practitioners. The point has been made in many documents that the profession needs to be valued for what we KNOW and not just what we do.

My hope is that in furthering the professionalization of physical therapy by recognized expertise in a physiological body system and use of diagnostic labels there could also be action to change the name of the practitioner. To clearly recharacterize our role in health care and be consistent with being doctors, the label of therapist needs to be changed. Speech therapy has made this change without an educational change to the doctoral level. They are now speech and language pathologists. The label pathologist conflicts with a role in prevention but a label using “ologist” would be consistent with other health care practitioners. However, the name of the profession does not need to change but an upgrade to the title of the practitioner to clarify that the next 100 years will be for growth in responsibility, recognition, and demand may propel the profession forward in an amazing way.

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REFERENCES


SUPPLEMENTARY MATERIALS

Appendix A
Diagnostic classification is a foundational underpinning of providing care of the highest quality and value. Diagnosis is pattern recognition that can result in categories of conditions that ideally direct treatment. While pathoanatomic diagnoses are common and traditional in orthopaedic practice, they often are limited with regard to directing best practice physical therapy intervention. Replacement of pathoanatomic labels with non-specific regional pain labels has been proposed, and occurs frequently in clinical practice. For example non-specific low back pain or shoulder pain of unknown origin. These labels avoid some disadvantages of tissue specific pathoanatomic labels, but are not specific enough to direct treatment. A previously introduced movement system diagnostic framework is proposed and updated with application to shoulder conditions. This framework has potential for broad development and application across musculoskeletal physical therapist practice. Movement system diagnostic classification can advance and streamline practice if considered while recognizing the inherent movement variability across individuals.

INTRODUCTION

In 2013, the American Physical Therapy Association adopted the vision of "Transforming society by optimizing movement to improve the human experience." Associated guiding principle language (pg. 1) includes "As independent practitioners, doctors of physical therapy in clinical practice will embrace best practice standards in examination, diagnosis/classification, intervention, and outcome measurement." "The physical therapy profession will demonstrate the value of collaboration with other health care providers, consumers, community organizations, and other disciplines to solve the health-related challenges that society faces".\(^1\)

In this collaborative spirit, we must ask ourselves how do we continue to advance the "best practice standards in examination, diagnosis/classification, intervention, and outcome measurement"? Diagnostic classification is a foundational underpinning of providing care of the highest quality and value. As noted by Zimny in 2004 (pg. 106),\(^2\)

"the basic advantage of, and therefore rationale for, classifying and diagnosing clinical problems in medicine is to impose order on information from clinical and laboratory findings that otherwise would remain chaotic and unconnected. Classification and labeling allow generalizations to be made that can then be used to identify and treat similar problems so that each new patient need not be treated de novo. Furthermore, diagnostic classification and labeling provide a structure which allows clinicians to better predict and compare outcomes of interventions for given categories of disease."\(^2\)

Despite the critical importance of diagnostic classification across all of medicine, many pragmatic challenges exist. Zimny\(^2\) succinctly summarized primary concerns to include subjectivity in classification, the lack of mutually exclusive and jointly exhaustive categorizations as relates to clinical problems, and difficulty determining the appropriate level of specificity at which to classify. Despite our 100-year history as a profession, and extensive existing diagnostic labels in medicine, limited diagnostic consistency
is present in orthopaedic physical therapy. An ongoing concern with a lack of diagnostic consistency or specificity in the profession, and in fact across medicine itself, is variation in practice. Practice variation limits our ability to define, educate, and provide best practice.

In a 2017 International Journal of Sports Physical Therapy article, we introduced a broad framework for shoulder movement system diagnostic classification as an alternative to traditional pathoanatomic diagnoses. The purpose of this current manuscript is to provide an update and further illustration of the framework.

MOVING AWAY FROM PATHOANATOMIC LABELS

Since 2017, there have been growing calls from varied perspectives to move away from medicine’s reliance on pathoanatomic labels. Rationale for such a change includes considerations of lack of connection between presence of tissue pathology and symptoms such as pain, increased understanding of pain processing, the presence of comorbid tissue pathologies, the high cost and uncertain value of diagnostic imaging, the limited value of clinical “special tests,” and the influence a diagnostic label may have on patient expected outcomes and perceived need for invasive treatments such as surgery. A recent investigation of over 100 patients with unilateral shoulder pain demonstrated a nearly equivalent prevalence of tissue pathology on the asymptomatic versus the symptomatic side. Importantly however, tissue pathology should not be uniformly dismissed either. More advanced pathology such as glenohumeral arthritis or full thickness rotator cuff tears were significantly more prevalent on the symptomatic side as compared to the asymptomatic side.

In addition to the above mentioned limitations to pathoanatomic diagnostic labels, it is important to keep in mind that tissue pathology is the “end stage” of multifactorial cumulative trauma injuries common to musculoskeletal conditions. There is evidence that malalignment or specific repetitive movement joint loading patterns can be risk factors for development of musculoskeletal disease such as osteoarthritis. If we strive as health care providers to provide risk mitigation interventions aiming to prevent pain and pathology, we need to be able to intervene before excess tissue stress or strain leads to tissue pathology. This approach has been used successfully with programs designed to reduce dynamic knee valgus to prevent anterior cruciate ligament injury, as an example.

In musculoskeletal health and disease, numerous diagnostic labels exist and are employed in clinical practice guidelines, as well as coding and reimbursement. There are advocates of moving from pathoanatomic labels to non-specific regional labels as preferred terms. Examples include diagnostic labels for non-specific low-back pain or shoulder pain of unknown origin. We agree with previous advocates that these non-specific labels may reduce unnecessary surgery or over reliance on expensive imaging modalities in cases where specific tissue pathologies are being labeled that do not relate to a patient’s symptoms or function. However, the lack of specificity of regional pain labels brings us back to the concern of how do such labels go beyond a restating of the patient’s chief complaint and move toward directing best practice? For example, recent changes in Medicare approved ICD-10 codes occurred in an attempt to require increased specificity regarding low back pain diagnoses.

MOVEMENT SYSTEM DIAGNOSTIC CLASSIFICATION

Advocacy has occurred for the use and development of movement system diagnostic labels and classifications as well. Several labels already exist within traditional musculoskeletal diagnoses that are compatible with movement system labels, for example - instability. A movement system diagnostic classification identifies characteristic movement system impairments, activity, or functional limitations that presumably cause, contribute to, or are caused by the patient’s pain or dysfunction. This classification leads directly to movement focused interventions (treating these impairments or functional limitations). Physical therapist practice already focuses on treating movement impairments. Diagnostic classifications within the movement system can subsequently further direct treatment. Demonstrates how for the same patient problem, a physical therapist will focus on a movement system classification to maximize functional outcome for a patient, while an orthopaedic surgeon will focus on tissue status. Both professionals need to understand the other’s area of expertise (pathoanatomy versus pathokinesiology), and how these components interact to impact function and dysfunction for the client.

It is important to recognize that a diagnostic classification within the movement system would not and should not require new physical therapy “profession specific” diagnostic labels used and understood only by physical therapists. Rather the classification is specific to the health of a system – the movement system, rather than specific to the health of musculoskeletal tissue (e.g. rotator cuff).
The American Physical Therapy Association (APTA) has endorsed the following criteria for use with a movement system diagnostic classification: 1) Use recognized movement-related terms to describe the condition or syndrome of the movement system. 2) Include, if deemed necessary, the name of the pathology, disease, disorder, anatomical or physiological terms, and stage of recovery associated with the diagnosis. 3) Be as succinct and direct as possible to improve clinical usefulness. 4) Strive for movement system diagnoses that span all populations, health conditions, and the lifespan. Whenever possible, use similar movement-related terms to describe similar movements, regardless of pathology or other characteristics of the patient or client.

Historically for atraumatic shoulder pain, the most common diagnoses have been shoulder instability, frozen shoulder/adhesive capsulitis, and shoulder impingement/rotator cuff disease. These conditions can be easily adapted to a movement system framework by reframing diagnoses broadly as hypermobility/stability deficit, hypomobility/mobility deficit, or aberrant motion/movement coordination deficit. This classification is not highly specific, but advances specificity beyond regional pain categorizations such as subacromial pain syndrome or shoulder pain of unknown origin. These general movement categories could be easily understood by other health professionals and patients alike, while also beginning to direct physical therapy interventions, since changing movement patterns can alter loading profiles. Physical therapists can manipulate environmental, individual, or task constraints to allow the patient to attain desired movement patterns through the principles of motor learning.

Even at this stage of rethinking a classification, there are a number of advantages to the movement system based framework, as noted in our previous manuscript. First, "the overall treatment goals are derived directly from the diagnostic category: improve functional stability in clients in the hypermobility category; improve functional mobility in clients in the hypomobility category; and improve functional movement coordination or balance of mobility and stability in clients in the aberrant motion category. We would not apply treatments to gain mobility with a client with hypermobility and so forth. This framework further prioritizes the movement in the classification system, and also in the diagnostic process". A movement examination assessing both quality and quantity of movement follows directly after the patient history. Special tests to identify tissue pathology are best used more selectively to potentially modify the intervention approach and inform prognosis and/or coordination of care after identifying a movement classification. Because the movement system is the focus of the diagnosis, there are no issues with scope of practice, and no over reliance on costly medical imaging. There is also not an assumed connection to immediate surgical intervention (e.g. tissue torn and not repairable without surgery), as opposed to an evidence-based consideration of all factors with surgical referral when needed.

**INCREASED SPECIFICITY**

Moving to a greater level of specificity in shoulder movement classification is illustrated in Figure 4. For shoulder conditions for example, based on the history (Appendix A), a qualitative movement examination is performed that includes alignment and repeated shoulder movement assessment. The serratus anterior inferior and trapezius muscles play a critical role in both moving and stabilizing the scapula, but have differential contributions in flexion versus abduction. Therefore, evaluation of arm elevation into both flexion and abduction overhead reaching is recommended, along with an evaluation of the "problem" movement as reported by the client history. The history and movement examination provide the ability to formulate hypotheses regarding what movement impairments are contributing to or resulting from the patient’s symptoms or dysfunction. The remaining examination can subsequently
be directed to confirming/refuting these hypotheses, and reducing reliance on special tests.

In our proposed framework, non-mechanical or unrelated causes (cervicogenic, cardiac conditions) of shoulder pain are ruled out, and primary glenohumeral impairments are distinguished from scapulothoracic impairments. Subtypes of each primary movement impairment are then considered with the understanding that movement emerges as a result of the interactions between individual, environmental, and task constraints.28 From this primary movement impairment pattern, we proceed with additional tests and measures to determine primary movement system contributors such as tissue flexibility, muscle force production, coordination, etc. (Figures 5 and 6). Finally, we assess for important pathoanatomic contributors, such as a tissue tear or nerve injury. This framework of movement system diagnostic classification is presented for shoulder conditions, however, a similar framework can be applied to an array of musculoskeletal conditions. A proposed diagnostic classification for temporomandibular disorders is presented in Figure 7. This classification integrates movement system and pathoanatomic considerations. The flowchart uses objective exam results to classify a movement dysfunction as mobility or coordination deficits with further refinement/specificity of muscle vs. joint involvement. Additional test results refine the pathoanatomic diagnosis according to the criteria outlined in the Diagnostic Criteria for TMD.32 Of note, this classification is inherently multidisciplinary, based on accepted diagnostic classification in dental practice.32,33

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Figure 3. Three proposed broad classifications of shoulder pain following a movement system diagnostic framework, after ruling out conditions not of shoulder origin.

Figure 4. Proposed classification of primary patterns of movement impairments.

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Changing our Diagnostic Paradigm Part II: Movement System Diagnostic Classification

International Journal of Sports Physical Therapy
With regard to the shoulder, Figure 4 presents common movement patterns recognized in a number of previously described classifications. \(^{34-37}\) These patterns are not typically present in isolation. For instance, insufficient scapular upward rotation is often associated with glenohumeral hypermobility, \(^{38,39}\) and excess scapular internal rotation and insufficient scapular posterior tilt may occur in combination. \(^{40}\) A classification is not determined based on simply the presence of an isolated movement impairment, but instead on the collective history and physical examination, including assistance or symptom relief tests\(^ {34,41,42}\) as well as pain provocation tests or movements. Clinical judgement is used to assimilate the collective examination findings in determining which classification is most representative of the client’s movement system dysfunction while incorporating the environmental and personal factors unique to each patient. Figure 5 illustrates that from a movement classification, a clinician can further assess for the associated movement system impairments that would be the focus of a treatment intervention. These representations are not considered all-inclusive or complete, but provide an example of a framework for further investigation. For example, the proposed scapulothoracic patterns represent movement dysfunction in each of the three planes (sagittal - scapular tilting; frontal - clavicle elevation or scapular downward rotation; transverse - scapular internal rotation). Structuring movement patterns in such a way may standardize the clinical evaluation process and the education of new clinicians. \(^ {37}\)

**CASE EXAMPLE**

A 22-year-old male presents with a chief complaint of right anterior shoulder joint pain specific to shoulder overhead motions. Pain is easily provoked with unresisted arm elevation, but is of minimal severity (2/10 on a 0–10 pain scale) and does not persist after exacerbating movements are discontinued. Thus he demonstrates a condition with low irritability. He reports aching pain in the joint without numbness, tingling, radiating pain, or substantively weak. He reports pain began after a feeling of excessive shoulder “strain” while playing volleyball. Arm elevation into flexion is most painful, there is no pain at rest, and arm elevation into abduction is not substantively painful. He is otherwise an active, healthy individual with no confounding demo-
Figure 7. Temporomandibular Disorder Sample Diagnostic Classification.
This classification uses objective exam results to determine movement dysfunction with further delineation of pathoanatomic conditions. MMO = Maximum mouth opening measured in millimeters (mm); TMJ arthralgia = Joint pain; DDwoR = Disc Displacement without Reduction; DDwR = Disc Displacement with Reduction; TMJ OA = TMJ Osteoarthritis (including joint and disc degeneration conditions). Proposed by Kahnert EK integrated with Schiffman diagnostic criteria.

Qualitative and quantitative alignment and movement assessment demonstrates reduced clavicle elevation and reduced scapular upward rotation with his arms relaxed at his side. Cervical and thoracic posture are unremarkable. As he elevates his arm into flexion, his scapula demonstrates increased anterior tilt rather than expected posterior tilt (Figure 8). This individual’s posterior tilt first begins at approximately 90 degrees of arm flexion as determined visually, and shoulder pain is present in the mid to end range of shoulder flexion. Flexion and abduction range of motion are within normal limits but demonstrate reduced scapular upward rotation throughout the range. A scapular assistance test with manual support to scapular posterior tilt and upward rotation is positive during flexion. Repetitive motion results in slight increases in his aberrant scapular movement patterns.

Incorporation of surface electromyographic (EMG) assessment into his evaluation demonstrates a substantial delay of his serratus anterior muscle activation as compared to activation of the anterior deltoid when raising his arm into flexion (Figure 9, Participant A). This is consistent with the “reverse action” movement pattern demonstrated whereby unopposed anterior deltoid contraction results in anterior rather than posterior tilt of the scapula as flexion is initiated. Serratus anterior activation begins to noticeably increase above 90 degrees humeral flexion corresponding to the onset of scapular posterior tilt. For comparison, Figure 9 Participant B depicts EMG from another individual who demonstrated typical scapular posterior tilting during shoulder flexion. Serratus anterior muscle activity was similarly increasing along with anterior deltoid muscle activity for the first 70 degrees of flexion producing simultaneous scapular posterior tilt and humeral flexion.

Even without EMG of the muscle activation pattern, the movement examination allows us to streamline our physical examination. We still must assess joint mobility (unremarkable in his case) and overall muscle strength (within normal limits). However, integrating the movement exam and the history allows us to more efficiently complete the physical exam. In this case we need to rule out long thoracic nerve palsy and can do so through basic manual muscle testing of his serratus (within normal limits) which can be further confirmed by surface EMG in this case.

Based on our classification, a movement system diagno-
sis of insufficient scapular posterior tilt associated with co-
ordination/control deficit is provided. Therefore, his treat-
ment follows from his diagnosis and includes movement 
training exercises to improve serratus anterior activation45 
timing including wall slides46 and scapular protraction with 
flexion movement training. Electromyographic biofeedback 
could be helpful in accelerating motor learning to improve 
serratus activation timing. Specific exercise or biofeedback 
selection based on the individual’s history and physical 
exam are examples of manipulating task and environmental 
constraints to attain a desired change in motor behavior of 
the movement system.

LIMITATIONS

Movement system classification is not without its limita-
tions. First, aberrant movement does not occur in isolation. 
Rather, movement patterns emerge based on interactions 
between the individual, environment, and task.28 Thus, it is 
imperative that clinicians encourage the patient to demon-
strate their painful activities in a context similar to that 
in which symptoms occur. Second, movement is inherently 
variable occurring on the backdrop of individual biology, 
anatomy, physiology, and task demands.15,47 Some vari-
ability is to be expected and can be assessed as part of the 
movement system’s ability to adapt to the changing con-
straints present in daily life, for example eccentric versus 
concentric loading.48–50 More research is needed to deter-
mine how to distinguish expected and potential beneficial 
movement variation from movement variation that alters 
tissue loading in detrimental ways. Third, there is potential 
for misinterpretation of movement systems classification as 
one "right way" to move. Education should be provided that 
there is a range of acceptable movement variation. Finally, 
symptom improvement as a result of interventions may not 
be related to permanent biomechanical change.27 Effective 
alterations in movement patterns will redistribute load to 
reduce symptoms with the goal of allowing a full return to 
previously aggravating activities. To achieve long-term bio-
mechanical changes, movement system training appears to 
require task specificity.27

SUMMARY

Meeting our professional vision requires us to "take a seat 
at the table" with regard to the development and refinement 
of diagnostic classifications best able to direct practice, 
maximize patient outcomes, and determine relative value 
of services. All of these goals further relate to our ability 
to produce effective clinical practice guidelines, educate fu-
ture professionals, and achieve the recognition deserved as 
advanced practice providers. While effectiveness of physi-
cal therapy is well demonstrated for shoulder conditions,51 
most outcomes do not demonstrate fully resolved symp-
toms or positive outcomes for all individuals.52 Continued 
development and refinement of our diagnostic framework 
is needed. Movement system diagnostic classification can 
advance and streamline practice if considered while recog-
nizing the inherent movement variability across individu-
als. To transform society, we must transform, validate, and 
translate a movement system diagnostic practice to "solve 
the health related challenges that society faces".

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APPENDIX A

Proposed elements of a basic diagnostic process for atraumatic shoulder pain:

1. Subjective key questions
   a. What is the patient’s chief complaint?
      i. Pain (constant or with movement)
      ii. Mobility deficit
      iii. Stability deficit
      iv. Weakness with or without pain, mobility or stability deficits
   b. What is the level of condition irritability (provation required, severity, pain persistence)?
   c. What type of symptoms are present (pain, numbness, tingling, weakness, stiffness, etc.)?
   d. What is the location of the symptoms (glenohumeral joint pain rarely radiates past the elbow)?
   e. Mechanism of "injury" – specific injury, cumulative trauma, insidious onset?
   f. What if any movements exacerbate/relieve symptoms?
   g. Demographics, confounding factors (e.g. smoking)?
   h. History/co-morbid conditions (e.g. diabetes)?
      i. Red flags?
      j. Yellow flags (e.g. pain catastrophizing)
2. Objective
   a. Focused posture/movement exam
      i. Thoracic posture/scoliosis
      ii. Cervical posture/ROM
      iii. Shoulder complex initial alignment
      iv. Bilateral shoulder flexion with and without resistance, repeated movements
      v. Bilateral shoulder abduction with and without resistance, repeated movements
      vi. “Problem movement”/hand behind back etc.
      vii. Symptom relief tests (scapular assistance test etc.)
   b. Seated follow up exam
      i. Cervical symptom provocation/relief tests as warranted
      ii. Shoulder mobility/stability tests (sulcus/AP load and shift)
      iii. Symptom provocation/strength tests as warranted
      iv. Select special tests
   c. Supine/prone follow-up exam
      i. Select length/strength/stability/nerve entrapment tests as warranted
      ii. Select special tests (e.g. apprehension, labral tests)
      iii. Shoulder internal/external rotation in 90 degrees abduction, active and passive

3. Assessment and Movement System Diagnostic Label
Invited Clinical Commentary

Application of the 4-Element Movement System Model to Sports Physical Therapy Practice and Education

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The 4-Element Movement System Model describes primary elements (motion, force, motor control, and energy) essential to the performance of all movements. The model provides a framework or scaffolding which allows for consistent processes to be used in examination and intervention decisions. The process starts with task identification followed by a systematic observation of control, amount, speed, symmetry, and symptoms during movement. Testable hypotheses are generated from the observations which inform the examination and the interventions. This commentary describes the use of the 4-Element Movement System Model in entry level and post-graduate residency educational programs and in clinical care with three common sports-related diagnoses.

Level of Evidence

INTRODUCTION

The analysis of human movement is central to the practice of physical therapy. Physical therapists analyze movement in order to identify impairments that contribute to activity limitations and participation restrictions in their patients. Movement analysis and interpretation is a hallmark skill of expert practitioners.\(^1\)

The movement system was adopted by the American Physical Therapy Association in 2015 and has been defined as the integration of body systems that generate and maintain movement at all levels of bodily function.\(^2\) There have been several approaches to defining the movement system,\(^3-5\) but the 4-Element Movement System Model (4-Element Model) has the advantage in that it captures a wide variety of disorders, can meaningfully guide practice and education, can readily be incorporated into entry level and residency training, and is consistent with existing professional models such as the International Classification of Functioning (ICF)\(^6\) and the Patient-Client Management Model.\(^7\)

The 4-Element Model describes the primary elements essential to all movement: motion, force, motor control, and energy (Figure 1). Motion refers specifically to the ability of a joint or tissue to be moved passively. Force refers to the ability of the contractile (i.e. muscles) and non-contractile structures (i.e. tendons) to produce movement, and provide dynamic stability around joints during static and dynamic tasks. Motor control refers to the ability to plan, execute and adapt goal-directed movements such that they are accurate, coordinated and efficient. Lastly, energy refers to the ability to perform sustained or repeated movements, and is dependent on the integrated functioning of the cardiovascular, pulmonary, and neuromuscular systems. The elements overlap in many patient conditions, but can be examined and tested separately. Since all movement occurs within an environmental context and is affected by personal factors specific to the individual, the model depicts how the environment and personal factors surround the 4 elements. Environmental factors are external items that can influence movement such as terrain, support surface, and external distractions. Personal factors include age, gender, comorbidities, self-efficacy, confidence, fear of movement and motivation.\(^5\) The comprehensive description of movement in the 4-Element Model is consistent with theories of human movement being a dynamic system involving complex interactions between the task, the person, and the en-

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The 4-Element Model encourages a systematic approach to the observation by using five observation targets abbreviated as CASSS (control, amount, speed, symmetry, symptoms). Briefly, control refers to the smoothness, coordination, and timing of movement; amount refers to the amplitude of movement at each joint; symmetry is observed in bilateral tasks or comparing unilateral performance between limbs; speed is the length of time; and symptoms most commonly refer to pain but also can include mechanical symptoms, reports of instability, or fatigue. After using the CASSS observation targets to describe the task, hypotheses are generated about the possible movement system elements that may contribute to the movements observed. Potential impairments are identified and tested which lead the clinician to implement treatment strategies. This commentary will address the application of the 4-Element Model to sports physical therapist practice, and its incorporation as part of the education of students and residents.

USE OF THE 4-ELEMENT MODEL IN EDUCATION

Case-based learning with the 4-Element Model is foundational in both the Arcadia University entry-level Doctor of Physical Therapy (DPT) and Orthopedic Residency programs. The model can be incorporated by academic faculty, clinical instructors (CIs), and residency mentors to assess and foster development of clinical reasoning of the learner. The focus of introducing the model in the entry-level DPT program is to help build decision making strategies before entering the clinical education curriculum. The model, terminology, and process are introduced in the first course of the curriculum and applied throughout the rest of the courses in the program. The repetition of 1) activity selection based on patient goals and safety, 2) use of observational targets, and 3) hypothesis driven exam and intervention design is a scaffold by which the student develops clinical reasoning in the didactic curriculum. It is this repetition that helps support the student when they enter the clinical environment and fosters the use of a common examination process and common language to explain the movement impairments with their CI.

CLINICAL EDUCATION

In order to facilitate successful clinical education experiences, the department’s clinical education team has provided clinical faculty with the published paper and a narrated video, as resources to educate them on the 4-Element Model. The video describes the 4-Element Model and applies it to a sample case of a young athlete with a knee injury. The paper and video help to share insight into the student’s foundational clinical reasoning strategies. We believe this knowledge may allow the CI to more accurately meet the student where they are and provide concrete tools for development. We encourage clinical sites to use the model as a conceptual and visual cue for clinical teaching and reflection in all levels of clinical education experiences, from beginner to terminal clinical affiliation. A CI may utilize specific components of the model in patient care preparation activities such as helping the student to identify meaningful goals that then drive observational targets. It is also beneficial to use the model as a cue to identify personal or environmental factors which may impact care, and therefore encourages an awareness of safety early on in any clinical experience. The CI may assist the student in streamlining the physical examination by discussing the element(s) contributing to the observed deficits and how each may be tested. To help develop basic clinical reasoning skills a CI may provide detailed prompting questions using common language such as “If this were a force problem, what is the relevant anatomy to test?” or “How do the elements of force and motor control interact during this jumping sequence?”

Plan of care development can be facilitated by revisiting the outcomes of hypothesis testing with the student to develop targeted interventions, and using these outcomes in reflection activities. CI’s may also use the 4-Element Model to advance non-linear thinking, the interaction between elements and systems, which is imperative when treating more specialized populations such as the athlete.

POST-GRADUATE TRAINING

A primary focus of a post graduate training program is to facilitate a partnership relationship with mentor and resident/fellow and to help the learner delve deeper into specialty practice for optimal patient care. A challenge with mentoring relationships in residency and fellowship education is that we do not use a common language or examination framework across physical therapy programs and practice. Frequently mentors and learners may have different backgrounds of education and training. The 4-Element Model provides a common framework for a systematic movement assessment of the athlete.

To implement the model, the resident and mentor start the examination by choosing and analyzing a specific functional task. The task is selected by what the patient reports having difficulty performing in their daily activities or sport specific tasks. We have found it beneficial to film the patient performing the challenging task such as a stair climbing, gait assessment, squatting mechanics, overhead throwing or jumping. Filming allows the mentor and resident to slow
the patient's performance to fully assess movement abnormalities. While looking at the specific functional task, the mentor will ask the resident to assess the observation targets listed in the CASSS. For example, limitations in control would prompt a discussion of what could be affecting the lack of control including poor balance, specific muscle weakness or a patient's decreased awareness of how to perform the movement. If the resident observes a limited amount of motion this would then prompt discussion of which joints specifically to look at further in the examination of mobility. Speed impairments would prompt a discussion of incorporating a timed functional test or discussion of the "normal" parameters for someone to complete the task (30 second sit to stand test, timed up and go). Symmetry issues would prompt discussions such as "why might a weight shift occur?" Symptom provocation during movement such as pain, clicking, or stiffness and when in the movement sequence these symptoms occur would prompt a mentor and resident to perform a more specific biomechanical assessment. After hypotheses are generated, the novice clinician would continue with the examination delving deeper into the areas of deficit. The mentor and clinician would then use the examination findings to decide which specialty interventions best help that area of deficit. In a post graduate mentoring relationship, the cases that are often discussed have complex clinical presentations, and likely more than one element needs to be addressed to optimize function. It is recommended to return to the specific functional task frequently to assess if the physical therapy interventions are translating into improved functional movement with the limited task.

It is our belief that use of the 4-Element Model in education can be beneficial to both the learner and CI/mentor to help assess and solidify clinical reasoning. This may be demonstrated in entry-level DPT programs, as we look to scaffold learning and build initial reasoning processes, and in post graduate education as we guide novice clinicians to make more effective and specialized care.

APPLICATION OF THE 4-ELEMENT MODEL TO CLINICAL CASE EXAMPLES

The 4-Element Model provides a systematic approach to the understanding and management of movement dysfunction for common musculoskeletal conditions that are encountered regularly in sports medicine and orthopedic physical therapist practice. The four elements of the movement system model are essential to all athletic type functional tasks. In the following sections, three clinical case examples will be presented to show how the 4-Element Model and CASSS framework can be used to establish testable clinical hypotheses for observed movement impairments. The findings can then be applied to help develop patient specific treatment plans aimed at improving functional task performance, and can also be used to guide overall clinical decision making.

CASE EXAMPLE 1: FEMALE SOCCER PLAYER POST-OPERATIVE ACL RECONSTRUCTION (ACLR)

Marie is a 23-year-old female college student. She ruptured her left anterior cruciate ligament (ACL) while playing soccer. She reported a non-contact injury in which her knee buckled upon attempting to change directions while playing defense. She underwent ACL reconstruction (ACLR) with a quadriceps tendon autograft approximately three weeks after the injury. Acute post-operative effects of edema and pain, which contribute to limitations in motion and force, are readily observed as the patient enters the treatment room. These findings guide initial treatment. However, once post-operative sequelae are resolved, functional tasks with increased physiologic demand are appropriate to examine. After six weeks of post-operative treatment, motion was restored and strength training was progressed.

Task selection: As closed chain exercises progressed from bilateral to unilateral movements, a lateral step down (8-inch step) was chosen as the task to examine as it was challenging to the patient (see links in reference for video).

CASSS & Key observations: In the sagittal plane, Marie demonstrated good control during the task; however, in the frontal plane, she demonstrated slightly less control of the lower extremity on the right (nonsurgical) side. When examining motion, she demonstrated the appropriate amount of motion through the lower extremity and trunk in the sagittal plane; but in the frontal plane, she demonstrated slightly greater amount of hip adduction on the right (nonsurgical) side during the task which was most apparent towards peak knee flexion. Marie demonstrated control speed during the task. She exhibited symmetry in the sagittal plane, but in the frontal plane she appeared asymmetric in the control and amount of motion, as described prior. Marie did not report any symptoms of pain, stiffness, or instability during the task. Based on the observational targets of the CASSS, Marie demonstrated slightly greater hip adduction, or greater dynamic lower extremity valgus, in the right (non-surgical) limb compared to the left limb.

Hypotheses and Exam: Hypotheses regarding this movement alteration included: 1) force impairment, weakness in the muscles controlling hip adduction; 2) motor control impairment, perhaps lower extremity valgus decreased in the left (surgical) limb due to extensive unilateral training and feedback; and 3) motion impairment, limited ankle dorsiflexion (DF) in the right limb. Based on the observational targets and hypotheses our evaluation included strength testing of the hip abductors and ROM evaluation of ankle DF. Our evaluation revealed symmetrical hip abduction strength and symmetrical DF ROM. Based on the evaluation of Marie's strength and ROM, we concluded that Marie's asymmetric performance of the lateral step was a result of learned behavior from extensive unilateral training. Discussion with Marie confirmed this as she was provided with cues to minimize lower extremity valgus throughout post-operative rehabilitation and did not perform substantial exercises with the nonsurgical limb.

Task selection: We chose to observe Marie performing a 32 cm drop vertical jump (DVI) (see links in reference for the...
video). The DVJ task was chosen as it may help identify athletes with a higher risk of knee re-injury or second ACL injury.14–16

**CASSS & Key observations:** Marie's control of the movement was smooth and coordinated. In the sagittal plane, she demonstrated a significant amount of hip and knee flexion and a forward trunk position. In the frontal/transverse planes, the amount of motion at the hip was greater on the left (surgical) side. Marie's speed during the task was normal. From a symmetry perspective, Marie demonstrated asymmetrical loading between the limbs. Specifically, she shifted her weight away from the left (surgical) limb. Marie did not report symptoms during the DVJ. Based on the observational targets, the most significant movement alteration was asymmetrical loading, characterized by greater weight acceptance in the right (non-surgical) lower extremity.

**Hypotheses and Exam:** Hypotheses regarding this movement alteration included: 1) force impairment, weakness in the surgical limb's quadriceps muscle may be present; 2) motor control impairment, learned behavior resulting off-loading the surgical limb since the injury, after ACLR, and/or during the rehabilitation process, and 3) psychological factors including readiness to return to sport, confidence, and fear of re-injury. Our evaluation with an isokinetic dynamometer revealed a quadriceps strength index of 85% (L peak torque/body weight = .82 Nm/kg; R peak torque/body weight= .96 Nm/kg). To determine whether motor control alterations were contributing to the asymmetrical loading pattern, Marie performed the drop vertical jump after being provided with external feedback. The external feedback was reaching (with her left hand) for a cone placed to her left. Marie demonstrated more symmetrical loading with the provided external feedback. Also, Marie completed the anterior cruciate ligament return to sport after injury questionnaire (ACL-RI), scoring a 4/100. Lower scores indicate less psychological readiness (i.e. more fear, less confidence, more concerned about future risks of knee injury). Based on the findings from the evaluation, Marie's altered loading strategy seemed to be driven primarily by altered motor control and personal factors (i.e. poor psychological readiness). A force impairment (i.e. quadriceps weakness) was likely also contributing to the altered movement. A single assessment of the DVJ, or any other single assessment task, did not allow us to determine if there was potentially an impairment with the energy element. Subsequent testing of Marie's movement during the DVJ or lateral step down could be evaluated after a fatigue protocol or with repetitive tests/movements. Repetitive tests appropriate for Marie would be the two-minute lateral step down test or the Tuck Jump Test.17,18

**Targeted intervention:** Treatment focused on motor control strategies, such as providing external cueing to promote symmetrical loading during various movement patterns following a graded exposure paradigm. Graded exposure was utilized to address low psychological readiness. Quadriceps strengthening exercises were also continued.

**CASE EXAMPLE 2: ACHILLES TENDINOPATHY IN A RUNNER**

JP is a 37-year-old male accountant who presented with complaints of an insidious onset of right Achilles tendon pain for the past six months. He denied any significant past medical history, but reported prior right distal iliotibial band pain approximately two years ago which resolved without formal medical attention. JP denied any other symptoms other than Achilles tendon pain, with noticeable pain in the morning upon waking which increases with walking and running. His pre-injury running weekly mileage was 15 to 20 miles per week, but now currently running five to seven miles per week. JP reported pain of 0/10 at rest, and 6/10 at worst on the numeric pain rating scale; he scored a 67/80 on the Lower Extremity Functional Scale and 25/36 on the University of Wisconsin Running Injury and Recovery Index. No diagnostic imaging of the right Achilles tendon was reported. The patient reported taking ibuprofen as needed for pain management.

**Task selection:** His movement assessment began with examining basic bilateral (i.e. squats, lunges) and unilateral lower extremity tasks (i.e. lateral step down) to obtain a baseline perspective on the patient's willingness to move and quality of movement. No major deviations were observed with these movement tasks, so a more complex activity, running, was selected. A running video analysis was conducted, given that this was the primary activity which caused the patient's pain and for which his participation was limited.

**CASSS & Key observations:** We used video to record running mechanics on the treadmill in the frontal and sagittal view. Running speed was self-selected by the patient. Using the CASSS framework, for control, we visually observed relatively good trunk and lower extremity control in the sagittal and frontal plane, but cadence was low. Observing amount, we noted excessive vertical displacement in the frontal plane during running. JP demonstrated a self-selected running speed of a 7:45 min/mile running pace. Numerous deviations in symmetry were observed from the frontal plane including increased trunk lean to the right when in mid stance on the right, excessive pelvic drop when in mid stance on the right, and the right lower extremity was in an externally rotated position in stance. (Figure 2) The patient was noted to have a symmetrical rearfoot strike pattern bilaterally from the sagittal plane, but increased right hip flexion in swing. JP reported pain symptoms of 4/10 to the right Achilles tendon during the task.

**Hypotheses and Exam:** The hypotheses regarding the movement alterations of this patient included: 1) force impairment may be present in the proximal hip/core musculature and right ankle plantar flexors; 2) energy deficit, a possible lack of ankle plantar flexion muscular endurance may contribute to excessive right hip flexion; 3) motor control impairment, the low running cadence rate observed may be contributory to excessive strain on the musculoskeletal system; 4) motion deficit, hip and ankle ROM could be limited contributing to the excessive external rotation of the right lower extremity in stance. Clinical examination revealed weakness of the right hip abductors (4-/5 right; 5/5 left) and hip extensors (4-/5 right; 5/5 left). In single leg an-
kle plantar flexion, JP could only complete eight repetitions of a heel raise on the right before not being able to continue, compared to completing 25 repetitions on the left. Achilles tendon pain was also reported during the plantar flexion strength test on the right. His cadence was 152 steps per minute which is lower than what is considered optimal (180 steps per minute), and a lower running cadence has been associated with increased vertical load rate, which in turn has been associated with lower extremity running related injuries. Hip ROM and Craig’s test did not reveal any meaningful differences between lower limbs, nor were differences found between left and right ankle ROM, therefore a motion deficit was not considered contributory to this patient case.

JP demonstrated significant tenderness and mild swelling at the mid-portion of the right Achilles tendon. A positive arc sign and Royal London Hospital test were noted on the right. While the pathoanatomic diagnosis of Achilles tendinopathy was confirmed through the clinical examination, the movement analysis findings guided the treatment beyond symptom management.

**Targeted intervention:** Treatment included core, hip abduction, and hip extension strength training, along with eccentric ankle plantar flexion exercises. The eccentric ankle plantar flexion strengthening is specifically designed to painfully load the Achilles tendon with the knee in an extended and flexed position and is supported by strong evidence. For the energy and motor control impairments, gait retraining to increase step rate with running were included in the treatment, as transitioning to a higher cadence has been shown to result in lower vertical loading rates during running which may benefit this patient.

The prognosis for this patient to achieve his goal of pain free running is good with the treatment plan noted. However, in cases which are not responding to traditional management clinicians may need to consider central sensitization as an explanation for chronic musculoskeletal pain. Although not specifically outlined in the 4-Element Model, the chronic pain symptoms were addressed directly through pain neuroscience education and via the inclusion of noxious electric stimulation in an attempt to modulate the nervous system through decreasing pain sensitivity.

**CASE EXAMPLE 3: FEMOROACETABULAR IMPELLGEMENT SYNDROME IN A YOUNG ACTIVE ADULT**

A.M. is a 30-year-old female graphic designer who presented with a two-year history of unilateral left hip pain. She reported that she was extremely active and participated in some form of exercise six days a week. Her regular forms of exercise were running, yoga, and high intensity strength training. AM reported her pain had progressively worsened over the last six months when she began training for a marathon. AM reported that she had difficulty walking a mile without hip pain, therefore, sought a consult from a primary care sports medicine physician. Radiographic evaluation of AM’s hip revealed an alpha angle of 75 degrees on the modified Dunn view, and a lateral center edge angle of 32 degrees on the anterior posterior pelvis (AP) view. AM was diagnosed with femoroacetabular impingement syndrome (FAIS) due to cam morphology and was referred to physical therapy.

**Task selection:** A single-leg squat has been shown as a useful task to evaluate performance in people with FAIS. Recently, hip biomechanics and muscle strength were also found to be predictors of impaired performance of a single-leg squat in people with FAIS. Since AM desired to return to a high level of activity a single-leg squat task was selected to assess her movement (see link in references for the video).

**CASSS & Key observations:** Using the CASSS, a visual observation was conducted during a single leg squat with her involved and uninvolved limbs. During the single-leg squat task AM demonstrated good control of the movement in the sagittal plane with both the involved and involved lower extremity. The movement was smooth and coordinated between the segments; however, there was a noticeable reduction in the amount of hip and knee flexion observed between the right and left hip, and slightly more contralateral pelvic drop during the left compared to right single leg squat. The speed of the squat movements between sides were similar. There was a clear asymmetry in the depth of the single leg squat between the left and right sides. She also demonstrated less forward trunk flexion when squatting on the left compared to the right. Symptoms- she reported a level of 3/10 pain when performing a left single-leg squat whereas she reported a 0/10 when performing this task on her right lower extremity.

**Hypothesis and Exam:** The clinical hypothesis for the movement deviations observed during the single leg squat task included: 1) a hip motion impairment that may be related to the reproduction of symptoms secondary to bony impingement at the hip; 2) knee flexion motion impairment that may be a potentially learned compensation as part of a strategy to limit the overall depth of the squat to avoid moving the hip to near end ranges; 5) motor control impairment as demonstrated by the greater amount of contralateral pelvic drop and hip adduction on the left compared to the right. Additionally, the patient may exhibit 4) force impairments of the hip abductors, extensor, and external rotator muscles that could also limit the ability to achieve equal single-leg squat depth.
The physical therapy examination of AM revealed a C-sign pain pattern at the hip described as a deep ache with occasional sharp pain during squatting and pivoting. Range of motion assessment showed reduced hip flexion (left: 90 degrees vs. right: 105 degrees) and hip internal rotation at 90 degrees hip flexion (left: 8 degrees vs. right: 20 degrees) with pain noted at end range for both motions. Knee range of motion was not limited, and symmetrical to the uninvolved side. Hip muscle strength measured with a handheld dynamometer revealed reduced hip strength of the left compared to right on the order of: 20% for hip flexion strength, 19% for hip external rotation, and 16% for hip abduction. Reduced hip muscle strength is a common clinical finding in patients with FAIS.39,42,43 AM also exhibited a positive anterior impingement sign, and a positive flexion abduction and external rotation test.

TARGETED INTERVENTIONS

The initial physical therapy treatment interventions for this patient focused on reducing symptoms and restoring pain free hip motion. Treatments in this initial phase included soft tissue mobilization techniques, dry needling, and manual joint mobilizations to help reduce pain, muscle guarding, and restore hip range of motion. Closed and open chain strengthening exercises were performed. Specific movement retraining exercises were also performed to help improve biomechanical faults such as greater contralateral pelvic drop during weight bearing function.

The patient completed 16 visits of physical therapy over 12 weeks. However, limited improvement in hip pain and functional activity occurred with PT management. The CASSS framework was used to evaluate the patient’s single-leg squat prior to discharge and there was little to no change in the observed movement deviations during the task. The patient was referred to an orthopedic hip surgeon for further evaluation, which included magnetic resonance imaging (MRI) to evaluate for additional hip soft tissue injury. In addition to confirming cam type morphology, the patient’s MRI also revealed an acetabular labral tear. The patient underwent hip arthroscopy to address the cam morphology and repair the acetabular labral tear.

In the applied case examples, the 4-Element Model was used to evaluate movement during different tasks in patients with three common clinical diagnoses. The tasks used to assess the patients’ movements were selected based on the functional demands of the patient, but also considered the type of injury and phase of healing in order to ensure safe performance of the task. The movement deviations identified were then used to guide the examination and treatment for each patient. These case examples demonstrate that the 4-Element Model can be applied to clinical conditions commonly seen in orthopedic and sports medicine practice.

SUMMARY

The process underpinning the 4-Element Model can be applied by clinicians, students, and residents to a wide variety of patients. The simplicity of the model is intuitive for master clinicians and provides the scaffolding needed for developing independent clinical reasoning in novice clinicians. Using a common framework and language across settings, patient types, and specialty programs will enhance communication between practitioners.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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Several negative adaptations to the musculoskeletal system occur following anterior cruciate ligament (ACL) injury and ACL reconstruction (ACLR) such as arthrogenic muscle inhibition, decreased lower extremity muscle size, strength, power, as well as alterations to bone and cartilage. These changes have been associated with worse functional outcomes, altered biomechanics, and increased risk for re-injury and post-traumatic osteoarthritis. After ACL injury and subsequent ACLR, examination and evaluation of the musculoskeletal system is paramount to guiding clinical decision making during the rehabilitation and the return to sport process. The lack of access many clinicians have to devices necessary for gold standard assessment of muscle capacities and force profiles is often perceived as a significant barrier to best practices. Fortunately, testing for deficits can be accomplished with methods available to the clinician without access to costly equipment or time-intensive procedures. Interventions to address musculoskeletal system deficits can be implemented with a periodized program. This allows for restoration of physical capacities by adequately developing and emphasizing physical qualities beginning with mobility and movement, and progressing to work capacity and neuromuscular re-education, strength, explosive strength, and elastic or reactive strength. Additional considerations to aid in addressing strength deficits will be discussed such as neuromuscular electrical stimulation, volume and intensity, eccentric training, training to failure, cross-education, and biomechanical considerations. The American Physical Therapy Association adopted a new vision statement in 2013 which supported further development of the profession’s identity by promoting the movement system, yet validation of the movement system has remained a challenge. Application of a multi-physiologic systems approach may offer a unique understanding of the musculoskeletal system and its integration with other body systems after ACLR. The purpose of this clinical commentary is to highlight important musculoskeletal system considerations within a multi-physiologic system approach to human movement following ACLR.

**Level of Evidence**

5
INTRODUCTION

The American Physical Therapy Association adopted a new vision statement in 2013 which supported further development of the profession’s identity by promoting ‘the movement system as the foundation for optimizing movement to improve the health of society.’ The movement system refers to the body’s ability to generate and maintain movement through integration of all body systems and functions. Although efforts are currently ongoing, adoption and validation of the movement system has been somewhat challenging across physical therapist practice, education, and research. Let alone in the context of specific clinical diagnoses including anterior cruciate ligament (ACL) injury. A framework for understanding movement development, motor control and skill acquisition may be better realized within the context of dynamical systems theory which aims to explain variability in human goal-directed movement. Dynamical systems theory is described as a multidisciplinary, systems-based approach to explain systems that change over time, and works to build understanding of a complex system through its individual component parts. Dynamical systems theory and the APTA movement system concept share a commonality, in that the interaction and integration of component systems contributes to the success of the system as a whole. Each physiologic system of an individual can be thought of as representing a component system necessary for efficient, goal-directed human movement. Therefore, the purpose of this clinical commentary is to highlight important musculoskeletal system considerations within a multi-physiologic system approach to human movement following ACL reconstruction (ACLR). Specifically, topics will be discussed related to 1) musculoskeletal adaptations after ACL injury and ACLR, 2) clinical examination and evaluation of musculoskeletal health after ACLR, and 3) musculoskeletal rehabilitation strategies to optimize human movement.

MUSCULOSKELETAL SYSTEM ADAPTATIONS AFTER ACL INJURY AND ACL RECONSTRUCTION

Many changes occur in the musculoskeletal system after ACL injury and ACLR. An important alteration occurring both after injury and surgery is loss of range of motion (ROM), which may impact functional activities that have task-dependent ROM needs in order for the task to be executed efficiently. In particular, incidence of knee extension loss greater than five degrees compared to the uninvolved limb has been reported to be as high as 25% at four weeks postoperatively in a sample of 229 patients. Twelve and five percent of patients may not have achieved equal ROM compared to the uninvolved side by six and 12 months, respectively. This is significant as it has been shown to be associated with post-operative complications such as arthrofibrosis, quadriceps inhibition, gait abnormalities, patellofemoral pain, altered patellofemoral and tibiofemoral arthokinematics and articular cartilage contact pressures, and early onset osteoarthritis (OA). Further, extension loss is a common factor leading to revision surgeries. While flexion ROM loss does occur after injury and surgery, it does not tend to affect the knee as much as extension loss. However, a loss of 15 degrees of flexion is considered unsatisfactory for most patients, and any degree of long-term flexion loss may be considered suboptimal for those intending to return to activities involving running, cutting, and/or jumping.

Two of the most documented changes after ACL injury and ACLR are reductions in size and strength of muscle groups around the knee. A recent meta-analysis reported that quadriceps cross-sectional area (CSA) and volume may be decreased in the ACLR limb compared to the contralateral limb. These negative quadriceps changes were evident when examined from 5 to 29 months post-surgery, indicating that they do not spontaneously resolve. Although all included studies reported negative effect sizes supporting this trend, only 56% of studies contained confidence intervals that did not cross zero, indicating other factors beyond muscle size likely contribute to the quadriceps strength deficits that are common in these patients. Other factors that can contribute to muscle strength include neural components (motor unit recruitment, recruitment thresholds, synchronization, firing frequency, intermuscular coordination, etc.), fiber type composition and pennation angle, fascicle length, and muscle fat content. Noehren et al. reported not only decreased quadriceps muscle volume, but also changes in type IIA fiber percentage, extracellular matrix, satellite cells per fiber, pennation angle, and physiological CSA are evident in the injured limb compared to the uninjured limb following ACL injury. Most of these deficits in the injured limb persist despite ACLR and subsequent rehabilitation. The combination of these factors with muscle size results in significant quadriceps strength deficits after ACL injury and ACLR. A review of 37 studies reported between-limb quadriceps strength deficits ranging from 3-40% and 3-28% at six and 12 months post ACLR, respectively. More recently, Toole et al. reported <45% of a cohort of 115 youth athletes who had undergone ACLR had <10% quadriceps strength deficit at the time of return-to-sport. In a large cohort of 450 individuals after ACLR, only 26% showed <10% quadriceps strength deficit six months post-ACLR.

Strength losses following ACLR are not limited solely to the quadriceps. Hamstring, hip, and ankle muscle strength deficits have been reported as well. Further, deficits in knee extension and knee flexion rate of force development (RFD), reactive strength, and power have also been shown after ACLR. These qualities are fundamental for many athletic endeavors, and ongoing deficits may limit successful return to sport. Not only is the injured limb subjected to these deficits, the contralateral limb also has been shown to experience muscle strength and RFD deficits following ACLR.

Musculoskeletal deficits after ACL injury and ACLR may also be due to a cascade of events after initial injury in the neurological system, which highlights one example of the interrelated nature of the system components that contribute to goal-directed human movement. Arthrogenic muscle inhibition (AMI) is the inability to fully contract a muscle despite the muscle not having sustained tissue damage. It has been theorized that inhibition occurs due to decreased spinal reflex excitability that travels to the cen-
the central nervous system which in turn inhibits muscle contraction. Prolonged AMI may lead to a delay in optimal loading of the quadriceps due to the inability of the entire motor unit pool to volitionally activate and produce force. Rice et al. reported that in those with an ACL-deficient knee, 57.1% failed to fully activate (less than 95% activation) their quadriceps on their injured side, and 54.2% failed to do so on their uninjured side. Further, after ACLR, up to 75% of individuals demonstrate quadriceps activation failure in the injured limb compared to 8% in the uninjured limb. This indicates that decreased quadriceps activation occurs immediately after injury and persists after surgery. Hart et al. reported that 21% of patients after ACLR had quadriceps activation failure of both limbs for up to four years after ACLR. However, Harkey et al. found no between-limb differences in quadriceps activation or spinal reflex excitability at six months and up to 12 years postoperatively, and that spinal reflex excitability did not predict six-month quadriceps activation. Although conflicting evidence exists regarding the mechanisms of AMI after ACL injury, AMI is important to address as soon as possible after both ACL injury and subsequent surgery as it may prolong quadriceps weakness and subsequently influence outcomes such as re-injury rates, patient-reported outcome measures, and early onset OA.

Effusion, or increased intraarticular fluid, can stimulate pressure-sensitive mechanoreceptors and may also contribute to AMI. These mechanoreceptors influence group-I1 joint afferent nerves reported to contribute to inhibition of quadriceps activation. Further, Rice and colleagues reported that an increased knee effusion reaching an intraarticular pressure of 50 mmHg is associated with increased motor-evoked potentials (MEPs). Theoretically, increased MEPs should result in increased volitional quadriceps contraction. However, previous studies showed decreased quadriceps volitional contraction after acute knee injury and pain, and Rice et al. speculated that the increased excitability they recorded was an attempted compensatory mechanism to maintain neural drive to the muscular system. This is supported by Grooms et al. who found altered activity in corticomotor pathways during a knee extension task between healthy controls and ACLR subjects. This theory may also explain why Lynch and colleagues found no relationship between quadriceps activation and different grades of effusion measured by the stroke test (described later in this commentary). Thus, it is unclear whether effusion is a direct contributor to AMI, and through what mechanism effusion may cause AMI.

The donor site of the ACL graft may have implications for musculoskeletal health. Several of the more common graft types include the hamstring, patellar, or quadriceps tendon. A systematic review reported mixed evidence for graft-related strength deficits according to graft site, graft preparation, postoperative timeframe, and method of strength assessment. Regardless, it is important to evaluate quadriceps and hamstring strength at appropriate postoperative timeframes to guide rehabilitation progression. Patellar tendinopathy is a concern in those with bone-patellar tendon-bone autograft, which may also have implications for graft failure if pre-existing patellar tendinopathy is present. In addition and although uncommon, up to a 0.2% complication rate of patella fracture or patellar tendon rupture has been reported with the use of a bone-tendon-bone graft. Recognizing the implications of ACL graft donor site should be considered when planning musculoskeletal assessments and interpreting outcomes.

The skeletal system may also demonstrate significant changes in addition to the muscular system after ACL injury. Many changes in bone, cartilage and meniscus have been reported after ACL injury and reconstruction. These include decreased bone mineral density of the hip, proximal and distal femur, proximal tibia, and calcaneus, altered articular cartilage thickness and composition, and changes in meniscal tissue structure including alteration of the collagen-proteoglycan matrix even in the absence of observed concomitant meniscal tear. Further, bone bruises occur in 80%-90% of individuals who sustain acute ACL injury, most often in the anterolateral femoral condyle and posterolateral tibial plateau. These bone bruises have been associated with degeneration of chondrocytes and decreased proteoglycans in overlying cartilage. Bone bruises and associated cartilage degeneration may persist years after injury and may play an important role in the elevated risk for OA development after ACL injury and ACLR. Although concomitant meniscal and chondral damage at the time of ACL injury increases the odds for knee OA development, it does not explain all of the risk. Alterations in factors such as muscle strength, biomechanical movement patterns, and participation in cutting and pivoting activities may inadequately load or overload the connective tissue structures of the knee joint including bone and articular cartilage and increase risk for OA development.

**CLINICAL ASSESSMENT OF MUSCULOSKELETAL HEALTH AFTER ACL RECONSTRUCTION**

The authors encourage rehabilitation professionals to understand sport-specific physical demands and utilize any available strength and performance normative data to guide the clinical reasoning process (Appendices A and B). The physical demands inherent to sport performance require the integration of multiple physiologic systems into movement solutions that satisfy task demands. Identification of impairments across multiple systems is recommended, but this section will focus on several clinically available methods that can be used after ACL injury and reconstruction to measure modifiable aspects of the musculoskeletal system. Limb symmetry indices (LSI) are often used to interpret muscle strength and functional test results although recent evidence suggests LSI may overestimate injured limb strength and function due to decreased performance of the uninjured limb.

**JOINT EFFUSION**

Circumferential measurement of the knee with a tape measure is a simple clinical assessment of knee effusion and swelling. It should be noted that clinical measurement of knee effusion is indirect in nature, as knee effusion is an intraarticular phenomenon and may be influenced by ex-
traarticular swelling. Measurement should be taken with the tape measure positioned one centimeter superior to the patella and care should be taken to avoid an ellipsoid path with the tape measure while maintaining consistent tension. Measuring tapes with a spring-loaded Gulick attachment offer the benefit of standardized tension application during measurement. Alternatively, the stroke test is a reliable and more direct assessment of knee effusion after ACL injury. This may be important to assess as even small amounts of effusion may be associated with AMI. This test uses a five-point ordinal scale (0, trace, 1+, 2+, 3+) to measure effusion that produces no fluid wave upon at the medial side of the knee upon the downstroke (effusion = 0) to effusion that cannot be moved out of the medial aspect of the knee during the upstroke (effusion = 3+). Knee effusion should be serially assessed to appropriately progress exercise and activity levels during rehabilitation.

**RANGE OF MOTION**

The most common clinical assessment of knee range of motion (ROM) is goniometry. ROM goals after ACL injury and ACLR include achieving full terminal knee (hyper)extension and flexion comparable to the contralateral limb. A loss of only three to five degrees of knee extension has been associated with OA development and a worse long-term outcome. Terminal extension should also be exhibited actively as a patient should be able to lift their heel in supine while keeping their knee in contact with the table. Inability to achieve this may be due to ongoing AMI, quadriceps weakness, or ROM deficits. A loss of maximal knee joint flexion may influence gait during high speed running as maximal knee flexion is reached during the swing phase as well as sport-specific tasks that require deep squatting (e.g. baseball catcher).

**MUSCLE GIRTH**

Quadriceps size can be indirectly assessed via muscle girth with circumferential measurements using a tape measure. Positioning the tape 20 cm above the anteromedial joint line is supported as the most relevant level to detect between-limb differences. It should be noted that the participants from Laupattarakasem et al had a mean height of 169 cm, and the position of the tape relative to the joint line may vary based on the height and limb length of the individual. Although circumferential girth may underestimate losses in actual muscle CSA, it has been correlated with muscle CSA and therefore remains a clinically relevant metric.

**MUSCLE STRENGTH**

Muscle strength can be defined as a muscle’s ability to exert force on an external object. This must be measured with isolated single joint testing of the targeted muscle group in order to eliminate compensations from other muscle groups (e.g. hip extensors during a leg press). When assessing single joint movements, torque may be calculated which takes into account limb segment length. Normalizing torque to body mass allows for comparisons across populations. The authors recommend a target for normalized isometric knee extension torque at 60 degrees of knee flexion to be 3 Nm/kg. Isokinetic dynamometers are the current gold standard for single joint testing of muscular torque, although more clinically available dynamometers such as in-line or hand-held (HHD) options have been shown to give valid and reliable measurements when set up in a rigid and repeatable manner. This may be implemented using belt fixation as previously reported. Options for dynamometers are currently available at a price point that is much more cost-effective than seen previously, which could increase utilization of clinically meaningful measurements.

A one-repetition maximum (1RM) test aims to measure the muscle force exerted in one maximal effort with good form, and is also quantified as the maximum load that can be lifted one time. Specific to the quadriceps muscle, using a leg extension machine to test 1RM from 90-45 degrees is also supported as a strength assessment, although this method may be more useful for ruling in asymmetry than ruling it out. A reliable and repeatable testing set-up for between-limb comparisons or serial testing of the injured limb is necessary for valid muscle strength assessments.

Other muscles to consider for examination include the hip abductors, hip extensors, and ankle plantarflexors. Alternative assessment of these muscle groups may include performing a task for repetitions to failure or repetitions completed in a given time frame such as 30 seconds. Ankle plantarflexor assessment can be completed with single-leg heel raises. Hip extensors and hamstring assessment can be completed with single-leg elevated bridges in varying degrees of hip and knee flexion. Although utilizing repetitions to failure or repetitions in a time frame for the above assessments can be done clinically, the clinician should acknowledge that proxy measures may not accurately assess maximum strength and could be more a reflection of muscle endurance or some other confounder.

In addition to single joint assessment, multi-joint testing can be completed to assess the lower extremity kinetic chain. Multi-joint testing can include qualitative evaluation assessment tools when used in a valid and reliable manner, such as the qualitative assessment scheme proposed by Herrington and colleagues which utilizes dichotomous criteria to rate the movement strategy of the arms, trunk, pelvis, thigh, knee, and foot during the specified tasks. Quantitative measures should also be obtained, and various multi-joint assessments have been utilized such as lateral or anterior step-downs, a single-leg squat test, and single-leg leg press test. Herrington et al recommend that the task requires a minimum of 90 degrees of knee flexion to increase the overall muscular demand compared to more shallow angles of knee joint flexion. The leg press may be used to assess for a 1RM or for reps to failure at a given intensity such as 100% bodyweight. For step-downs or single-leg squats, repetitions to failure or repetitions completed in a given timeframe such as 30 seconds may be utilized as discussed above, again acknowledging that this is not a maximum strength assessment.

**RATE OF FORCE DEVELOPMENT (RFD)**

Explosive strength is the ability to produce force rapidly and...
is typically assessed via RFD during isometric tasks by evaluating rate of change in force over some time epoch which is represented by the slope of the force-time curve (e.g., slope of force-time curve between 0-250 milliseconds).\textsuperscript{76} Rate of torque (RTD) or RFD is commonly measured using an isokinetic dynamometer for single joint tasks or force plates for multi-joint tasks such as an isometric mid-thigh pull. Access to these devices is necessary but insufficient for accurate RTD/RFD measurement since assessment is challenging and current methods of both testing and interpretation of results vary widely in the literature. For example, it is suggested that isokinetic dynamometers are modified during RTD/RFD assessment to account for factors such as system compliance, sampling rate, and software processing to obtain a reliable measure.\textsuperscript{77} Additionally, previous literature reports RTD/RFD over various epochs (e.g. 0-100 milliseconds, 50-150 milliseconds, 20%-80% of peak, etc.), as an average, or as a peak.\textsuperscript{77,78} Thus, one must be cognizant of these factors when interpreting results.\textsuperscript{77} Regarding assessment without access to modified isokinetic dynamometers or expensive force plates, valid and reliable methods have yet to become widely available to clinicians. However, affordable force plates and software are becoming increasingly available and may present a future direction for clinically assessing explosive strength via RTD/RFD. Recently, HHD measurements of quadriceps peak torque and late RFD (250 ms) derived from raw data demonstrated acceptable validity when compared to isokinetic dynamometry; however, this feature is not yet clinically available in most HHD testing devices.\textsuperscript{79}

**REACTIVE STRENGTH**

Reactive strength can be measured to determine a patient’s ability to utilize the stretch-shortening cycle and quickly change from eccentric to concentric muscle action as performed during plyometric activities. Examples of clinical assessments include modified reactive strength index (RSI-mod) during a single or double leg vertical countermovement jump\textsuperscript{80} and reactive strength index (RSI) during a drop vertical jump (DVI).\textsuperscript{81} RSI can be calculated by dividing flight time by ground contact time, although other calculations also exist. Jump height and RSI can be assessed with force plates, but also can be reliably measured clinically with the My Jump 2 application (available for download using Apple App Store for iOS, Google Play for Android).\textsuperscript{82} If assessing a DVI, it should be noted that RSI will differ based on the height from which the drop is performed. Thus, a consistent height should be used between limbs and for reassessments. Repeated hopping such as the side hop test\textsuperscript{83} may also be used as a surrogate clinical measure of reactive strength. Reactive strength tests should also be evaluated qualitatively as discussed above with multi-joint strength.

**HOP TESTS**

Single leg hop tests have long been used as a functional assessment after ACLR.\textsuperscript{84} as they have demonstrated acceptable reliability to measure progress during rehabilitation.\textsuperscript{85} However, it should be noted that hop tests are a valid measure of a patient’s ability to perform a hopping task rather than assessing any specific physical quality. Because of this, a critical examination of single leg hop tests showed that clinicians tend to overestimate lower extremity function when using hop distance alone.\textsuperscript{86} Given these inherent limitations, it may be necessary to rethink the interpretation of hop testing or add qualifications to the test such as evaluating two-dimensional movement quality during single leg hop tests which can be done using commercially available video cameras and video analyzing software (Kinovea 0.8.15 available at [Kinovea.org]),\textsuperscript{87} as patients post-ACLR often demonstrate deficiencies during landing compared to the uninjured limb and uninjured individuals.\textsuperscript{88}

Finally, LSIs for muscle and lower limb performance (e.g. muscle strength, rate of force development, reactive strength, single-legged hop tests) that reach 90% are often considered functional targets during rehabilitation.\textsuperscript{94} However, LSI has been reported to overestimate injured limb function due to deterioration of the uninjured limb.\textsuperscript{30,31,58} Other criteria such as pre-injury baseline measures or normative values can provide valuable alternatives to LSIs. However, in the absence of these data, LSI provides a useful metric during rehabilitation when taken in context of known shortcomings.

**MULTI-PHYSIOLOGIC SYSTEM INTERVENTIONS FOR THE MUSCULOSKELETAL SYSTEM AFTER ACLR**

Addressing changes in the musculoskeletal system after ACL injury and ACLR should be a priority given their associations with altered biomechanical movement patterns, poor long-term function, re-injury risk, and risk of OA development.\textsuperscript{36,90–92} By appropriately addressing musculoskeletal impairments, it allows for further integration of interventions to allow for recovery of other components (cardiopulmonary, nervous, integumentary) with the aim to ultimately resolve movement dysfunction. Foundational concepts and progression principles in strength and conditioning should be implemented through a multi-physiologic system lens, recognizing that strength training impacts multiple body systems important for human movement. Primary principles to be discussed include progressive overload, specificity, and variation.\textsuperscript{93} These principles can be used to target any fitness parameter (endurance, strength, power, speed, etc.).

**INTERVENTIONS FOR RANGE OF MOTION**

Addressing extension loss in the early post-operative period should be a high priority. Ideally restoring full knee extension should also be accomplished pre-operatively as risk of prolonged extension loss after surgery has been reported to be five times more likely if full extension was not achieved prior to surgery.\textsuperscript{94} Risk of developing arthrofibrosis is two and eight times more likely if extension loss remains at three and six weeks post-operatively, respectively.\textsuperscript{95} After surgery, the tensile strength of the skin gradually improves over time, so one must also be mindful of integumentary system health and the healing surgical site when applying ROM interventions.\textsuperscript{96}
When addressing ROM deficits, the clinician must first consider factors that may be limiting the ROM. This may be pain, effusion, muscle guarding, or arthrofibrosis. If pain and guarding are limiting factors, techniques and modalities such as electrical stimulation, cryotherapy, joint mobilizations, or soft tissue massage may be helpful. For effusion one may consider pneumatic compression devices, active range of motion, and adherence to loading principles. Patients should also be instructed in self stretches for knee extension at least three times per day which may include supine heel props, self-applied overpressure, and active quad contractions in terminal extension. Patellar mobility may limit ROM and can effect patellofemoral arthrokineamatics. Therefore, the clinician and patient may implement patella mobilizations to ensure appropriate mobility. If loss of knee extension persists, implementing the concept of total end range time (TERT) is recommended. This may include low load long duration stretching in supine with the heel propped and 5-15 pounds placed on the distal thigh for 10-15 minutes at a time for 60+ minutes per day. The intensity of the stretch should allow for the patient to tolerate the stretch without pain or muscle spasm. Although less frequently implemented, persistent extension loss may also be treated with splinting or additional surgical procedures. Knee flexion ROM should also be progressed during the early post-operative period. General guidelines include targets of 90-100 degrees by one week post-operatively and increases of ~10 degrees per week after that. This may be delayed if there are concomitant injuries or procedures (e.g. meniscus repair), or excessive effusion. Knee flexion ROM can be achieved with exercises such as heel slides, wall slides, or stationary biking. To achieve full terminal flexion that is requisite of high speed running and other sport-specific tasks later in rehabilitation, patients may utilize a short kneeling position to attempt to sit on their heels and active heel to gluteal drills in standing. Achieving normal ROM is an integral initial step for recovery of the musculoskeletal system and its components, but also contributes to carrying out movement-related interventions that impact other physiologic systems after ACLR.

**MUSCULOSKELETAL INTERVENTION PRINCIPLES**

**PROGRESSIVE OVERLOAD**

Progressive overload is the gradual increase in demand placed upon a system in response to the adaptation to previously imposed demands. Exercise prescription should aim to apply an appropriate stress or dosage to elicit a desired adaptation within a system at that time point. This dosage is affected by the manipulation of variables including: intensity, volume load (reps x sets x resistance), frequency, repetition speed and tempo, exercise selection and order, and rest periods. These variables are manipulated so that the dose is sufficient to elicit adaptation but within an individual’s recovery capacity. The individual response can be affected by several factors including comorbidities, training history, time, nutrition, stress, and sleep. Tolerance to exercise loads can be monitored via pain and effusion (see earlier sections regarding assessment). Musculoskeletal adaptations to resistance training are typically better understood, but adaptations in other physiologic systems should be considered when developing treatment plans to address movement limitations. Some of the nervous system adaptations to resistance training include changes to higher brain centers, motor unit recruitment, and the neuromuscular junction. Acute responses to resistance training have been described for the cardiopulmonary system and include increased cardiac output, greater blood flow to working muscles, among several others. In essence, resistance training adaptations are not isolated to the musculoskeletal system but rather impact multiple physiologic systems that are important for goal-directed human movement.

**SPECIFICITY**

The SAID principle, which is an acronym for "specific adaptation to imposed demands", states that any given adaptation will be specific to the applied stimulus. While there can be complimentary adaptations to the stimulus across multiple fitness and musculoskeletal adaptations, specific training goals are most effectively addressed by applying a training stimulus that specifically targets the desired adaptation. This idea compliments the principle of progressive overload discussed previously as both work together to ensure progress towards the desired goal.

**VARIATION**

Variation is the process of changing program variables so training stimuli are challenging for a system. This is necessary because as individuals adapt to training, desensitization to the training stimulus can occur and the magnitude of adaptations can decrease. Variation is commonly achieved through periodization, for which several models have been developed and demonstrated effectiveness. It should be noted that nearly all available literature on periodization is conducted in healthy individuals rather than an injured or post-surgical population. Nevertheless, the principles can be applied effectively to individuals after ACL injury and ACLR when combined with clinical reasoning and monitoring.

Linear or classic periodization involves structuring a program with progressive decrease of volume and increase in load across several mesocycles. A mesocycle has been described as a medium-sized training cycle with two to six weeks being the most typical duration. Each cycle prioritizes one fitness parameter and progresses to the next parameter in a predictable, structured manner. In rehabilitation, this typically begins with relatively low intensities and high volumes, and gradually progresses to higher intensities and lower volumes.

Nonlinear or undulating periodization utilizes either systematic or random alteration of intensity and volume within a training cycle. This can occur daily or weekly. This allows for multiple fitness parameters to be developed simultaneously. No differences between linear and nonlinear periodization have been established in the healthy population. Block periodization involves attempting to maximize
### Table 1. Training Variables for Fitness Parameters

<table>
<thead>
<tr>
<th>Training Goal</th>
<th>Volume</th>
<th>Intensity</th>
<th>Frequency</th>
<th>Exercise selection</th>
<th>Rest Periods</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Local muscle endurance</strong></td>
<td>Option 1: 10-25 reps of multiple sets per exercise</td>
<td>Option 1: Light (&lt;10-15RM)</td>
<td>Novice: 2-3x/wk, Advanced: 4-6x/wk for muscle group split routines</td>
<td>Option 1: Unilateral and bilateral; single and multi-joint</td>
<td>1-2 min for high reps (15+), &lt;1 min for low reps (&lt;15)</td>
<td>Slow velocities for &lt;15 rep schemes; Moderate to fast velocities for 15+ rep schemes</td>
</tr>
<tr>
<td></td>
<td>Option 2 (EMOM): 5-10 sets of 3-10 reps</td>
<td>Option 2 (EMOM): 60-80% 1RM</td>
<td></td>
<td>Option 2 (EMOM): Mostly multi-joint</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hypertrophy</strong></td>
<td>Novice: 1-3 sets of 8-12 reps per exercise</td>
<td>Novice: 70-85% 1RM</td>
<td>2-3x/wk per muscle group</td>
<td>Single and multi-joint; OKC and CKC</td>
<td>1-2 min that can be extended to 2-3 min with heavy loading</td>
<td>Muscle actions should include con, ecc, iso at long muscle lengths; Controlled velocities</td>
</tr>
<tr>
<td></td>
<td>Advanced: 3-6 sets of 1-12 reps per exercise; 10+ total sets per muscle group per week</td>
<td>Advanced: 70-100% 1RM</td>
<td></td>
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</tr>
<tr>
<td><strong>Strength</strong></td>
<td>1-3 work sets per exercise; 3-10 reps (progressing to lower rep range as training age/status and intensity increases)</td>
<td>Novice: 70-85% 1RM</td>
<td>2-3x/wk</td>
<td>Unilateral and bilateral; single and multi-joint; OKC and CKC</td>
<td>2-3 minutes for multi/joint/ large muscle groups</td>
<td>Muscle actions should include con, ecc, iso; intent for max velocity during concentric</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Advanced: 80-100% 1RM</td>
<td></td>
<td></td>
<td>1-2min for single joint/ small muscle groups</td>
<td></td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>1-3 sets of 3-6 reps</td>
<td>0-60% 1RM</td>
<td>Novice: 2-3x/wk, Advanced: 4-5x/wk</td>
<td>Mostly multi-joint</td>
<td>2-3 minutes for complete recovery</td>
<td>Maximal intent with each rep and minimal drop off in velocity</td>
</tr>
</tbody>
</table>

EMOM= every minute on the minute, RM= repetition maximum, OKC= open kinetic chain, CKC= closed kinetic chain, wk= week, con= concentric, ecc= eccentric; iso= isometric

Adaptation for one specific parameter in a given time period, typically within two to four weeks. This allows for the maintenance of the most important physical qualities for an athlete's sport. Each block includes three phases: accumulation which includes a high volume of general exercise at 50-70% 1RM to build work capacity; transmutation, which includes more specific exercises at 75-95% 1RM; and realization, which includes even more specific movements when compared to the transmutation phase with the goal of >90% 1RM.105

Linear periodization may be most appropriate for initially structuring a program for an individual after ACL injury or ACLR. This presents a logical starting place and a safe, effective progression when aiming to address the musculoskeletal deficits previously described. This programming can be accomplished utilizing Vermeil’s Hierarchy, a widely utilized model of athletic development that is designed to adequately load the musculoskeletal system in a systematic and logical manner.106 Implementation of this model first requires the development of a patient’s work capacity, which is the ability to sustain work and accumulate workload to prepare the body to tolerate increases in load. This progresses in a stepwise manner to strength, explosive strength, reactive strength, and speed. While qualities within the hierarchy can be trained concurrently, optimal development of any one quality in the hierarchy requires the preceding quality to be adequately developed. By definition, training multiple qualities concurrently means that the program shifts more to non-linear periodization, although one quality may be emphasized. Table 1 depicts training variables based on the goal.95 The reader is referred to Table 2 for an example of programming schemes utilizing an adaptation of the hierarchy.
Table 2. Example of Programming Progression Utilizing Vermeil’s Hierarchy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Duration</th>
<th>Volume</th>
<th>Intensity</th>
<th>Frequency</th>
<th>Exercise Examples</th>
<th>Other Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work Capacity/Endurance</td>
<td>2-4 weeks</td>
<td>1-2 exercises per muscle group; 2-4 sets x 12-20 reps</td>
<td>Low - moderate (&lt;70% 1RM)</td>
<td>3x/wk</td>
<td>leg press, leg ext, leg curl, bridges, sidelying hip abduction, heel raises</td>
<td>BFR, NMES, cross-education</td>
</tr>
<tr>
<td>Hypertrophy/Strength</td>
<td>4-8 weeks</td>
<td>6-10 sets x 8-12 reps per muscle group</td>
<td>Moderate (~70-80% 1RM)</td>
<td>2-3x/wk</td>
<td>Leg press, leg ext, leg curl, squat and lunge variations, deadlift variations, banded lateral walks, heel raises</td>
<td>NMES, cross-education, supramaximal eccentrics</td>
</tr>
<tr>
<td>Strength</td>
<td>4-8 weeks</td>
<td>3-5 sets x 5-8 reps</td>
<td>Moderate-high (&gt;80% 1RM)</td>
<td>2-3x/wk</td>
<td>Leg press, leg ext, leg curl, squat and lunge variations, deadlift variations, heel raises</td>
<td>NMES, Cross-education, supramaximal eccentrics</td>
</tr>
<tr>
<td>Explosive Strength/RFD</td>
<td>2-4 weeks</td>
<td>3-6 sets x 3-6 reps</td>
<td>Low (BW or 30-45% 1RM)</td>
<td>2-3x/wk</td>
<td>Squat jumps, drop lands, ballistic isometrics (IMTP or leg press), accels, decels, Olympic derivatives (i.e. jump shrug)</td>
<td>Perform exercises with intent of max velocity</td>
</tr>
<tr>
<td>Elastic/Reactive Strength</td>
<td>2-4 weeks</td>
<td>3-6 sets x 3-6 reps</td>
<td>Low (BW or &lt;30% 1RM)</td>
<td>1-3x/wk</td>
<td>Ankling, CMJ, DJV, sprints (&gt;7m/s)</td>
<td>Minimize ground contact time</td>
</tr>
</tbody>
</table>

Accels= accelerations, decels= decelerations, RM= repetition maximum, RFD= rate of force development, BW= body weight, ext= extension, BFR= blood flow restriction, NMES= neuromuscular electrical stimulation, IMTP= isometric mid-thigh pull, CMJ= countermovement jump, DVJ= drop vertical jump, m/=, meters/second, wk= week

INTERVENTIONS FOR ARTHROGENIC MUSCLE INHIBITION

A multi-physiologic systems approach to target AMI requires integrative knowledge of the nervous system to appropriately incorporate interventions within a comprehensive treatment plan. The most common intervention for AMI after ACL injury is neuromuscular electrical stimulation (NMES). Fitzgerald et al.\textsuperscript{107} showed that a modified NMES program (twice per week, 2500 Hz alternating current, two second ramp up and down, ten second stimulation period with visible contraction, and 50 second rest period for 11-12 minutes) as an adjunct to standard rehabilitation was more effective in restoring quadriceps activation at 12 and 16 weeks postoperatively compared to standard rehabilitation alone. More recent studies also support these findings.\textsuperscript{108,109} Lepley et al.\textsuperscript{109} compared an NMES-only group to NMES with eccentric strength training, eccentric strength training only, and standard care. Their findings demonstrated that both eccentric strength training alone and NMES with eccentric strength training showed less quadriceps strength and activation loss at time of return-to-sport testing compared to preoperative testing. Although NMES is commonly used in early stages of ACLR rehab, these findings suggest that NMES may be implemented throughout the rehabilitation stages to influence quadriceps strength.

In addition to active interventions, passive modalities may also help with increased quadriceps activation such as specific applications of transcutaneous electrical nerve stimulation (TENS)\textsuperscript{110} or focal joint cooling.\textsuperscript{111} Although the two aforementioned investigations on TENS and focal joint cooling prior to rehabilitation seem to be effective interventions for AMI, the generalizability of applying these interventions to ACLR populations is limited due to the populations studied and clinical feasibility of the treatment protocols. It is important to be mindful that sensory deficits around the knee can persist for months or years after ACLR as a result of the surgical procedure,\textsuperscript{112} which may place patients at elevated risk for other sensory impairments including burns and poor thermoregulation.\textsuperscript{113}

INTERVENTIONS FOR MUSCLE STRENGTH

Adequate muscle strength provides the foundation for RFD and reactive strength required by most sporting movements and activities. It has been suggested that until a healthy individual can squat 1.6 times their body mass, continued benefits from strength training will occur.\textsuperscript{114} Haff and Nimm-phius\textsuperscript{115} suggest that for healthy individuals the associations among strength, power, and RFD are maximized when a 2x body mass squat can be achieved. Although RFD and power training modalities may be implemented prior to reaching the 2x body mass squat threshold for most individuals, achieving this squat threshold is indicative of strength no longer being the main limitation for the ability to pro-

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duce force. Muscle hypertrophy is stimulated via muscle mechanical tension which leads to stimulation of pathways contributing to anabolism and muscle growth.116 These pathways can also be stimulated via metabolic stress and accumulation of metabolites causing hypoxia within a muscle. Although debated, muscular strength can be influenced by muscle CSA, so any increases in hypertrophy may also contribute to potential for strength.117 Strength is influenced by many other factors as well including muscle architecture, biomechanics, and several neural factors including motor unit recruitment and synchronization, firing frequency, and inter-muscular coordination.117 Further, it is important to be aware that atrophy after traumatic joint injury may occur through different mechanisms than disuse atrophy.118 Emerging evidence suggests neurophysiological changes occur after ACL injury which affect the corticospinal and spinal reflexive pathways to the quadriceps muscle.119,120 If these pathways are not restored by suggested interventions for AMI, then hypertrophy may not occur despite attempts of mechanical loading. Therefore, the importance of addressing AMI in conjunction to traditional methods of muscle strengthening must be stressed. Training for hypertrophy and strength should utilize the variables in Table 1 to provide these stimuli. In addition, the rehabilitation professional may consider the following concepts:

VOLUME AND INTENSITY

Higher volumes tend to be more effective than lower volumes for muscle growth to a certain extent, possibly due to inducing more metabolic stress and acute local hypoxia within a muscle.121 Schoenfeld et al.122 reported that performing 10 or more sets per muscle group per week trended toward greater hypertrophy than performing less than 10 sets. However, too much volume can begin to exceed the ability of the muscle to recover and diminish the hypertrophic response. The optimal volume of strength training varies among individuals, so monitoring and feedback should be utilized to ensure appropriate recovery. When examining the interactions between musculoskeletal interventions and the cardiopulmonary system, heavy resistance training does little to enhance long-term resting cardiac function, but some cardiovascular benefits may be observed with a high volume program that includes shorter rest periods such as circuit training.69

Patients’ tolerance to exercise can be monitored through assessment of knee soreness via visual analog scale or using soreness rules (knee soreness experienced during warm-up, within session, or the following day) to appropriately progress or regress exercise.123 Additionally, daily joint effusion can be assessed via limb circumference at the patella or with the stroke test as previously described.60,124 An acute change after exercise of one cm of effusion or a one-step increase on the stroke test has been suggested to indicate excessive tissue overload.75 The American College of Sports Medicine guidelines recommend exercising at >70% 1RM for muscle hypertrophy and >60-80% 1RM for strength depending on training status. For an individual’s knee to tolerate these intensities after ACLR, a periodized program should be implemented.

Training to failure is commonly utilized in healthy individuals and is defined here as performing consecutive repetitions of an exercise until the concentric portion can no longer be completed for another repetition or completion would require a significant change in form. While training to failure is generally not necessary to elicit adaptations in hypertrophy and strength, it does ensure that the dosage is sufficient for these adaptations. Motor unit activation is increased as a muscle becomes fatigued and new motor units are recruited to complete the repetitions. Utilizing greater loads will also elicit increased motor unit activation, but lower loads may be required in the earlier phases of rehabilitation when higher loads are not tolerated or safe. Blood flow restriction (BFR) is an intervention to augment taking low loads to failure and has been shown to be an effective hypertrophic stimulus.125 The reader is referred to recent publications126,127 for considerations and application of BFR. To maximize effects from training to failure, adequate rest cycles are required to avoid overtraining and mitigating positive hypertrophic adaptations.

CONTRACTION TYPE CONSIDERATIONS

Concentric, eccentric, and isometric muscle contractions should all be included in a comprehensive rehabilitation program following ACLR. Isometric exercises allow for greater force production than concentric contractions and can be implemented with multi-joint exercises such as leg press or an isometric mid-thigh pull, or with single joint exercises such as leg extensions or leg curls. Strength improvements with isometric exercise tend to be largest at the joint angles in which the exercise is completed, so angle-specific weaknesses can be targeted with this contraction type. Further, lengthened state isometrics may be more effective for hypertrophy and carryover of strength gains throughout the range.128

Previous evidence has shown that supramaximal eccentric exercises may lead to enhanced adaptations of hypertrophy, strength, RFD, and reactive strength compared to isometric contractions and traditional isotonic exercises involving a concentric and submaximal eccentric phase.129–131 To elicit the increased muscle forces that eccentric exercise affords, the load usually must be supramaximal relative to the concentric force producing capacity. This can be implemented in rehabilitation by performing the concentric portion of an exercise bilaterally and subsequently performing the eccentric portion unilaterally. It is important that the load selected for this is supramaximal for one limb to complete concentrically. An example that is widely available includes a patient attempting a single limb leg extension and increasing the weight until they are no longer able to complete the concentric portion. Then they are instructed to complete the exercise by pushing the weight up with both legs, removing the uninjured leg from the plate, and using the injured leg to lower the weight through the full range to the starting position (Figure 1). Other examples include training on a flywheel device or isokinetic dynamometer.
BIOMECHANICAL PRINCIPLES DURING STRENGTH TRAINING

Exercise selection and coaching should be based on biomechanical principles to ensure that specific muscle deficits are addressed. Using both open kinetic chain (OKC) and closed kinetic chain (CKC) exercises in clinical rehabilitation will maximize the likelihood that this is accomplished. The primary advantage of OKC exercises is the constraint it imposes on the training task which ensures that the target tissue is addressed. This compliments the higher systemic and coordinative demands seen in CKC exercises. Therefore, both should be utilized in a comprehensive program. Because compensatory patterns to decrease quadriceps muscle utilization are common during CKC strengthening exercises, clinicians should also implement single-joint OKC exercises to facilitate quadriceps strengthening. OKC in addition to CKC exercises has been shown to be more effective at increasing quadriceps strength compared to CKC alone following ACLR. Additionally, OKC and CKC movements have been reported to have different patellofemoral joint reaction forces at different ranges of motion. OKC results in greater patellofemoral force in lower knee flexion angles while CKC movements will have greater force in higher flexion angles. Therefore, these may be used concurrently in a program in order to load the knee and quadriceps muscle throughout the range of motion while respecting the patellofemoral joint as it adapts to increased loading. OKC knee extension has been the topic of considerable debate due to potential safety concerns and graft implications, although these concerns may not be warranted and have been challenged. OKC knee extension to target quadriceps strength should be included in ACLR rehabilitation with consideration of individual patient factors such as anterior knee pain with appropriate periodization and progression.

It should be noted that when addressing quadriceps atrophy and strength deficits, the selected exercise must create an external knee flexion moment (eKFM) sufficient to require force production demands of the quadriceps at a level that stimulates adaptation. An example of using biomechanical principles to increase quadriceps demand can be illustrated during multi-joint CKC exercises. If individuals squat with their knees moving forward past their toes the external knee flexion moment and required quadriceps force requirements will increase. However, patient tolerance to this increased eKFM must be closely monitored. For example, anterior knee symptoms may be less tolerant to increases in eKFM if a quadriceps tendon or patellar tendon graft was used during ACLR and a slower progression may be necessary.

CROSS-EDUCATION

Cross-education refers to the ability to improve strength in the contralateral limb by performing unilateral exercises. This has been achieved through various training protocols, and a recent meta-analysis suggested eccentric muscle contractions and moderate volumes of exercise to best implement cross-education. Following ACLR, eight weeks of cross-education in addition to standard care improved quadriceps strength 28–31% more than control participants receiving standard care. The benefits of cross-education can be used throughout the continuum of rehabilitation, but perhaps most effectively in the early phases when the injured limb is not able to tolerate higher intensity strength training or when comorbidities such as patellofemoral chondrosis or anterior knee pain are limiting loading of the involved knee.

INTERVENTIONS FOR RATE OF FORCE DEVELOPMENT

RFD refers to the ability of the neuromuscular system to produce force quickly following the initiation of a muscle contraction. Force application during most sporting activities such as jumping and changes of direction occurs within very short time frames, with some activities such as ground contact times while sprinting occurring in under 200 ms. The momentum change in these activities is directly related to the impulse generated. In this context, impulse can be defined as force multiplied by time. Because there is a time constraint to these tasks, a higher RFD will allow more impulse to be generated in the same time frame and lead to better performance. Optimal development of RFD is dependent upon adequate development of muscle strength as maximal strength may account for 52–81% RFD variance. Improving RFD and impulse is typically targeted via training at high velocities, or with intent to perform exercises and movements explosively. It should be made clear that the intention to complete a movement with a high velocity is more important than the actual movement velocity. This has practical implications as one may train across a loading spectrum including both high and low loads as long as the intention to move explosively is present. Common training modalities include high intensity
strength training, Olympic weightlifting derivatives, plyometrics, accelerations, decelerations, and ballistic isometrics. The patient should be cued to “explode” or complete a repetition as fast and hard as possible to maximize the benefits of these exercises. While most interventions to improve RFD typically occur later in rehabilitation, one may begin targeting this earlier by manipulating tempos or intending to complete the concentric or eccentric portion of an exercise as quickly as possible, provided that the patient has already demonstrated proficiency in the same task in a slow and controlled manner. Even an intervention such as a quadriceps setting exercise may be utilized with an RFD emphasis by intending to complete the quad set “fast and hard.” The intensity of interventions for RFD should be increased in a gradual progressive manner to ensure the patient has adequate tissue loading capacity to tolerate increased forces.

Additionally, eccentric, concentric, and isometric muscle actions may be trained separately with examples of phase-specific exercises including drop lands, squat jumps, and isometric mid-thigh pulls, respectively. Once RFD and explosive strength are adequately developed, training may shift to place more emphasis on reactive strength. Reactive strength involves tasks utilizing the stretch-shortening cycle and uses the ability of muscles to store and utilize elastic energy to perform a concentric action in rapid succession from an eccentric action. Reactive strength is typically trained with plyometrics of progressive training intensities. During these exercises, the patient should attempt to minimize their ground contact time to promote reactive strength adaptations. It should be noted that literature has shown decreased knee flexion angles during landings following ACLR, so the clinicians should ensure that the patient is not adopting this strategy to offload the knee. The minimum detectable change for knee motion during landing during 2D video analysis has been reported to be 6–15 degrees, but this has not been established for visual inspection. When detected, it is suggested to implement task regressions to ensure proficiency prior to reimplmenting the task with the observed movement impairments. Additionally, one may promote increased knee flexion during landing by incorporating strategies previously reported to facilitate motor learning such as implicit instructions and external focus of attention, which further emphasizes the interdependency of several physiologic systems. Reactive strength training modalities may also aid in mitigating deleterious skeletal changes discussed earlier such as reduced bone mineral density.

CONCLUSION

This commentary has highlighted musculoskeletal considerations for rehabilitation following ACL injury and ACLR from a multi-physiologic systems approach. Several musculoskeletal alterations that occur after ACL injury and ACLR have been identified and serve as a foundation for guiding the rehabilitation process. Various clinically available testing methods for identifying and monitoring these deficits have been discussed, as well as interventions that integrate with other body systems to ultimately resolve movement limitations.

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SUPPLEMENTARY MATERIALS

Appendix A. Normative values of strength for each Level 1 cutting sport

Appendix B. Normative values of performance for each level 1 cutting sport
Invited Clinical Commentary

A Multi-Systems Approach to Human Movement after ACL Reconstruction: The Nervous System

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Postoperative rehabilitation of anterior cruciate ligament (ACL) reconstruction mainly focuses on the restoration of strength and range of motion with a long-term goal to return athletes to their prior level of activity. Of those wanting to return to sport, many are either unable and/or experience protracted recovery despite extensive rehabilitation. To holistically care for patients recovering from ACL reconstructions, reframing rehabilitation to consider a comprehensive systems approach (including musculoskeletal, cardiovascular, endocrine, and neurologic systems) may help improve treatment outcomes. The American Physical Therapy Association has adopted a vision statement that embraces the concept of a ‘movement system,’ but validation of the movement system has been challenging. Application of a multi-physiologic systems approach may provide a unique perspective to better understand the nervous system and its interactions after ACL reconstruction. The purpose is to focus on the nervous system contributions to a multi-physiologic system approach to rehabilitation from ACL reconstruction.

Level of Evidence 5

INTRODUCTION

Following anterior cruciate ligament reconstruction (ACL R), many athletes experience suboptimal outcomes including low rates of returning to sports, high rates of reinjury (graft and contralateral ACL ruptures), and early onset post-traumatic osteoarthritis. Traditionally, rehabilitation from ACLR focuses on restoring the musculoskeletal system to its pre-injured state (i.e., normalize strength, range of motion, biomechanics, etc.) with little targeted recovery of the neurophysiologic consequences of both the peripheral (PNS) and central nervous systems (CNS), coupled with the psychological contributions to physical recovery.

ACL injuries most commonly occur in strategy sports (i.e., soccer, basketball), that require high-velocity cutting, pivoting and deceleration. These high-speed sports require not only physical quickness, but also quick sensory integration and cognitive processing of the environment (i.e., sports balls, opponents, teammates) likely resulting in movement prediction errors. Feedforward (anticipatory/prediction) and feedback (reactive) loops of the nervous system allow an athlete to navigate and demonstrate success within these highly chaotic environments. For movement, the nervous system makes predictions based on previous experiences, then uses feedback (and error) from the movements to update future movement plans. The nervous system is a highly sophisticated and a crucial contributor to goal oriented, efficient movement during athletic activities.

As an effort by the American Physical Therapy Association (APTA) to establish the profession’s identity, the adoption of a new vision statement in 2013 called for physical therapists to ‘transform society by optimizing movement
to improve the human experience. From this, the human movement system was promoted as an effort to further establish professional identity. The movement system has been described by the APTA as being comprised of a collection of body systems including the nervous, musculoskeletal, endocrine, cardiopulmonary, and integumentary systems. In many ways, the integration of the body systems described in the movement system approach to rehabilitation integrates similar elements of a common theoretical model in motor learning, the dynamical systems theory. The dynamical systems theory is a well adopted framework pertaining to movement development, motor control, and skill acquisition which aims to explain variability in human goal-directed movement. Dynamical systems theory is a conceptual framework that builds understanding of a complex system (human movement) through individual component parts. The interaction and collaboration of component systems is what drives the success of the entire system, which is similarly described in the APTA movement system framework. This commentary provides a perspective where each physiologic system can be thought of as a component system necessary to efficiently optimize human movement. The purpose of this commentary is to focus on the nervous system contributions to a multi-physiologic system approach to rehabilitation from ACLR.

NERVOUS SYSTEM CONSEQUENCES ASSOCIATED WITH ACL INJURY AND RECONSTRUCTION

Models describing the neurophysiologic consequences to the sensorimotor system after ACL injury have previously been developed. In short, these models provide a framework outlining the impact of ACL rupture (i.e., mechanoreceptor instability, joint instability, and pain) on central nervous system (CNS) reorganization. CNS reorganization due to an afferent disruption (ligament rupture) leads to changes in efferent output to muscles, impacts reflexes, and involves voluntary and involuntary movement strategies. Common clinical manifestations of altered sensorimotor processing include altered knee mechanics during squatting, running, jumping, and hopping. Previous authors have aimed to better understand the cortical contributions to altered sensorimotor processing, potentially predisposing individuals to ACL injury risk as well as protracted recovery following ACLR. Research tools such as neuroimaging (functional magnetic resonance imaging [fMRI]) and transcranial magnetic stimulation (TMS) are commonly used to determine whole brain and efferent drive to the quadriceps bilaterally after ACLR. Greater deficits in quadriceps H-reflex are seen.

The spinal cord contributes to the recovery of quadriceps muscle activation, especially in the early phases after ACLR. Greater deficits in quadriceps H-reflex are seen.
acutely post operatively, but as time from surgery increases, deficits in spinal reflex excitability decrease relative to healthy individuals.\textsuperscript{39} In fact, evidence supports that at late timeframes (>24 months) post-reconstruction spinal reflex excitability is potentially increased.\textsuperscript{20} Therefore, the literature suggests that prolonged quadriceps activation deficits are mediated by the supraspinal level (corticospinal tract excitability) in the chronic stages of injury recovery.\textsuperscript{19,20} 

Ia afferent contributions to quadriceps activation deficits are difficult to quantify clinically, as they require expensive equipment (recording and stimulating electrodes, stimulator), time, and expertise to complete and interpret.\textsuperscript{40} The spinal cord with integration from cortical/subcortical regions is also critical for proprioception, pain (at rest), and vibration pain thresholds which continue to be impaired years after ACLR.\textsuperscript{41} Future research is required to understand the neurophysiologic contributions of each sub-system to overall recovery from ACLR and develop targeted interventions.

After ACL injury, alterations within the PNS secondary to afferent disruption manifests as diminished proprioceptive and balance control.\textsuperscript{42–44} Whenever sensory input is disrupted, spinal reflexes (e.g. H-reflex),\textsuperscript{39} vestibular responses (e.g. balance, proprioception),\textsuperscript{45} and motor responses (e.g. strength, speed, and power),\textsuperscript{46} are altered due to impaired/inhibitory afferent input. Originally the pathophysiology of poor dynamic control of the knee with diminished single-leg balance were attributed to the loss of ACL proprioceptive feedback, capsular disruption after surgery, and edema.\textsuperscript{45} However, Krosggaard et al.\textsuperscript{47} found that the reconstructed ACL graft required higher sensory stimulation than the native posterior cruciate ligament to elicit an inhibitory (afferent) muscular reflex response eight or more months after the ACLR, identifying that the ACL graft does not fully reinervate after reconstruction.\textsuperscript{47} Furthermore, Bonfim et al.\textsuperscript{45} found individuals after ACLR had increased anterior-posterior and medial-lateral sway that improved with heightened sensory input (light touch to a bar), as compared to the healthy cohort.\textsuperscript{45} Thus, the somatosensory deficit that occurs from ACL disruption appear to have negative consequences to both proprioception and balance long after ACLR surgery. Rehabilitation should aim to upweight the somatosensory system to promote restoration of afferent function. Over time, feedback loops like the H-reflex\textsuperscript{48} and some metrics of single-leg static balance improve.\textsuperscript{49,50} However, there continue to be alterations in afferent feedback and nervous system responses that cause poor biomechanical control during dynamic tasks such as jumping or cutting.\textsuperscript{39}

In addition to ACL mechanoreceptor disruption from the ligament rupture, skin sensory organs are also impaired secondary to surgical reconstruction. Pacinian corpuscles and Ruffini endings within the skin are thought to contribute to proprioception\textsuperscript{51} and pain responses. It has been assumed these sensory afferents from Pacinian corpuscles and Ruffini endings associated with light touch normalize within a month\textsuperscript{52,53} following reconstruction. However, if superficial skin sensation, pain, and sense of position are impaired long-term, they will likely alter somatosensory (afferent) input and influence CNS, interneuron, and pain-response pathways.

PSYCHOSOCIAL CONSIDERATIONS AND PAIN

While the biomechanical and biological factors for consideration after ACLR are of utmost importance, the psychosocial factors cannot be overlooked. The biopsychosocial model has continued to grow in acceptance among health care providers through the years since its introduction by Dr. George Engel.\textsuperscript{54–57} As understanding of the interplay between the biological, psychological, and social mechanisms continues to evolve, it is undeniable that each of these factors plays a significant role in recovery from ACLR. The biomedical deficit of a torn ACL and subsequent reconstruction are universal in all patients that present to rehabilitation after ACLR, however, the psychosocial aspects of each individual’s recovery are diverse. The literature surrounding the psychosocial factors impacting recovery from ACLR is growing.\textsuperscript{58,59} A large body of evidence in other populations, such as those with whiplash syndrome or chronic low back pain, exists that may help inform clinicians in understanding the psychosocial aspects of injury recovery.\textsuperscript{60–65} Wiese-Bjornstal’s biopsychosocial sport injury risk profile serves as a framework representing the various internal (biological and psychological) and external (physical and sociocultural) factors contributing to injury recovery.\textsuperscript{65} Utilizing the sport injury risk profile promotes consideration for the sociocultural influences (i.e., coach/team RTS time expectations), mixed psychological states (i.e., fear of reinjury), and acknowledgement of shifted athlete goals throughout the recovery process. Biologically, an athlete’s musculoskeletal, cardiopulmonary, integumentary and nervous system have been altered. The athlete must also process the confounding neurocognitive and environmental components of RTS (i.e., weather, fan/opponent reactions, altered decision making in sport). It is well established that neurocognition and emotions can influence adherence to rehabilitation programs.\textsuperscript{66} Adherence is a crucial component to successful recovery. With that in mind, clinicians should consider the multitude of psychosocial factors the athlete with ACLR must navigate during the rehabilitation process in order to maximize rehabilitation outcomes. 

The current understanding of pain has advanced significantly in the last couple of decades, which has led to changes in pain assessment methodology.\textsuperscript{57} Historically, pain rating scales have been used clinically as a measure of intensity, but are also viewed by some clinicians to be associated with the amount of tissue damage. It is now understood that pain rating scores are poor indicators of tissue health, especially as pain persists.\textsuperscript{67–69} However, utilization of pain rating scores,\textsuperscript{70} such as the numeric rating scale (0=no pain, 10=worst imaginable pain), still hold clinical value. Pain rating scores allow patients to express their pain and for the clinician to demonstrate compassion for the patient and their pain experience. During the rehab process, pain rating scores can provide a marker to acknowledge that some pain increase is normal and safe and a means to develop a patient-centered agreement on an acceptable pain experience.

Newer scales, such as the PROMIS Pain Interference Scale,\textsuperscript{71} may have utility with patients who are experiencing pain that is interfering with daily and functional ac-
tivities.\textsuperscript{72} This scale provides a self-reported measure of the consequences of pain on relevant aspects of the patient’s life. The Pain Interference Scale comes in a computer adapted testing format or short-form versions with four, six, and eight Likert questions. Because of the normative data collected, a representative T-score can be calculated to provide a standardized score with a mean of 50 and a standard deviation of 10. Other measures to assess catastrophizing (Pain Catastrophizing Score),\textsuperscript{73} kinesiophobia (Tampa Scale for Kinesiophobia)\textsuperscript{74} or sensitization (Central Sensitization Inventory),\textsuperscript{75} may be beneficial for patients experiencing ongoing pain and poor recovery to assess more complex constructs of the patient’s pain experience. Each self-reported outcome measure is best if chosen individually based upon a specific patient’s presentation and not applied universally to all patients.

**MULTI-PHYSIOLOGIC SYSTEM INTERVENTIONS FOR THE NERVOUS SYSTEM AFTER ACLR**

A major challenge clinicians face in clinical practice is concurrently addressing alternations in the nervous system after ACLR while simultaneously addressing deficits in the musculoskeletal, cardiopulmonary, and other systems. Thus, the purpose of this section is to provide explanations, interventions and rationale for integrating targeted nervous system interventions into rehabilitation post-ACLR within the context of a multi-physiologic systems approach to human movement.

**NERVOUS SYSTEM INTEGRATION WITH THE MUSCULOSKELETAL SYSTEM**

Immediate priorities in rehabilitation from ACLR consist of limiting knee joint effusion, pain and restoring full extension range of motion and quadriceps muscle function. A cascade effect exists where joint injury and effusion results in quadriceps arthrogenic muscle inhibition,\textsuperscript{76} making it difficult to achieve and maintain active end-range knee extension motor control.\textsuperscript{77} Therefore, it is standard of care to provide neuromuscular electrical stimulation (NMES) for at least six weeks after ACLR to optimize recovery of quadriceps function.\textsuperscript{78} Other modalities such as sensory transcutaneous electrical nerve stimulation (TENS) and focal knee joint cooling promote improved quadriceps function for a therapeutic window of targeted intervention.\textsuperscript{78,79} More recently, improving quadriceps muscle strength utilizing cross-training\textsuperscript{80} and eccentric exercise\textsuperscript{81} has also demonstrated effectiveness.

Motor control dysfunctions after ACLR are likely present immediately post-operatively but become more apparent in the intermediate stages of recovery, manifesting as a biomechanical tendency toward limb stiffness with decreased hip and knee flexion on the involved limb upon landing during single-limb hopping tasks.\textsuperscript{82} Additionally, trunk lean, hip drop, and dynamic valgus are biomechanically faulty positions that place the ACL in a position of excessive torque (force), load, and tension.\textsuperscript{83,84} As a result, rehabilitation interventions focus to restore biomechanical symmetry and often excessively raise the patient’s self-awareness of their lower limb position for all tasks (i.e., internal focus of attention). Growing evidence in motor learning indicates that for learning a goal-oriented skill, an internal focus of attention may be less optimal than an external focus of attention, in which the patient’s attention is directed toward the environment and actionable goal.\textsuperscript{15,85} For strategy sports, which comprise the majority of ACL injuries, promoting an external focus of attention in rehabilitation more closely mimics both the sport environment and associated neurocognitive demands. An external focus of attention and neurocognitive challenges can easily be implemented throughout the rehabilitation continuum.\textsuperscript{86,87} Neurocognitive interventions aim to challenge cognitive processes such as working memory, decision making, and response inhibition, which are a common requirement of team-based sports. In the early phases of rehabilitation through late stages and return to sport, incorporating interventions that challenge neurocognitive processing is attainable with little added time and resources (Table 1).\textsuperscript{88,89} Table 1 presents examples of internal and external intervention classes as well as clinical intervention examples with progression of both the motor and cognitive skills. The internal class consists of interventions that aim to manipulate the patient’s attentional focus and neurocognitive processing, whereas the external class are examples to manipulate the task or environment. Although motor learning, cognitive-motor, and visual-motor intervention categories are often displayed independently, it is essential to note the overlap in utility between them.

Acutely after ACLR, regaining standing balance control is one of the first interventions implemented to restore postural control and is the basis for progressing to more dynamic tasks such as walking, stair climbing and squatting. Balance requires sensory integration from multiple systems, the most pertinent being the somatosensory, vestibular, and visual systems.\textsuperscript{90} Multi-system integration for balance allows the nervous system to reweight or change the level of dependence between systems depending on the given context.\textsuperscript{90} After ACL injury, the use of the somatosensory system is decreased due to the disruption of ligamentous afferent receptors and a shift to visual dependence to maintain stability is noted.\textsuperscript{91} To appropriately restore balance, a clinician should aim to upweight the somatosensory system and decrease compensatory reweighting to the visual system.\textsuperscript{15,92,93} This can be accomplished by using visual disturbances (i.e., eyes closed, flashing glasses, etc.), virtual reality (i.e., smartphone or headset), and integrating neurocognitive challenges (Table 1) while simultaneously training balance and dynamic tasks. Clinicians should aim to increase somatosensory input using dynamically challenging positions such as squatting/lunging, and by adding unanticipated reactions such as squatting to an adjustable plinth and varying the plinth height between repetitions. When using movement-related interventions within the context of a multi-physiologic systems approach, it is paramount to consider the interaction between the musculoskeletal and nervous systems to optimize a patient’s recovery.
### Table 1. Classes of Interventions and Examples

<table>
<thead>
<tr>
<th>Class of Intervention</th>
<th>Intervention Example</th>
<th>Motor Task</th>
<th>Progression Ideas</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Focus of Attention    | External Focus of Attention  
"Keep your knee pointed at the cone as you lunge forward." | Forward lunge → Multidirectional lunge | "Perform a lunge in the direction where I am pointing." |
|                       | Arithmetic           
"As you perform straight leg raises, count backwards from 100 by 7s." | Straight leg raises → Straight leg raise hold/oscillate | "As you perform your straight leg raises, tell me the answer of the math problems on the flashcards I show you." |
|                       | Working Memory        
"As you perform your double leg squats, I want you to name all the professional basketball teams." (or something patient-centered) | Double leg squat → Split squat | "As you perform your double leg squats, I want you to try to name the professional basketball teams in alphabetical order." |
|                       | Auditory              
"Perform a 45° lunge when you hear the command ‘ball’!" (simulating a basketball pass to an open teammate) | 45° lunge → Drop step lunge | "Perform a 45° lunge if you hear the command ‘ball’ (simulating a basketball pass), and a drop step lunge if you hear the command ‘match up’ (simulating defensive shuffle)." |
|                       | Single-Step           
"When I flash the number 3, perform a forward lunge, when I flash the number 1 perform a curtsy lunge." | Increase difficulty in motor task accordingly | Use more challenging methods of arithmetic |
|                       | Double-Step           
"When the math problem sums to an even number jump left. When the math problem sums to an odd number jump right." |                  |                  |
| **External**          |                      |            |                  |
| Manual (object manipulation) | Ball Toss "As you perform continuous single leg squatting, we will toss this ball back and forth." | Forward toss → Lateral toss | "As you perform continuous single leg squatting, I want you to catch the yellow ball with your left hand and the red ball with your right hand." |
|                       | Ball Dribble          
"Dribble the ball in place as you perform a single leg squat and hold." | Single leg squat → Alternating sides single leg squat | "Dribble the ball using a front-back dribbling direction as you perform a single leg squat and hold." |
| Perturbation (external force) | During any exercise, a quick manual perturbation to the patient is given. | Providing perturbations toward the center of mass (trunk) versus extremities | Moving from anticipated to unanticipated perturbations. |
| Environment           | Clinic Environment    
Interventions might start in quiet treatment room and progress to busy weight area. | Interventions in a clinic environment progressing to on-field/court |                  |
|                       | Vision                
Interventions using eyes open versus closed | Transition to a dimly lit area or use visual disturbance training systems/glasses; Visual tracking with numbers written on a ball – "tell me the number written on this tennis ball before you catch it." |                  |
The PNS and CNS are extremely metabolically active tissues. The human nervous system accounts for two to three percent of an individual’s total body mass, yet 20-25 percent of the available oxygen circulating in the bloodstream is consumed by the nervous system. Improved aerobic exercise has been shown to have multiple effects on the brain and neurocognition. Evidence supports the link between aerobic activity and improved cognition in older populations with and without cognitive impairment. Even in younger populations (ages 20-67) without cognitive impairment, improved executive function and increased cortical thickness were found after participating in a six-month, four times per week aerobic training regime. Acute bouts of moderate intensity exercise also appear to promote improved cognitive processing speed. Therefore as an athlete recovers from ACLR, the importance of cardiovascular exercise for overall health, returning to prior level of function, and impact on cognitive function should be appreciated.

Integrating neurocognitive training and cardiopulmonary conditioning can begin as soon as the wound is healed, and range of motion is adequate for the task (such as aquatic therapy, swimming, and stationary biking). When implementing neurocognitive training with cardiopulmonary tasks, one consideration is not just the physical retraining of the cardiopulmonary system but the psychological aspects of being able to break through mental/emotional barriers.

As the athlete progresses to RTS tasks, biomechanics, neurocognitive training, psychological readiness, and cardiopulmonary conditioning all converge. If any of these factors have not been addressed prior to RTS tasks, they will likely hinder an athlete's ability to return to full activity safely. Repetitive tasks such as walking, biking, and jogging should be seen as opportunities for neuromuscular retraining and neurocognitive training. As running, jumping, and cutting tasks are added, psychological readiness and neurocognitive training should progress to more complex neurocognitive problem-solving and increased speed and power once strength, form, and psychological readiness goals have been met. Prior to RTS, cardiopulmonary conditioning should be assessed, using speed and endurance tests, as well as resting heart rate and VO2max recovery to evaluate cardiopulmonary recovery prior to progressions. The interplay between the cardiopulmonary and nervous systems are strong contributors to physical function after ACLR.

NERVOUS SYSTEM INTEGRATION WITH THE INTEGUMENTARY SYSTEM

Elements of the PNS should be evaluated and integrated into the treatment plan post ACLR and can be directed cohesively while performing neurocognitive challenges as previously discussed. This can include range-of-motion exercises and early exercises such as quadriceps sets, long arc knee extensions, and standing pre-gait exercises (i.e., weight shifts, squats, calf raises, etc). Additionally, interventions to normalize sensation should start early with scar mobility and addressing areas of decreased or altered sensation. Sensation can be addressed through TENS for pain relief during provocative activities that cause pain. Such activities can be progressed through different textures (from a mat table to a floor) or intensity (kneeling weight in quadraped transitioning to tall kneeling). The afferent input from the integumentary system, including tactile sensation from the skin and incision healing, provides constant feedback that is integrated with the rest of the neurological input of the body.

The integumentary system is best treated by first keeping the incision site clean and hydrated and second, maximizing healing and normalization of sensation. If the wound becomes infected, an uptake in inflammatory cytokines will increase the inflammatory state. The increased inflammatory state can lead to increased PNS sensitivity, leading to inflammatory and neuropathic pain. Antibiotics can help decrease inflammation and the residual inflammation and neuropathic pain should be addressed. Creams and wraps can help the hypertrophy, but a scar revision surgery may be warranted if they are not successful. Another side-effect found with alteration of the integumentary system is the development of numbness along the saphenous nerve. Damage to the saphenous nerve after surgery is common, and appropriate retraining of the somatosensory system during the peripheral nerve regeneration process is needed. In the context of a multi-physiologic systems approach, interventions dual-targeting the integumentary system and nervous system impairments are warranted.

NERVOUS SYSTEM INTEGRATION WITH THE CARDIOPULMONARY SYSTEM

The PNS and CNS are extremely metabolically active tissues. The human nervous system accounts for two to three percent of an individual’s total body mass, yet 20-25 percent of the available oxygen circulating in the bloodstream is consumed by the nervous system. Improved aerobic exercise has been shown to have multiple effects on the brain and neurocognition. Evidence supports the link between aerobic activity and improved cognition in older populations with and without cognitive impairment. Even in younger populations (ages 20-67) without cognitive impairment, improved executive function and increased cortical thickness were found after participating in a six-month, four times per week aerobic training regime. Acute bouts of moderate intensity exercise also appear to promote improved cognitive processing speed. Therefore as an athlete recovers from ACLR, the importance of cardiovascular exercise for overall health, returning to prior level of function, and impact on cognitive function should be appreciated.

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As the athlete progresses to RTS tasks, biomechanics, neurocognitive training, psychological readiness, and cardiopulmonary conditioning all converge. If any of these factors have not been addressed prior to RTS tasks, they will likely hinder an athlete’s ability to return to full activity safely. Repetitive tasks such as walking, biking, and jogging should be seen as opportunities for neuromuscular retraining and neurocognitive training. As running, jumping, and cutting tasks are added, psychological readiness and neurocognitive training should progress to more complex neurocognitive problem-solving and increased speed and power once strength, form, and psychological readiness goals have been met. Prior to RTS, cardiopulmonary conditioning should be assessed, using speed and endurance tests, as well as resting heart rate and VO2max recovery to evaluate cardiopulmonary recovery prior to progressions. The interplay between the cardiopulmonary and nervous systems are strong contributors to physical function after ACLR.

<table>
<thead>
<tr>
<th>Class of Intervention</th>
<th>Intervention Example</th>
<th>Progression Ideas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distraction/Attention</td>
<td>Gradually introduce relevant distractors according to sport</td>
<td>Moving from anticipated to unanticipated distractors (sound, play calling, simulated game situations, etc.); Progress from stationary to moving objects (chair v. coach); Incorporate teammates into return to sport drills</td>
</tr>
<tr>
<td>Object/Opponent Navigation or Avoidance</td>
<td>“While performing this squatting exercise, don’t let the tennis ball contact you after it’s thrown. You may need to duck or shift your weight.”</td>
<td>“While performing this side-stepping exercise, don’t let the tennis ball contact you after it’s thrown. You may need to duck or shift your weight.”</td>
</tr>
<tr>
<td></td>
<td>Therapist is positioned (hidden) behind an object and uses a foam roll to serve as the “opponent.” As the athlete moves toward the barrier, the therapist quickly positions the foam roll on either side of the barrier – requiring the athlete to move in the opposite direction.</td>
<td></td>
</tr>
</tbody>
</table>

A Multi-Systems Approach to Human Movement after ACL Reconstruction: The Nervous System
PAIN & PSYCHOSOCIAL CONSIDERATIONS

A comprehensive approach to rehabilitation after ACLR demonstrates a critical need for clinician mindfulness to treat each patient as a whole, including acknowledging psychosocial factors such as patient’s changing their “sense of self” or athletic identity. Some patients may no longer view themselves as an “indestructible high performing athlete,” but as someone who can get injured and may not return to the same level of performance. When an individual has doubts and suffers loss, fear and anxiety are natural psychological responses.105,106 Rebuilding a sense of safety and security is vital within the rehabilitation process to overcome those fears. Evidence demonstrates that lower levels of fear and higher self-efficacy scores are associated with better resolution of knee impairments.107 Discussions over normal psychological states of fear and worry need to occur within the context of using psychological informed practices throughout recovery. The use of graded exposure with exercise and activities has been shown to help reduce fear and improve functional gains.108–110

CONCLUSION

In alignment with a multi-physiologic systems approach to human movement, clinicians should aim to comprehensively treat patients through a multi-system lens. The nervous system is vastly integrated with the other system components essential for promoting optimal patient function after ACLR. Incorporating intervention strategies that target the nervous system, address the psychosocial aspects of rehabilitation, and incorporate an integrated systems approach are needed throughout the continuum of recovery.

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Clinical Commentary/Current Concept Review

A Multi-Systems Approach to Human Movement after ACL Reconstruction: The Cardiopulmonary System

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Keywords: anterior cruciate ligament, anterior cruciate ligament reconstruction, cardiopulmonary, movement system, rehabilitation

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The cardiopulmonary system plays a pivotal role in athletic and rehabilitative activities following anterior cruciate ligament reconstruction, along with serving as an important support for the functioning of other physiologic systems including the integumentary, musculoskeletal, and nervous systems. Many competitive sports impose high demands upon the cardiorespiratory system, which requires careful attention and planning from rehabilitation specialists to ensure athletes are adequately prepared to return to sport. Cardiopulmonary function following anterior cruciate ligament reconstruction (ACLR) can be assessed using a variety of methods, depending on stage of healing, training of the clinician, and equipment availability. Reductions in cardiovascular function may influence the selection and dosage of interventions that are not only aimed to address cardiopulmonary impairments, but also deficits experienced in other systems that ultimately work together to achieve goal-directed movement. The purpose of this clinical commentary is to present cardiopulmonary system considerations within a multi-physiologic systems approach to human movement after ACLR, including a clinically relevant review of the cardiopulmonary system, assessment strategies, and modes of cardiopulmonary training to promote effective, efficient movement.

Level of Evidence

5

INTRODUCTION

Systems with multiple levels cannot be fully understood by examining their component parts, as the outcome of their interactions is different from the sum of the parts. Since 2013, the American Physical Therapy Association (APTA) has promoted the movement system in physical therapist practice, education, and research as ‘the foundation for optimizing movement to improve the health of society.’ Through the integration of body systems and functions, the movement system essentially refers to the body’s ability to produce and sustain movement. Barriers to implementation and validation have arisen since the adoption of the term movement system with efforts ongoing to promote its use. A framework that has been more readily accepted for describing motor control, movement dysfunction, and skill acquisition is a dynamical systems theory approach. Dynamical systems theory aims to explain variability in goal-directed human movement and enhance the understanding of a complex system through its component parts. Similarly, the APTA movement system and dynamical systems theory place importance upon the functions and interactions of component systems in support of the entire system as a whole. A physiologic system, individually, can be representative of a component system that is needed for achieving purposeful, goal-oriented human movement. With this understanding, a multi-physiologic systems approach may offer a useful perspective for clinicians during rehabilita-

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tion after anterior cruciate ligament reconstruction (ACL R). The purpose of this clinical commentary is to present cardio pulmonary system considerations within a multi-physiological systems approach to human movement after ACLR, including a clinically relevant review of the cardiopulmonary system, assessment strategies, and modes of cardio pulmonary training to promote effective, efficient movement.

CARDIOPULMONARY SYSTEM CONSIDERATIONS AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION (ACLR)

The cardiopulmonary system has important roles when interacting with other systems such as thermoregulation when performing cardiovascular training, providing blood flow to working muscles during strength training, and supporting a highly metabolically active nervous system. This is not to mention the association between aerobic activity and improved cognition in older populations and enhanced executive function in younger individuals. The cardiopulmonary system, along with other body systems, experiences change after ACLR. Anterior cruciate ligament (ACL) injuries typically occur while landing from a jump or with change of direction, which is common in several team sports such as basketball, soccer, and football. These sports require high-intensity intermittent actions interspersed with sustained low-intensity activities. Since most of these sports are predominantly running based these efforts fall under "repeated-sprint ability" (RSA) which is defined as brief sprints (<10s) followed by incomplete (<60s) recovery. These activity requirements place unique demands on both the anaerobic and aerobic energy systems. Ultimately all three energy systems (phosphocreatine, glycolytic, aerobic) will be involved during intermittent cycles of sprint-recovery, but the degree to which each energy system is utilized depends on factors including but not limited to the particular sport, the position played, and game/match situation or phase.

For example, a recent systematic review examining the activity demands during basketball reported guards performed more high-intensity movements throughout the course of a basketball game compared to forwards and centers. Although the demands for each sport and individual may be unique, the general energy system demands seen across field and court sports (which also tend to involve most ACL injuries) are broadly similar. After an ACL injury, these energy systems become detrained secondary to the reduction in stimulus in accordance with the specific adaptation to imposed demands (SAID) principle. This shift in ability can be viewed as the envelope moving "to the left" if viewed within the "envelope of function" model. This model, initially proposed by Scott Dye for the musculoskeletal system, contrasts the individual’s physiological capacity with the task demands on an intensity/duration spectrum and has been adapted for this commentary to apply to the cardiopulmonary system, as depicted in Figure 1. The goal of rehabilitation is to shift the envelope of function to the right so that the task demands fall below the maximum tolerated line. Unfortunately, rehabilitation often fails to fully address this shift, resulting in athletes returning to play without the energy system development needed for their sport.

Since clinical tests of the cardiopulmonary system predominantly measure change in performance as a proxy for cardiopulmonary system changes, it is important to understand that performance can improve due to a combination of underlying factors and may not reflect the adaptations desired. For example, cardiac output is the product of heart rate (HR) and stroke volume (SV) which is further determined by ventricular volume and ejection fraction. An increase in performance after an intervention to address central factors such as SV could be seen due to an increase in HR alone which would indicate a failed intervention but still show an increase in performance. As such, the clinician must interpret test results with caution and rely on sound exercise prescription principles that maximize the probability of seeing the desired adaptations being addressed. The impacts of undergoing ACLR on the cardiopulmonary system are under-represented in the scientific literature compared to other areas of the rehabilitation and recovery process. Most of the available literature addressing detraining of the cardiopulmonary system focuses on issues secondary to cessation of activity in an uninjured population. In turn, much of the available literature on detraining and re-training post-ACLR focuses on neuromusculoskeletal impairments and return to sport.

CARDIOPULMONARY SYSTEM REVIEW

Competitive athletics impose high demand upon the cardiorespiratory system. For example, during a 90-minute soccer game, players have been reported to run ~10km at intensities as high as 75% of their peak oxygen uptake (VO2 peak) as well as covering 215 +/- 100 meters at sprint speeds. Significant demands on the cardiopulmonary system are seen across a wide variety of sports including those viewed as anaerobic such as American football which requires wide receivers to cover 5,530.6 +/- 685.6 yards in a game that includes 22 +/- 8 max acceleration efforts. Human physiology relies on the energy stored in one of the phosphate bonds in adenosine triphosphate (ATP) to power all activities. Breaking this bond

Figure 1. Physiological Response to Task Demands

changes ATP to adenosine diphosphate (ADP) which must then be converted back to ATP by one of the three main energy systems: phosphocreatine (ATP-Pcr), glycolytic, and aerobic. The cardiopulmonary system plays a key role in supplying the required energy resources and shuttling off by-products such as carbon dioxide, lactate and H+ ions. The following section briefly outlines some of the key considerations for the various energy systems.

PHOSPHOCREATINE (ATP-PCR) SYSTEM

An important component of the ATP-Pcr system, creatine-phosphate (CP), assists with anaerobic production of ATP for quick bursts of activity and muscle contractions in response to the demands of the sport as outlined in Table 1. These CP levels fall significantly during brief intense activity, such as during high-speed efforts in soccer where they can drop below 75% of resting levels due to the energetic demands. In fact, it has been estimated that the actual drop in CP may be closer to 60% of the resting levels. It has been reported that CP levels in individual muscle fibers experience near depletion when fatigue occurs as a result of repeated intense activities showcasing the importance of the energy system’s ability to rapidly replenish. This system is limited by the storage of ATP and phosphocreatine, relies on the aerobic system for recovery, and is limited in trainability. Due to its nature and the limited adaptive potential of this system it tends to both train and detrain rather quickly (<2-3 weeks) which means that it is best trained and maintained via brief and frequent exposures when needed to supplement practice and game demands.

GLYCOLYTIC SYSTEM

Lactate is a key byproduct of the glycolytic system due to cellular metabolism in muscles working to meet the demands of exercise. This process occurs when pyruvate production exceeds the uptake ability of the glycolytic muscle fiber resulting in its reduction to lactate. This molecule has had an interesting history and was viewed as a waste product and cause of fatigue for most of the 20th century. The reality is that it acts a buffer against fatigue due to its use of 70-75% of the released H+ ions for transportation out of the working muscle and becomes an important energy source during high intensity exercise when it is aerobically metabolized by an oxidative muscle fiber. It can also be used by the heart, liver, or brain as an energy source and functions as a pseudo-hormone where it interacts as a signaling molecule with multiple anabolic pathways and plays a role in norepinephrine release and brain plasticity. Multiple studies have described the average blood lactate threshold ([BLa]) among athletes during soccer games to be 2-10 mmol with muscle lactate concentrations ([MLa]) increasing to approximately 4 mmol/kg after periods of intense activity, which is an increase of 400% from resting values. Lactate can be converted to pyruvate and subsequently glucose through the process of gluconeogenesis where it functions as a fuel source for the aerobic system.

Glycogen is a "readily mobilized storage form of glucose" which is an important energy source during prolonged athletic activity. Studies have reported inconsistent levels to which glycogen is reduced during the course of a soccer game, with some noting decreases of 90% (from 100 mmol/kg to 10 mmol/kg) while others report decreases of only 35-60% (from 100 mmol/kg to 40-65 mmol/kg). Much like with CP levels, muscle glycogen levels have been found to decrease dramatically in individual muscle fibers in direct relation to the duration of activity over the anaerobic threshold regardless of muscle fiber type. The glycolytic energy system is fairly trainable but produces energy at a slower rate (50% of ATP-Pcr) and also adapts at a faster rate compared to the aerobic system (~3-4 weeks).

Table 1. Sport Specific Demands

<table>
<thead>
<tr>
<th>Sport</th>
<th>Work:Rest Ratio</th>
<th>Total Locomotor Distance (mean ± SD)</th>
<th>Intensity</th>
<th>Movement Demands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basketball</td>
<td>6 sec:22 sec</td>
<td>7.558 ± 575 meters</td>
<td>Sprint Efforts = 55 ± 11</td>
<td>- COD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>COD/Lateral Movement = 94 ± 16</td>
<td>- Lateral movement</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Jumps = 44 ± 7</td>
<td>- Jumping</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Acceleration/ Deceleration</td>
</tr>
<tr>
<td>American Football (WR)</td>
<td>5.23 sec:36 sec</td>
<td>5.530.6 ± 685.6 yards</td>
<td>Sprints = 13 ± 6</td>
<td>- Sprint</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max Accel Efforts = 22 ± 8</td>
<td>- Acceleration/ Deceleration</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max Decel Efforts = 16 ± 5</td>
<td>- Collision/Contact</td>
</tr>
<tr>
<td>Soccer</td>
<td>8.5:4.4 purposeful movements</td>
<td>11.393 ± 1,016 meters</td>
<td>Sprint Distance = 215 ± 100 meters</td>
<td>- Sprint</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- Acceleration/ Deceleration</td>
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<tr>
<td></td>
<td></td>
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</tbody>
</table>

COD= change of direction
AEROBIC SYSTEM

The aerobic system produces ATP at the lowest rate per unit time but is limited by oxygen supply and uptake as well as the availability of various substrates and enzymes. It also plays a significant role in recovery between intense bouts and contributes a significant portion of the ATP used during repeated sprints. This system is highly trainable due to its high ceiling for adaptation but also takes much longer to train (four to eight weeks for initial changes and three to four months for significant adaptations) compared to the previous two systems. After cessation of training, the athlete’s aerobic performance can be maintained for ~1 month with increases in HR at similar intensities compensating for early detraining effects such as blood volume changes and loss of ventricular size. As detraining continues, all adaptations will reverse at a rate similar to the initial adaptation and by 3–4 months the majority of previous adaptations will have been lost.

Of primary concern following ACLR is the effect of detraining on cardiovascular fitness. Reductions in cardiovascular function may influence the selection and dosage of interventions that are not only aimed to address cardiopulmonary impairments, but deficits experienced in other systems as well. In an athlete who has undergone ACLR, long term (>4 weeks) changes in cardiovascular fitness are generally the most relevant. Studies on detraining show a longer term drop of maximum rate of oxygen consumption (VO2max) in highly trained individuals of up to 20% after cessation of exercise. In trained individuals, this decrease in VO2max was much more significant with some studies showing a complete regression to untrained levels in a similar timeframe after cessation of exercise.

When examined in a ACLR population, VO2max was 20% lower pre- and 15% lower six months post-ACLR in professional soccer athletes when compared to controls. However, while VO2max is a metric that is often used it suffers from lack of ability to predict performance, especially in RSA type settings, and changes in VO2max do not always accurately reflect underlying adaptations to training and detraining.

In the same study on soccer players, athletes post ACLR had significantly slower running speeds compared to controls pre- and six months post-ACLR at both anaerobic threshold (VT1), which is the point at which lactate begins to accumulate within the blood and ventilation rate increases in an attempt to clear the increased production of carbon dioxide (CO2), and lactate threshold (VT2) which occurs when the buffer system is no longer able to clear lactate at the rate it is produced.

The acute deconditioning following an ACL injury results in a reduction in peak VO2 (VO2peak) due to changes occurring both in the peripheral muscle and due to myocardial remodeling. Even after completing a full ACLR rehabilitation program many athletes may still demonstrate reduced VO2peak and ventilatory threshold (VT). This reduction in aerobic conditioning is of concern, as certain field tests have been shown to be valid assessments of estimating aerobic endurance performance while also holding predictive value for lower extremity musculoskeletal injuries.

Attaining adequate sport-specific fitness levels may be important to better prepare for the demands of the sporting tasks. Participating in a preseason seven-week conditioning program that included cardiovascular conditioning was associated with reduced lower extremity injury rates compared to those who were untrained, and should be included as part of a comprehensive conditioning program. By adequately training cardiopulmonary fitness, this may have an impact on musculoskeletal health and should be considered when taking a multi-physiologic systems approach to rehabilitation after ACLR.

RESULTS OF DETRAINING

CARDIOVASCULAR

Complete cessation of exercise training (detraining) results in a multitude of physiological changes in the cardiovascular system which are initiated primarily by reductions in circulating plasma volume. Significant reductions in plasma volumes have generally been reported following four weeks of detraining but may occur after only two days. This reduction in circulating plasma volume reduces cardiac preload which induces a concomitant remodeling to the heart. This cardiac remodeling appears to follow a structure-specific pattern. Pedari et al reported that four weeks of detraining caused significant reductions in left ventricular (LV) wall thickness, LV mass, and right atrial area. However, after eight weeks of detraining a significant reduction in right ventricle chamber size was observed but without any additional changes to the LV wall thickness.

Along with these structural changes to the heart, many functional changes occur. Following two to four weeks of detraining, a 12% reduction in exercise SV, and an 11% increase in submaximal HR have been reported. These changes to HR responses following detraining have been attributed to multiple mechanisms including reduced parasympathetic outflow to the sinoatrial node, altered baroreceptor sensitivity, and beta-adrenergic hypersensitivity. Additionally, total heart volume (THV) and ventricular end diastolic volume decreases following ACLR, however, it appears as though only THV spontaneously improves upon reinitiating exercise training. Furthermore, reductions in end diastolic volume, SV, cardiac output (CO), ejection fraction, hemoglobin concentration, and hematocrit and increase resting heart rate have been observed in soccer players after ACLR. Altogether these physiological adaptations to the heart following detraining impair CO and reduce peak exercise capacity, which in turn may impact other interventions that target other body systems that ultimately work together to create efficient, goal-directed movement. In addition to changes in the heart, detraining may augment circulatory and ventilatory responses to exercise. After two to four weeks of detraining has been shown increase total peripheral resistance, reduce skeletal muscle capillarization, and reduce conduit artery diameter and blood flow. These vascular changes impair perfusion and oxygen delivery to working muscles and also increase cardiac afterload. The changes in blood flow to working muscles may be an important physiologic system integration especially

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after ACLR, as recovery of quadriceps strength is a key facet of rehabilitation and impacts patient outcomes.57,58

PULMONARY/VENTILATORY

The effects of detraining on ventilatory responses are inconsistent in the literature. Attenuated initial ventilatory responses have been reported following 20 days of inactivity.59 Detraining has also been shown to reduce maximal ventilatory volume and oxygen pulse during exercise.40 However, these effects on the respiratory system appear to be more pronounced in highly trained athletes.40 No significant changes in ventilatory responses or markers of ventilatory efficiency (VE/VCO2 slope) were found following six weeks of detraining in young soccer players.60

CARDIOPULMONARY SYSTEM ASSESSMENT AFTER ACL RECONSTRUCTION

Cardiopulmonary function following ACLR can be assessed using a variety of methods, depending on stage of healing, training of the clinician, and equipment availability. It is important to consider what is being measured when a test is chosen. Broadly speaking, the workload and the individual's response can be divided into external (the workload imposed on the organism), internal (the physiological response to the external workload), and psychophysiological (the perception of effort by the individual).61 Heart rate is one of the most common methods used to evaluate and predict overall cardiorespiratory fitness for team-based athletes; however, other assessments have been utilized including blood lactate concentration ([BLa]), estimated VO2max, rating of perceived exertion (RPE), metabolic equivalent testing (MET), respiratory exchange ratio (RER), and VT.13,14,62 A method for determining overall fitness that has become more accessible due to advances in technology is energy expenditure (EE).63,64 EE is a useful metric as it can be expressed as the amount of energy an individual expends across several conditions, which may include rest, submaximal/maximal exercise, or recovery after exercise.65 EE can be assessed in a variety of ways including wearable options like accelerometry, pedometry, and more intensive options such as indirect calorimetry (IC) or the doubly-labeled water (DLW) method.64

HEART RATE

HR assessment is a measure of internal workload and has many options of implementation such as a manual or automated measure of pulse rate, electrocardiogram (ECG), and Holter machine monitoring. These methods have been utilized since at least the 1970's to quickly assess HR with varying degrees of accuracy.56,67 However, starting in the 1980's, access to HR monitoring via ECG chest straps and wrist-worn electronic devices have been the preferred option. HR monitoring with chest-worn ECGs as well as wrist-worn optical blood flow monitors have provided accurate HR readings when compared to ECG, though it is believed that chest-worn devices provide greater accuracy.56,68-70 As with any measurement, the proper use of the device is key for determining an accurate HR regardless of the model. Speed is another factor that can influence readings with some data showing the accuracy of HR monitoring devices may decrease with increased speed, particularly when running.67-70 While there is a large amount of data on HR in team sport athletes at various levels of play, most of this research has been conducted on male subjects.

RATING OF PERCEIVED EXERTION (RPE)

The use of RPE is based on the subject’s perception of effort to the external load and is therefore a measure of psychophysiological load. However, it has been shown to correlate well with other measures such as HR and blood lactate levels.71 Gunnar Borg developed the Borg Scale in 1982 to quantify perceived exertion during activity and modeled it on measures of heart rate.72 In the Borg Scale, the participant typically rates their perceived level of exertion on a scale of 6 to 20, with higher numbers representing a greater effort. A modified version of the Borg Scale (CR-10) has also been developed with perceived exertion rated on a 1 to 10 scale.73,74 The Borg Scale is highly correlated with HR as well as [BLa] and has been found to be a valid method for estimating session workloads.71 While both the original or modified Borg Scale can be utilized at various stages throughout the course of rehabilitation following ACLR, the modified scale tends to be easier to implement. This is especially true if using session RPE which gives a rating of total session workload (sRPE). The sRPE is calculated by taking the total duration of the session and multiplying it by the RPE obtained after the session ends. In general, it is advised that the sRPE be taken a short period after the session has ended but there is no need to wait the original 30 minutes.18 For reliability, it is important to use both the verbal and visual anchors and perform the collection the same way every time.

CARDIOPULMONARY EXERCISE TESTING (CPET)

While various field tests can provide an assessment of aerobic fitness which may estimate VO2peak, the most accurate method is the use of Cardiopulmonary Exercise Testing (CPET) with analysis of expired ventilatory gases.75,76 Guidelines on standardized testing parameters have been provided by various professional organizations.76 Most protocols utilize either a stationary cycle ergometer or treadmill.76 There have also been protocols adopted using motor driven skate treadmills for hockey players77 and treadmill skiing. Additional measures obtained from CPET such as VT are also indicators of training status and physical condition across sports.21,78 There is some data to suggest the implementation of CPET such as in pre-season where VO2peak was shown to be an independent predictor of injury at any point during the competitive season in collegiate soccer players.79 Despite the well-established relationship between the data obtained from CPET, notably VO2peak and VT, its use in return to sport decision making following ACLR is limited, likely due to equipment availability and time constraints. Most of the available literature investigating the role of CPET for return to sport following ACLR has been in soccer players.13 De Almeida et al reported that even after
six months of rehabilitation following ACLR in professional soccer players both VO2peak and VT were still reduced compared to non-injured athletes. It is worth noting that VO2peak typically remains stable within season and between seasons in elite soccer players. Therefore, the differences in the study by De Almeida essentially reflects reductions compared to population-based norms. These results suggest that CPET can be used to accurately identify persistent impairments in VO2peak and other markers of aerobic fitness following ACLR. These measurements obtained by CPET can be compared to sport specific measures to accurately and objectively determine if an athlete has attained the requisite aerobic fitness for their sport. The use of preseason CPET may also permit athlete-specific comparisons following ACLR and assist in screening and injury risk reduction processes.

MAXIMUM AEROBIC SPEED (MAS)

Much like RPE, maximum aerobic speed (MAS) is one of the most clinically friendly ways to both assess an individual’s fitness and obtain a metric that can be used for programming. This combined with the fact that it only takes five minutes makes it a very easily implemented option. This test is designed to give the maximum speed at which the task can be performed while relying on the aerobic system. The test can be performed on any piece of equipment that allows for a measurement of total work done but traditionally is used with running, biking, or rowing. To perform the test, the individual is encouraged to go as far/hard as they can for a 5-minute period after which the total distance is divided by time. For a detailed review of prescription in rehabilitation based on MAS see Morrison et al.

WINGATE TEST

The Wingate Test is one of the most frequently utilized tools for assessing anaerobic conditioning and muscle power production. The test involves cycling with 100% effort on a stationary bike ergometer for 30 seconds with a resistance, sometimes referred to as breaking force, of 7.5-8.9% of the participant’s body mass, though some authors advocate for the resistance to be as high as 11%. The Wingate Test has been researched significantly and has been determined to be a reliable assessment. Normative values have been established for men’s soccer and highly-trained women participating in various sports.

While the Wingate Test primarily assesses anaerobic performance, it has been estimated 18-30% of the participant’s performance can be tied to their aerobic conditioning. Because the Wingate Test does not require a change in motion and is largely non-weight-bearing, it can be conducted earlier in rehabilitation compared to other tests that place higher demands on the musculoskeletal system. It can be completed once the athlete has obtained sufficient quadriceps control and has been cleared to exercise on a stationary bike. Specific timeframes will vary, but it is feasible the Wingate Test may be implemented as early as one to three months post-ACLR depending on surgical and patient factors.

YO-YO INTERMITTENT RECOVERY TEST

The Yo-Yo intermittent recovery test comes in three different variations and assesses both aerobic and aerobic conditioning. It involves the participant running from one marker to another placed 20 m away and then back to the first followed by a 10 second recovery interval where they walk/jog to a third cone five meters back from the starting cone. This test progressively increases the velocity in stages until the subject fails to arrive at the designated cone in the allotted time for the second time. The participant’s speed is dictated by electronic beeps that sound more rapidly as the test progresses. The full Yo-Yo intermittent recovery test can be completed on two levels, with level one having a starting speed of 10-13 kph and level two starting at 13-15 kph. There is also a rehabilitation specific variation that has been proposed using time as a cutoff and tracking HR at that point. The assessment has been found to have high reproducibility, sensitivity, and it is a valid aerobic conditioning test for male athletes, however, its validity among female athletes has been questioned. Reference values have been established for males and females across multiple sports and various levels of play. The Yo-Yo intermittent recovery test requires running at fast speed as well as multiple changes of direction. Therefore, the rehabilitation specialist should be confident that the athlete has reached the appropriate rehabilitation milestones prior to administering the assessment. It is the perspective of the authors that the Yo-Yo intermittent recovery test is usually conducted beginning six months following ACLR depending on clinical status.

MODES OF CARDIOPULMONARY SYSTEM TRAINING

The mode and progression of cardiopulmonary training is typically determined by several factors such as postoperative timeframe, clinical status, and training goal(s). The reader is referred to Buckthorpe et al 2020 for a ten task-based progression following ACLR. The tasks in the progression include walking, bilateral foundational movements, unilateral foundational movements, bilateral landing, running, bilateral plyometrics, unilateral jumping/landing, unilateral plyometrics, pre-planned multidirectional movements, and sport-specific movements. Although many options for cardiopulmonary training exist, several common applications for post-ACLR will be discussed.

The primary focus of cardiopulmonary training during the first few months after ACLR is to maintain and (re)develop a baseline level of aerobic conditioning as the surgical graft heals and impairments in other physiologic systems (musculoskeletal, integumentary, nervous) are addressed. For example, interventions that target the musculoskeletal system typically aim to address deficits in range of motion and strength during the early postoperative timeframe, which impacts the mode and dosage options available for cardiopulmonary training. Many modes of exercise exist that address aerobic deconditioning while subjecting the healing ACL to minimal amounts of force. More traditional activities such as some aquatic exercise (considerations for...
draft strain with kicking motion are discussed below), upper extremity ergometry, cycling, or elliptical running may be viable options. Additional modalities such as battling ropes, kettlebell swings, and sled drags are less commonly discussed but allow for the same goal to be accomplished. Stationary biking can be used to address aerobic deconditioning during the early rehabilitation phase partly due to the minimal stresses placed on the healing graft. Fleming et al. reported that stationary biking using toe clips placed a mean 1.7% peak strain on the ACL and did not differ between three power levels (75, 125, and 175 Watts), but peak ACL strain values were highly variable between subjects. This amount of strain during stationary biking is compared to 3.6% ACL strain observed during squatting and 4.4% during a 30 Newton-meter (NM) isometric quadriceps contraction at 15° knee flexion.

Various types of aquatic exercise (walking, deep water cycling, swimming) can be effective methods to improve aerobic conditioning early in the rehabilitation process as weight-bearing status can be more closely controlled in a buoyant aquatic environment. With swimming, careful attention needs to be given to the type of kick utilized. For example, the breaststroke kick, also known as the whip-kick, combines hip extension, knee extension, tibial external rotation, and ankle dorsiflexion, which places a relatively high load through the knee. For this reason, the breaststroke kick should be avoided in athletes until a complete recovery from ACLR has been achieved. Alternatively, the flutter kick, which is used in both the freestyle and backstroke, should be utilized as load is directed primarily to the quadriceps and patellofemoral interface. Underwater treadmill training is another option when clinically appropriate, as similar cardiorespiratory training effects for VO2, RPE, and respiratory exchange ratio were observed during underwater treadmill versus land-based running when performed at maximal exertion levels; however, HR was greater during land-based training comparatively.

Further, a less rigorous training stimulus may occur (VO2) with underwater versus land-based training at submaximal workloads. Some types of underwater treadmills contain cameras to better visualize movement patterns, provide resistance jets, and allow for water depth adjustment via a movable deck. Exercising in water offers a unique environment with the added property of viscosity, where the amount of resistance experienced from viscosity is proportional to the velocity of a movement. From a multi-physiologic systems approach, one must consider the type of movements performed due to potential implications from water resistance on the musculoskeletal system.

Elliptical running can challenge the cardiopulmonary system to a similar extent to that of running on a treadmill and stair climbing while inducing a greater RPE of the lower extremities, despite similar overall RPEs. However, while elliptical training reduces reaction force during the early stance phase and loading rates during heel strike compared to walking, medial and posterior shear forces placed on the knee as well as peak hip flexor and knee extensor moment were greater; additionally, hip, knee, and ankle flexion angles were greater.

Overground treadmill running is a commonly utilized cardiopulmonary training method post-ACLR, however, the vertical ground reaction forces applied to the lower extremity are typically much greater when compared to walking, but less than exercises such as unilateral or bilateral drop landing. However, recent technologies including the use of an unweighted treadmill, such as an AlterG® treadmill (AlterG, Inc., Fremont, CA), may provide a means to reduce loads to the lower extremities during running. A recent scoping review of 201 studies identified and examined 205 time-based criteria for return to running after ACLR, and found that the median time to allow return to running was 12 weeks, although it is unclear whether this timeframe is safe. Less than one in five studies reported clinical, strength, or performance-based criteria for decision making regarding return to running after ACLR, which is problematic. Rambaud et al. recommended a combined goal- and time-based criteria to determine return to running after ACLR. Debate exists regarding whether an athlete’s kinematics and kinetics are altered when running on a treadmill versus flat ground, however, most research appears to suggest that any alterations are mild, including flight phase time, stride length, cadence, stride frequency, step length, support phase time, foot position, and lumbo-pelvic-hip kinematics. The mild gait alterations reported with treadmill running suggests that treadmill running is an appropriate step in returning to on-field/court running that may have a carryover effect; however, clinicians will need to determine whether their patient is appropriate for running based on several factors including surgical procedure, clinical status, and activity demands of the athlete. Progression to sport-specific or higher demand cardiopulmonary training is determined on an individual basis, but typically is begun once the athlete has demonstrated the ability to tolerate submaximal loads and built a foundation of cardiopulmonary fitness, not to mention the resolution of necessary impairments in other physiologic systems.

High-intensity interval training (HIIT) has become a popular aerobic conditioning method and involves short bouts (0.5 – 8 min) of moderate to high intensity activity, performed in the “severe” intensity domain near the anaerobic threshold, which are alternated with bouts of partial recovery performed at low-intensity or complete rest. This should not be confused with sprint interval training (SIT) which is performed at maximal effort for short bouts (<30s) followed by complete recovery. HIIT is often completed via running or biking, however, functional exercises utilizing one’s own body weight have also been explored. Previous research has found HIIT to be effective at improving lower extremity power, sprint speed, HR, VO2max, and muscular endurance as effectively or to a greater extent than traditional aerobic training and in a shorter amount of time.

Research on HIIT training among healthy soccer and basketball athletes has produced similar findings. Wong et al. found that vertical jump height, 10-m and 30-m sprint times, laps completed in the Yo-Yo intermittent recovery test, and maximal aerobic speed increased in professional soccer players after completing HIIT training compared to controls. In another study, VO2max, 1,000-m run time, and sprint performance improved after 5-weeks of HIIT training in adolescent soccer players. Aschendorf et al. found that Yo-Yo intermittent recovery test as well as sprint and...
agility test performance without a basketball improved significantly in adolescent female athletes after undergoing a 5-week, basketball-specific HIIT program compared to controls. Specific application of HIIT training with patients post-ACLR has yet to be explored, so clinicians need to determine whether their patient is appropriate for the demands of HIIT training.

CONCLUSION

Cardiopulmonary system adaptations post-ACLR require careful assessment and intervention planning by the rehabilitation specialist. The integration of the cardiopulmonary system with other physiologic systems supports the aim of attaining efficient, goal-directed human movement after ACLR. Training the cardiopulmonary system after ACLR will in turn impact the health of the integumentary, musculoskeletal, and nervous systems. Selective cardiopulmonary testing and intervention should be integrated along the continuum of rehabilitation. By addressing cardiovascular deficits after ACLR within a multi-physiologic systems approach to resolve movement limitations, clinicians can help to optimize recovery and readiness for sport.

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Postoperative management of anterior cruciate ligament (ACL) reconstruction has traditionally focused on the evaluation and intervention of musculoskeletal components such as range of motion and patients’ reports of function. The integumentary system can provide early indications that rehabilitation may be prolonged due to protracted or poor healing of the incision sites. Full evaluation of the reconstruction over time, including direction of the incisions, appearance of surgical sites, level of residual innervation, and health of the individual should be considered when determining time-based goals and plans for returning an athlete to activity. Skin care techniques should be used to minimize strain and promote wound healing at the surgical sites, which in turn allows for implementation of other interventions that target other body systems such as locomotion, strength training, and cardiopulmonary conditioning. The integration of the integumentary system with cardiovascular, neurological, and muscular systems is required for a successful return to activity. A multi-physiologic systems approach may provide a unique viewpoint when aiming to attain a greater appreciation of the integumentary system and its integration with other body systems following ACL reconstruction. The purpose of this clinical commentary is to discuss integumentary considerations within a multi-physiologic systems approach to human movement after ACL reconstruction, including an anatomical review, key elements of assessment, and integrated intervention strategies.

Level of Evidence

5

INTRODUCTION

In 2013, the American Physical Therapy Association (APTA) adopted a new vision statement that called for physical therapists to "transform society by optimizing movement to improve the human experience." A product of this vision was the development of the movement system, where the APTA described the movement system as a term to represent the interaction of a collection of systems that ultimately contribute to human movement. Several physical therapy publications (position papers, editorials, commentaries) have voiced support for using the movement system as a foundation for physical therapist practice, education, and research. One of the most critical elements of the proposed movement system model is the integration of physiological systems and the multi-system contributions to purposeful, efficient human movement.

The integumentary system (IS) is rarely the focus of rehabilitation after anterior cruciate ligament reconstruction (ACL); however, impairments of the IS can contribute to deficits in other physiologic systems that lead to movement limitations. The IS contributes to thermoregulation during cardiovascular training, sensation for neuromuscular control, and fascial mobility for range of motion of the
ivascular grafts. The bone-patellar-tendon-bone (BPTB), hamstring (HS), quadriceps tendon (QT), and allograft are the most frequently used ACLR grafts.9,10 The organization of the IS and the impact scarring has on the body varies depending on the incision site's location, the depth and direction of the incision, the underlying tissues (muscle, fascia, tendon, bone, etc.), and the overall health (including blood flow and mobility) of the soft tissues being incised. Skin tension lines run vertically along the shin and horizontally at the knee.13 Scars that run contrary to the skin tension lines are more likely to require revision due to increased strain and risk of dehiscence or spread.15 A visual of surgical site locations and skin tension lines can be seen in Figure 2.

Each of the autografts (BPTB, HS, QT) requires healing of the harvest site and the healing of the ACL graft including bone, cartilage, and soft tissue remodeling.9,11 Not all graft sites heal at the same rate; BPTB and QT grafts recover slower than HS and allografts in muscle and tendon strength.14,16 Despite a quicker recovery of strength, HS grafts and allografts have been associated with higher retear rates, especially in younger athletes.17 While not interdependent, the healing of the fascia, harvest sites, and skin progress concurrently. Gradually increasing weight-bearing and progressively increasing the resistance of exercises throughout the range of motion can simultaneously facilitate remodeling of the integumentary and other body systems, including the neuromuscular and musculoskeletal systems.11 Weight-bearing progression may have specific implications for the musculoskeletal system, given decreased bone mineral density has been reported across several joints of the lower extremity.18–20 Protracted healing and adverse scarring can slow the athletes’ progression in multiple facets of rehabilitation (range of motion, locomotion, strength training) due to limited range of motion and pain.

Several methods exist to approximate the skin in order to promote healing.15 The most frequent technique after ACLR is closure of the dermis and subcutaneous tissue with absorbable sutures and reinforcement with superficial epidermal sutures, steri-strips or cyanoacrylate adhesive (such as Dermabond; Ethicon Inc, Somerville, NJ). Surgical sutures that are not absorbable are typically removed within two weeks to prevent hash marks (a series of parallel scars connecting suture sites perpendicular to the incision) due to re-epithelialization at the suture puncture sites. Steri-
Cutaneous wounds heal in three phases: inflammatory (two to three days), proliferative (two to three weeks) and remodeling (up to 12 months). Creating an optimized environment for wound healing allows these phases to progress appropriately. After surgery, the tensile strength of the skin progresses from 3% of normal tissue at week one to 20% at week three and roughly 80% at week twelve. Increased age, smoking status and other comorbidities (diabetes, nutritional deficiencies, etc.) that hinder nutrient and oxygen delivery to wound tissue will prolong healing. If the healing of the incision site is protracted due to bleeding, pain, infection or dehiscence, it could contribute to limitations in achieving range-of-motion goals and adversely affect multiple body systems.

The first 12 days post-operatively are the most important for management of the incision site and prevention of wound dehiscence. Wound care for the incision site is essential for efficient healing and prevention of infection. Surgical sites should be gently cleaned daily with soap and water followed by application of semi-occlusive hydrating emollients, such as petroleum jelly, and a dressing. Emollients can provide a protective barrier as well as hydration to the healing skin. These interventions promote mobility of the IS and decrease stress on the newly developing skin.

Patients should avoid submersion into a public water source such as a pool until the incision is completely closed. Hot tubs and other environments that pose a high risk of infection (lakes, rivers) should be avoided until the remodeling phase which starts approximately one month post-operatively. If an infection occurs, systemic antibiotics prescribed by the referring physician are considered the first-line treatment with subsequent operative debridement if the antibiotics are ineffective. Silicone sheets and gels, as well as scar massage, have shown efficacy in minimizing excess scar tissue formation. Athletes should also be encouraged to use sunscreen the first year post-operatively to protect the new skin around the incision site.

Providers should be aware that many topical products used during wound care can lead to contact sensitization. Allergy to adhesives (as found in postoperative bandaging), antimicrobial products, and other agents may produce an inflammatory rash that can be confused with infection. It is important to recognize that a geometric distribution of an erythematous, scaly rash (typically very pruritic) with a lack of other infectious signs and symptoms are suggestive of an allergic reaction and can be treated with topical steroids and removal of the offending agent.

Range of motion goals are critical to achieve during this time as well. However, because wound strength is lowest in the early period after surgery, a conservative mobility routine is advised the first weeks. Keeping the incision clean...
and hydrated while maintaining skin mobility and promoting neural regeneration of cutaneous receptors will provide the best results of managing the rehabilitation of the IS following an ACLR. Addressing underlying IS impairments contributes to optimizing the recovery of other physiologic systems after ACLR, which in turn impacts the patient’s ability to participate in movement-related interventions.

**TREATING SENSORY LOSS**

Due to the knee’s use as a kneeling structure and the somatosensory changes throughout the limb after ACLR, superficial nerves of the knee, foot, and ankle should be evaluated pre- and post-operatively.

Locations around and below the knee may feel numb due to sensory nerve severance during the surgical procedure. These areas can remain numb for weeks, months, or years after ACLR. The greatest risk for sensation impairments is found along the infrapatellar branch of the saphenous nerve. The graft’s incision site is also likely to suffer superficial nerves. Zones of the leg with decreased sensation should be identified as potential risks of other sensory impairments such as: burns, razor burns (or shaving injuries), poor thermoregulation, hypersensitivity, or altered proprioceptive feedback. The loss of the native ACL diminishes proprioceptive input and likely affects movement during functional tasks, requiring rehabilitation interventions that target the neuromuscular system.

Sensory integration training should attempt to promote neural regeneration by providing a gradual progression from non-noxious stimuli to more noxious (painful) stimuli, utilizing electrical stimulation and manual therapy interventions to decrease pain and promote healing and mobility of the skin. Skin care promotes an optimal environment for neural regeneration, starting with electrical stimulation, scar massage, and regular use of emollients. An easy way to progress and promote normal sensation, and potentially help identify neurogenic pain, is for athletes to wear clothes and coverings on the injured leg as soon as possible. Gentle massage can also provide the skin sensory feedback and improve skin mobility. Concerns of chronic pain or hypersensitivity should be communicated with the physician. Conditions such as nerve entrapment, complex regional pain syndrome (CRPS), or chronic pain may require additional surgical corrections or methods of analgesia (nerve block or medication changes) and pain reduction (such as TENS) techniques to reduce the neurogenic pain. Progressive return to less than comfortable activities should be integrated pre- and post-operatively.

**ADDRESSING POOR SCARRING**

The two most common scars that concern patients are those that are stretched and atrophic and those that are thickened (i.e. hypertrophic or keloidal scars). Scars that stretch occur when tension on the wound, created by movement of underlying muscles, overcomes the strength of the skin at the line of closure. These changes are most remarkable in the first eight weeks post-operatively and typically do not worsen after the twelfth week. Referral to dermatology or plastic surgery for scar revision may be warranted if the patient is displeased with the scar aesthetics.

Hypertrophic scars and keloids are due to excess deposition of collagen at the surgical site. There may be a genetic predisposition for keloid formation thus inquiry into previous wound healing and family history of keloids is important in the preoperative period. Keloids and hypertrophic scars often are associated with pain or pruritus and are managed with scar massage and silicone sheets. More aggressive therapy includes intralesional steroid injections, intralesional 5-fluorouracil injections, radiation treatments, and cryotherapy, among others. These are typically performed by a dermatologist or plastic surgeon. Frequent conversations should be had with the surgeon with a potential referral warranted if symptoms interfere with the knee's functional movement. As a collaborative practitioner, physical therapists are able to offer a unique perspective on movement-related impairments and interventions to optimize functional capacity and recovery after ACLR.

**CONSIDERING HEALTH OF THE PATIENT**

It is important to assess patients’ underlying medical conditions and behaviors as pre-existing conditions could prolong or complicate the healing of the incision or scar. The skin of younger individuals tends to heal better than older adults after surgery given healthy cardiovascular system and lack of actinic damage (damage from the sun) to the skin. However, these patients are more at risk for hypertrophic or keloidal scars, especially if there is a family or personal history. Genetic conditions such as hypermobility syndromes (i.e., Ehlers Danlos Syndrome) that alter the normal function of connective tissue elements (i.e. collagen, elastin, etc.) predispose affected patients to the potential for poor wound healing and protracted rehabilitation and should be considered. Being prepared to address each patient’s potential obstacles to rehabilitation will allow providers to tailor programs appropriately and positively impact the recovery of multiple body systems throughout rehabilitation.

**CONCLUSION**

The IS contributes to success after ACLR and can provide an early indication of a prolonged rehabilitation process in certain instances, which may ultimately impact other physiologic systems and the patient’s ability to participate in movement-related interventions. Creating incisions along skin tension lines, keeping the incision clean and hydrated with appropriate dressings, and regular close assessment
of wound and scar progression will improve the aesthetic
of the scar and limit the potential for poor scar mobility.
Furthermore, proper care of the IS can decrease the risk
of an infection that could delay or severely dismantle the
progress of an individual's ACL rehabilitation. Despite be-
ing overlooked at times, the IS plays a crucial role in the
functioning of other physiologic systems after ACLR.

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Despite the prevalence of forefoot related problems in athletes, there are few comprehensive summaries on examination and intervention strategies for those with forefoot related symptoms. While many factors may contribute to pathology and injury, the presence of abnormal foot alignment can negatively affect lower extremity biomechanics and be associated with injuries. Physical therapists may use the characteristics associated abnormal pronation or abnormal supination to describe the movement system disorder and serve as a guide for evaluating and managing athletes with forefoot pathologies. Athletes with an abnormal pronation movement system diagnosis typically demonstrate foot hypermobility, have decreased strength of the Tibialis posterior muscle, and present with a medially rotated lower extremity position. Athletes with abnormal supination movement system diagnosis typically demonstrate foot hypomobility, decreased strength of the fibularis muscles, and a laterally rotated lower extremity position. Interventions of manual therapy, taping, strengthening exercises, and neuromuscular reeducation can be directed at the identified impairments and abnormal movements. The purpose of this clinical commentary is to integrate a movement system approach in pathoanatomical, evaluation, and intervention considerations for athletes with common forefoot pathologies, including stress fractures, metatarsalgia, neuroma, turf toe, and sesamoiditis. By applying a prioritized, objective problem list and movement system diagnosis, emphasis is shifted from a pathoanatomical diagnosis-based treatment plan to a more impairment and movement focused treatment.

Level of Evidence
5

INTRODUCTION

It is well known that athletes are at risk for foot and ankle injuries. These include injuries in the forefoot, defined as the region of the foot distal to the tarsometatarsal joints. The forefoot, unlike the mid- and hindfoot, is unconstrained with movement occurring freely in all three planes. Because the forefoot is the most distal weight-bearing segment of the lower extremity, it can undergo a substantial amount of stress and strain, and can be affected by footwear, terrain, and biomechanical factors in the entire lower kinetic chain. Despite the prevalence of forefoot related problems in athletes, there are few comprehensive summaries on examination and intervention strategies for those with forefoot related symptoms. The purpose of the clinical commentary is to integrate a movement system approach in pathoanatomical, evaluation, and intervention considerations for athletes with common forefoot pathologies, including stress fractures, metatarsalgia, neuroma, turf toe, and sesamoiditis.

ANATOMY OF THE FOREFOOT

The forefoot is composed of five rays that are functionally...
divided into a medial component, including the first metatarsal and great toe (hallux), and the lateral component, consisting of metatarsals and toes two to five. The distal aspect of the medial longitudinal arch is formed by the first metatarsal. The first tarsometatarsal and Lisfranc articulations join the midfoot to the forefoot, with these joints being supported by a dense interconnection of dorsal and plantar tarsometatarsal, intermetatarsal, and Lisfranc ligaments. Distally, the hallux is joined with the first metatarsal by the first metatarsophalangeal (MTP) joint and is supported by the joint capsule and plantar, medial collateral, and lateral collateral ligaments. The five rays of the forefoot are supported by a tensed interconnection of ligaments, joint capsules, and fascia that create a transverse arch.\(^1\)

This interconnected weave of tissue includes the plantar plate, which is a fibrocartilaginous structure that runs from each metatarsal head to the respective proximal phalanx. The plantar plate also serves as an attachment for the plantar fascia and supports the transverse arch.\(^1\)

While it is recognized that abnormal function of the medial longitudinal arch can affect lower extremity biomechanics and contribute to pathology, abnormalities of the transverse arch and forefoot may also affect lower extremity biomechanics and contribute to pathology. Robberecht et al.\(^1\) found collapse of the transverse arch to be associated with forefoot pathology. During the propulsive phase of gait, representing the last 30% of the stance phase, only the forefoot is in contact with the ground. Consequently, abnormal forefoot biomechanics may negatively affect the entire lower extremity during propulsion. Likewise, any abnormal biomechanics in the lower extremity can affect propulsion and contribute to forefoot pathology. A comprehensive examination and intervention plan for forefoot pathologies therefore needs to consider the entire lower extremity and how biomechanical abnormalities may affect movement and thus contribute to symptoms.

**BIOMECHANICAL CONSIDERATIONS**

While many factors may contribute to pathology and injury, the presence of abnormal foot alignment can negatively affect lower extremity biomechanics and be associated with injuries.\(^2\)–\(^8\) Abnormal pronation is typically defined by excessive calcaneal eversion, plantarflexion and adduction of the talus, collapse of the medial longitudinal arch, and abduction of the forefoot on the hindfoot. Abnormal pronation has been associated with increased foot mobility, collapse of the transverse arch, and compensatory knee and hip medial rotation.\(^9,10\) Abnormal supination is typically defined by excessive calcaneal inversion, dorsiflexion and abduction of the talus, high medial longitudinal arch, and adduction of the forefoot on the hindfoot. This foot type is usually more rigid and may be associated with compensatory knee and hip lateral rotation.\(^9,10\) Altered movement patterns caused by abnormal pronation and supination may be identified during static standing, gait, and functional movement testing. The single leg squats and step-down tests are functional movement tests that can be used to assess neuromuscular control and identify potential impairments of the trunk, pelvis, hip, knee, and ankle with evidence of reliability and validity to support its use.\(^11,12\) Because the step-down test may place a greater emphasis on ankle motion, it may be a better measure than the single leg squat test in those with foot and ankle pathologies.\(^13\) Compensatory lower extremity movements can be identified and characterized as being associated with abnormal pronation or supination during gait and functional movement assessment. Physical therapists may use the general characteristics associated abnormal pronation or abnormal supination to describe the movement system disorder and serve as a guide for evaluating and managing athletes with common forefoot pathologies such as stress fractures, metatarsalgia, neuroma, and sesamoiditis.

**FOOT PATHOLOGIES**

**STRESS FRACTURE**

Stress fractures are microscopic bone injuries resulting from repeated bouts of physiological overload without adequate time for tissue remodeling and adaptation.\(^14,15\) Athletes who have a sudden increase in weight bearing activities are at risk for a stress fracture, with runners and military recruits seemingly being at higher risk.\(^16–20\) The shafts of the metatarsal bones are common locations for stress fractures, with the occurrence at the second and third metatarsals being more common than at the fourth and fifth.\(^15–17,19\) Athletes with a movement system diagnosis of abnormal supination may be at risk for metatarsal stress fractures because of the reduced ability to attenuate weight bearing stressors associated with a more rigid foot. An abnormal pronation movement system diagnosis can also increase the risk of sustaining a stress fracture because of atypical loading pattern associated with a more mobile foot.\(^15,21,22\) Increased risk for stress fracture has been associated with poor pre-participation condition, older age, female sex, Caucasian race, decreased bone density, hormonal and menstrual abnormalities, low calorie and low fat diet, inadequate sleep pattern, and collagen disease.\(^22\) Athletes with a stress fracture may complain of an insidious onset of chronic aching pain that is activity related and associated with an increase in weight bearing activity or training intensity.\(^22,23\) Examination should find the involved metatarsal shaft to be tender with palpation.\(^25\) Stress fractures of the second and third metatarsals generally heal well requiring only activity modification without a reduction in weightbearing.\(^14\) Stress fractures of the proximal intermediate zone of the fifth metatarsal are considered high risk for delayed healing or non-union and require more restrictive weight bearing, partial immobilization, and may progress to surgery if healing does not occur.\(^14\) Imaging such as radiographs or MRI may be necessary to identify and grade stress fractures. Higher grade stress fractures may require 16 or more weeks of activity modification while lower grade stress fractures may improve with just three weeks of relative rest.\(^24\) Treatment for stress fractures should include modifications of factors that contributed to the injury.\(^14,22,25\) A comprehensive lower quarter biomechanical examination and a sport-specific movement analysis will help identify and guide treatment to address contributing factors such as leg length discrepancy, abnormal foot posture, lower extremity malalignment, muscle imbal-

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ance, flexibility insufficiency, and range of motion (ROM) deficits. Athlete education should address any training errors, improper diet, or inadequate sleep patterns that are identified. Relative rest with low/non-impact aerobic activity, stretching and strengthening exercises, and immobilization in a removable boot are generally recommended until the pain resolves. Training can resume with a 10% increase in intensity per week after the patient has been pain free for 10–14 days.

METATARSALGIA

Metatarsalgia is a non-specific diagnosis given to athletes with pain on the plantar aspect of one or more of the metatarsal heads that is exacerbated by physical activity, barefoot walking, and/or walking in shoes with an elevated heel. This condition typically results from repetitive overloading of the metatarsal head(s) due to anatomic or biomechanical abnormalities such as first ray hypermobility, hallux abducto valgus (HAV), ankle equinus, claw or hammer toe deformities, lesser MTP joint instability, atrophy of the plantar fat pad, and/or improper footwear. A movement system diagnosis of abnormal pronation or supination may also contribute to overload the development of metatarsalgia because of altered loading of the metatarsal head. Athletes, particularly middle-aged females, may note a gradual onset of pain related to a rapid increase in training intensity, inappropriate shoe wear, or a change in running terrain. Examination should identify local tenderness at the metatarsal head and possibly a prominent metatarsal head(s). Muscle imbalance, ROM deficits, and/or biomechanical abnormalities in the lower quarter that may contribute to overloading the metatarsal heads should be identified and corrected. Assessing for and addressing any loss of ankle dorsiflexion ROM should be a primary focus. Treatment can also include orthoses, a metatarsal pad, and shoe modifications which may promote redistribution of plantar pressures and reduce pain. Taping to redistribute the plantar fat pad with or without techniques to correct hammer or claw toe deformity, when appropriate, may be beneficial (Figure 1A-B).

NEUROMA

An interdigital neuroma (Morton’s neuroma) is a mechanical entrapment neuropathy of one or more of the interdigital nerves in the forefoot. The nerve may become enlarged because of fibrotic tissue and/or endoneural edema. This condition primarily involves the third common (64%–91%) digital branch of the medial plantar nerve between the third and fourth metatarsal heads, followed by the second (18%–51%), first (0%–2.5%), and fourth (0%–6%) interdigital nerves. Runners and dancers are especially susceptible to interdigital neuroma due to repetitive hyperextension and longitudinal metatarsal torsional trauma at the MTP joints and resultant tissue thickening and swelling which may compress the nerve. Narrow shoes, over-training with repetitive MTP extension are the primary risk factors for developing an interdigital neuroma. A movement system diagnosis of abnormal pronation may also contribute to the development of a neuroma. Athletes with abnormal pronation and a hypermobile foot may be a higher risk because of the narrower intermetatarsal space associated with a collapsed transverse arch. Signs and symptoms of interdigital neuroma typically begin insidiously and include neurogenic pain in the plantar aspect of the foot. The pain may be associated with tenderness, cramping, burning, tingling, and/or numbness in the toes of the involved interspace. Some athletes will report a sensation of walking on a lump. During the examination, manual compression of the transverse arch and Mulder test should reproduce symptoms in athletes with interdigital neuroma. In athletes with chronic interdigital neuroma, weakness of the intrinsic muscles may be present. Interventions such as shoe modifications, such as custom orthotics, rocker-bottom shoes, the use of a wide toe box, and metatarsal head unloading with a metatarsal pad may also be helpful at decreasing symptoms. Metatarsal mobilization (Figure 2) and taping to correct abnormal pronation and promote the transverse arch for patients with interdigital neuroma.

SESAMOIDITIS

Hallux sesamoid syndrome, or sesamoiditis, are nonspecific descriptive terms referring to pathologies, anatomical anomalies, or adaptive changes of the sesamoid bones. These injuries are associated with inflammation of the peri-

Figure 1. Fat pad repositioning and correction for metatarsophalangeal joint extension.

A. Fat pad taping for distal displacement of fat pad. Manually reposition the fat pad to be better positioned beneath the metatarsal head. Apply two 0.75” wide strips of leukotape from distal to proximal to reposition the fat pad under the metatarsal head.

B. Fat pad repositioning with correction for metatarsophalangeal joint (MTP) extension as seen in claw or hammer toe. Flex the involved MTP joint (second toe is involved in photo below). Apply 0.75” wide strips of leukotape from the dorsal aspect of the first phalanx to the proximal aspect of the plantar surface of the foot. Tape should be crossed at the plantar aspect of the foot.

Figure 2. Sesamoid mobilization.

A-B. Sesamoid mobilization (Figure 2) and taping to correct abnormal pronation and promote the transverse arch for patients with interdigital neuroma.
tendinous structures of the sesamoids and possible osteo-
chondritis. Most sesamoid injuries are overuse injuries,
but direct trauma or forced extension of the hallux can
cause an acute injury. Overuse of the sesamoids and the
supporting structures can occur with repetitive activities
such as running, jumping, tennis, and ballet. Those with
an abnormal supination movement system diagnosis may
be at risk to overload the sesamoids because of the as-
associated high arch and plantar flexed first ray. Symptoms
of sesamoiditis include pain that occurs with weight bear-
ing, direct palpation, or with passive extension of the first
MTP joint. Forefoot swelling, tenderness, crepitus, de-
creased strength of the flexor hallucis longus and brevis
tendons, decreased extension of the first MTP joint,
and impaired first ray and/or first MTP joint mobility may
also be present. Decreased sesamoid mobility or ab-
normal position of the sesamoids may also be determined
during palpation by comparing sesamoid position between
the involved and uninvolved sides. Interventions for
sesamoiditis should focus on unloading the sesamoids and
forefoot or protecting the first MTP joint. Orthotics can be
used to decrease the load on the involved sesamoid and foot
and may include a cut-out for the sesamoids, metatarsal
bars, a rigid shank, and/or a first metatarsal extension.
Taping of the sesamoids can help improve forefoot position
and function and may decrease shear forces on the
sesamoids and plantar aspect of the forefoot. If malpo-
sition or decreased sesamoid mobility is found, corrective
sesamoid mobilizations and/or taping can be implemented
(Figure 3).

EVALUATION AND TREATMENT TECHNIQUES

A comprehensive examination of an athlete with forefoot
pathology should include a comprehensive assessment of
the foot and ankle as well as static standing, gait, and func-
tional movement evaluations. An appropriate lower quarter
screen may also be needed to identify potential contribut-
impairments. A standard examination can consist of
range of motion and strength assessment of the lumb-
osacral spine, hip, knee, ankle, and foot, with select special
tests being used based on the athlete's history and potential
differential diagnoses. Specific attention should be directed
toward ankle dorsiflexion ROM, assessing for potential limi-
tations in gastrocnemius-soleus flexibility, and talocrural
joint posterior capsule mobility. The weight bearing lunge
test can be used as a functional measure of tibiopodatal dor-
siflexion, with ROM coming from not only the talocrural
joint but also the subtalar and midtarsal joints as well. An
assessment of great toe extension ROM in weightbearing
and non-weightbearing should include evaluating mobility
of the first ray tarsal-metatarsal joint, first MTP, and
sesamoids. Likewise, assessment of hindfoot and forefoot
ROM should include evaluating subtalar, calcaneocuboid,
and talonavicular joint mobility. Because foot alignment is
commonly associated with forefoot pathology, the Foot
Posture Index-6 (FPI-6) can be used to assess static weight
bearing alignment in the sagittal, frontal, and transverse
planes and classify foot type as being normal, abnormally
pronated, or abnormally supinated (Table 1). A total score
of 0 to +4 on the FPI-6 indicates a normal foot posture
in adults. Gait assessment, single leg squat test, and the
step-down test can be used to identify abnormalities in the
movement system. The findings from this comprehensive
Table 1. Summary Table for Abnormal pronation and supination disorders

<table>
<thead>
<tr>
<th>Movement Disorder</th>
<th>Characteristics</th>
<th>Interventions</th>
<th>Forefoot Pathologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abnormal Pronation</td>
<td>FPI-6 score &gt; +4 Medially rotated lower extremity position Decreased strength of the tibialis posterior muscle</td>
<td>Anti-pronation taping Single leg squat with proximally resisted hip lateral rotation Grade V mobilization to the navicular to facilitate tibialis posterior function</td>
<td>Stress fracture Metatarsalgia Neuroma</td>
</tr>
<tr>
<td>Abnormal Supination</td>
<td>FPI-6 score &lt; 0 Laterally rotated lower extremity position Decreased strength of the fibularis muscles</td>
<td>Joint mobilizations to improve foot mobility; emphasize lateral subtalar glide Outward pivot exercises</td>
<td>Stress fracture Metatarsalgia Sesamoiditis</td>
</tr>
</tbody>
</table>

FPI: Foot Posture Index

examination of the entire lower quarter will identify impairments and generate a prioritized, objective problem list that can be used to develop an intervention plan within the context of the specific forefoot pathoanatomical diagnosis. The results of the FPI-6 and movement examination can identify a movement system diagnosis of abnormal pronation or supination to assist in directing intervention strategies.

Forefoot pathologies can be difficult to diagnose and often present with common impairments and movement system disorders. Using a prioritized, objective problem list and movement system diagnosis will place less emphasis on a pathoanatomical diagnosis-based treatment plan and more emphasis on the identified impairments and abnormal movements. Athletes with an abnormal pronation movement system diagnosis typically demonstrate foot hypermobility, have decreased strength of the tibialis posterior muscle, and present with a medially rotated position of the lower extremity. Treatment for those with abnormal pronation can include a grade V mobilization to the navicular to facilitate tibialis posterior function (Figure 4A-C) and anti-pronation taping to support the medial longitudinal arch (Figure 5A-D). Neuromuscular reeducation and strengthening exercises can be directed at the intrinsic and extrinsic foot muscles that support medial longitudinal and transverse arches. These exercises can also work to correct the medially rotated lower extremity and stabilize the hip and lumbosacral spine. The single leg squat with proximally resisted hip lateral rotation (Figure 7) can be used to facilitate the tibialis posterior, hip lateral rotators, hip abductors, and lumbosacral spine stabilizers. Athletes with abnormal supination movement system diagnosis typically demonstrate foot hypomobility, decreased strength of the fibularis muscles, and a laterally rotated lower extremity position. Treatment for those with abnormal supination can include joint mobilizations to improve foot mobility, with an emphasis on improving lateral subtalar glide (Figure 8). Exercises to facilitate fibularis activity and foot pronation while engaging the trunk and hip musculature can include the outward pivot (Figure 9A-B). The characteristics, select treatment techniques, and forefoot pathologies associated with abnormal pronation and supination movement system disorders summarized in the Table. Joint mobilization, taping technique, and exercise should be appropriately selected based the athlete’s impairment and movement system diagnosis while considering their unique treatment goals and desired outcome.

CONCLUSION

Forefoot injuries are common in athletes because of the stress and strain that occur during competition and training. Many biomechanical factors can contribute to forefoot symptoms and therefore a thorough examination, that includes a functional movement assessment, should be per-
formed in order to identify contributing factors throughout the entire lower quarter. An evaluation should include a comprehensive history with a description of training and competition regimen, as well as a systematic examination for the entire quarter to identify impairments and generate a prioritized objective problem list. Using a movement system diagnosis of abnormal pronation or supination may also help in directing treatment to correct the associated abnormal movements.

CONFLICTS OF INTEREST

The authors have no conflicts to disclose.

DISCLOSURES

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Figure 5. Anti-pronation taping

A. Step 1: Plantarflex the first ray and apply a strip of athletic tape from the dorsal aspect of the distal first metatarsal, around the plantar aspect of the foot, to the dorsal-lateral forefoot. Apply a second strip of tape from the dorsal-medial aspect of the great toe, around the calcaneus, to the lateral aspect of the foot.

B. Step 2, medial view: Starting at the distal strip that was applied in figure 6B, wrap strips of 1" athletic tape around the sole of the foot, beginning at the dorsal-lateral foot and ending at the dorsomedial foot. Lift the foot into a supinated position as you apply each strip. Continue applying supination strips until about half of the heel is covered with tape.

C. Step 2, superolateral view: Do not overlap the supination strips on the superior aspect of the foot.

D. Step 3: With the patient in standing, apply strips of tape to the superior aspect of the foot to connect the supination strips applied in the previous step.

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Figure 6. Single leg squat with proximal resistance for hip lateral rotators

A. Starting position: The patient is in single leg stance on the affected extremity, holding a resistance band in the contralateral upper extremity. The patient should stabilize to maintain a neutral hip and pelvis position with elevated medial longitudinal arch throughout the exercise.

B. The patient begins the exercise by performing a row with the contralateral upper extremity so that the hip lateral rotators are engaged.

C. The patient maintains the row position from 7B and performs a single leg squat while not allowing trunk leaning or rotation, pelvis rotation or tilting, medial rotation or adduction of the hip, valgus at the knee, or loss of balance.

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Shoulder and elbow injuries in overhead athletes, especially baseball pitchers, have become more common and result in limited participation. Upper extremity injuries in baseball can occur secondary to high velocity repetitive loading at extreme ranges of motion causing microtrauma to the musculoskeletal structures. With the vast number of youth and young adult baseball players in the United States and the increasing number of throwing related injuries, it is crucial that clinicians can perform a movement system evaluation of the throwing motion. An adequate evaluation of the movement system as it relates to the throwing motion can provide insight into abnormal throwing mechanics and provide rationale for selecting appropriate interventions to address identified impairments that may lead to injury. The purpose of this clinical commentary is to present a recommended movement system evaluation that can be utilized during both pre-season and in-season to assess for modifiable injury risk factors in youth and young adult baseball players.

Level of Evidence

5

INTRODUCTION

Shoulder and elbow injuries in overhead athletes, especially baseball pitchers, have become more common and result in limited participation. Upper extremity injuries in baseball can occur secondary to high velocity repetitive loading at extreme ranges of motion causing microtrauma to the musculoskeletal structures. Given the number of youth, high school, and collegiate baseball players in the United States along with the high prevalence of throwing related injuries, assessments to screen for potential risk factors could be valuable in injury prevention.

Approximately 15 million adults and children play organized baseball in the United States each year, with children in eighth grade or lower accounting for 17% of participants. A 2014 survey reported that half of individuals attending high school in the United States are involved in competitive sports, with baseball ranking fourth in participation among males. At the collegiate level, the popularity of baseball has risen from 667 school sponsored teams during the 1988-89 season to 1,702 school sponsored teams during the 2019-2020 season. Throwing related injuries have become a concern as 26-51% of youth pitchers report shoulder or elbow pain at some point during the season. In fact, a 10-year prospective study conducted by Fleisig et al. reported youth pitchers had a 5% chance of sustaining a serious throwing injury within a 10-year time frame. Upper extremity injury at the high school and collegiate level is even more common with the incidence of shoulder injuries reported between 1.39-1.72 injuries per 10,000 athlete exposures (AEs). Elbow injuries are less frequent than shoulder injuries at the high school level with 0.86 injuries per 10,000 AEs. However, elbow related throwing injuries may be more severe as athletes usually miss at least one to three weeks of participation compared to shoulder injuries where athletes usually return within one week.
to the National Collegiate Athletic Association (NCAA) Injury Surveillance program during a 10-year period between the 2004–2005 season and the 2013–2014 season, the rate of shoulder injuries in collegiate baseball players was 4.02 per 10,000 AEIs with 7.1% requiring surgery and 14.5% unable to return for the season. The rate of injuries at the elbow was 2.44 per 10,000 AEIs with 17.5% requiring surgery and 28.9% unable to return for the season.1 Because of the high incidence and time required to recover from a throwing related upper extremity injuries in youth and young adult athletes, it is important for clinicians to be able to identify those at risk through a screening process. The purpose of this clinical commentary is to present a recommended movement system evaluation that can be utilized during both pre-season and in-season to assess for modifiable injury risk factors in youth and young adult baseball players.

RISK FACTORS

While pitch count and arm fatigue have been well documented as significant risk factors for throwing injuries in youth athletes,12–14 musculoskeletal impairments have also been identified as risk factors for upper extremity injury. Repetitive throwing can lead to musculoskeletal adaptations in the upper and lower extremity that contribute to increased stress on ligamentous and other soft-tissue structures surrounding the elbow and shoulder. Adaptations may include changes in numeral torsion with abnormal shoulder range of motion as well as abnormal hip range of motion.15–20 It may be particularly important to screen for upper and lower extremity deficits in the skeletally immature athlete as overhead throwing at a younger age has the potential to change soft tissue and osseous development.21–23

There is conflicting evidence regarding the effect of abnormal shoulder range of motion (ROM), and limited evidence for deficits in shoulder strength on upper extremity injury in high school athletes. Shitara et al24 reported a reduction in glenohumeral internal rotation (IR) ROM at 90 degrees of shoulder abduction to be a risk factor for shoulder injury. Shanley et al.25 found a passive shoulder IR loss greater than 25 degrees was predictive of arm injury. Conversely, Tyler et al.26 found a loss of IR ROM or total shoulder ROM was not associated with shoulder or elbow injury risk. With regard to glenohumeral strength, Tyler et al.26 reported supraspinatus weakness was the only strength measure associated with shoulder injury. Similarly, Shitara et al.24 identified side-to-side differences in prone external rotation strength as a risk factor for shoulder and elbow injuries. Despite this conflicting evidence, these factors should be assessed, especially in the presence of faulty throwing mechanics observed during a movement system evaluation.

Musculoskeletal impairments of the lower extremity and trunk should not be overlooked as risk factors for upper extremity injury. In fact, the lower extremity is primarily responsible for initiating the pitching motion and it is estimated that 50% of the kinetic energy during pitching comes from the hip and the core.27 Improper force transfer and poor sequencing of the pitching motion from the lower to the upper extremity results in increased load through the arm.28–30 Lumbopelvic strength, particularly of the core and gluteus medius, and single leg stability is crucial as pitchers who demonstrate reduced lumbar control have greater time lost from participation.29 Furthermore, an excessive lateral trunk lean, defined as greater than 10 degrees away from the pitching arm, has been shown to lead to increased valgus moment at the elbow and internal rotation moment at the shoulder.31

With an adequate assessment of movement system dysfunctions during the throwing motion and complementary static and dynamic examination procedures, appropriate interventions may be prescribed to address ROM, strength, and neuromuscular control deficits to facilitate safe participation in baseball.

THROWING MECHANICS

An understanding of normal throwing mechanics is necessary to be able to assess for movement system dysfunctions during the throwing motion and allow for appropriate interventions youth and young adult athletes. Throwing is a coordinated sequence of movements with the ultimate goal of achieving high ball velocity and accuracy. Sequential motions of acceleration and deceleration begin from the ground up, with each transferring energy until the point of ball release and upper extremity deceleration.32 Throwing mechanics may be best defined using the five phases typically used to describe a pitching motion. These defined phases, which have been previously described in the literature, include: wind up, stride/early cocking, late cocking, acceleration, and deceleration.33 These phases can also be used to identify the specific movement dysfunctions associated with ROM, strength, and neuromuscular control deficits.

MOVEMENT SYSTEM DYSFUNCTIONS DURING AN ABNORMAL WIND-UP PHASE

Wind up begins from a static position with the pitcher facing towards the catcher and ends when the lead leg reaches max knee height. The final stage of wind up occurs when the pitcher removes the ball from the glove.33 Isometric hip abduction strength is crucial as the body balances on the trail leg while the body winds up away from the intended target to develop potential energy before acceleration. The hip abductors work to maintain the center of gravity over the base of support and prevent pelvic tilting.34 Faulty mechanics during this phase can negatively affect the movement system secondary to reduced lower extremity strength, mainly in the hip abductors, poor trunk control, poor balance, premature forward motion, posterior center of gravity, and high hand placement with the shoulder in greater than 90 degrees of abduction.35

MOVEMENT SYSTEM DYSFUNCTIONS DURING AN ABNORMAL STRIDE/EARLY COCKING PHASE

The stride/early cocking phase begins with maximum knee height to point of foot contact of the lead leg. During this phase, 50% of ball velocity comes from appropriate stride mechanics and trunk rotation.33 Deviations in stride mechanics, in terms of stride length, foot angle, and stride an-
glenoid. The allows the upper extremity to achieve the ex
ternal oblique muscles.

internal oblique and erector spinae and the stance side ex
ternal rotation of the throw.

ABNORMAL DYSFUNCTIONS DURING AN ABNORMAL ACCELERATION PHASE

The acceleration phase is initiated at shoulder maximal ex-
ternal rotation and ends at ball release. The latissimus dorsi
generates the greatest force during acceleration and results in
increased ball velocity. Poor trunk control and decreased
activity of the scapular stabilizers result in excessive trunk
flexion and decreased abduction angle of the humerus, respec-
tively. These lower and upper extremity deviations result in an
‘over the top ball release’ and side arm throwing. Throwing with a side arm position places excessive stress through the medial elbow and can result in ulnar collateral ligament (UCL) injury.

MOVEMENT SYSTEM DYSFUNCTIONS DURING AN ABNORMAL DECELERATION PHASE

The final phase of throwing is deceleration, which starts at
ball release and ends with the shoulder in maximum internal
rotation and 35 degrees of horizontal adduction. Adequate lead leg hip internal rotation and flexibility of the lower extremity will allow for a balanced position during follow through. Loss of balance during follow through is a consequence of mechanical problems during the stride phase. Additionally, without adequate eccentric muscle activity of the posterior shoulder, which is responsible for decreasing external rotation and distraction forces, pitchers are susceptible to glenohumeral internal rotation deficit (GIRD).

SCREENING

Upper extremity injuries occur with biomechanical over-
load, meaning the throwing force exceeds the strength of
ligamentous and soft tissue structures. In order to minimize
the risk of biomechanical overload, screening examinations
for potential risk factors may be important in preventing
upper extremity injuries caused by abnormalities in the
movement system during throwing. For all throwing ath-
letes, especially younger players, this risk factor screen
should include monitoring of pitch count. While a well-defined battery of tests is currently lacking for youth, high
school, and collegiate throwing athletes, the authors pro-
pose an evaluation of the movement system during the
phases of the throwing motion, as outlined above, along
with objective range of motion, strength, and functional
tests to assist with screening for potential injury. Recom-
mandations for static and dynamic screening measures to
complement the movement system evaluation are pre-
sented below. A summary of recommendations regarding
movement system dysfunctions and screening examina-
tions and interventions can be found in Table 1.
Table 1. Recommended Screening Examinations and Interventions

<table>
<thead>
<tr>
<th>Movement System Dysfunction</th>
<th>Abnormal Movements</th>
<th>Related Impairments</th>
<th>Screening Tests</th>
<th>Interventions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abnormal Wind-Up</td>
<td>Premature forward motion, posterior center of gravity, high hand placement with shoulder in greater than 90 degrees of ABD</td>
<td>Poor trunk control, poor balance at maximal lead knee height, lower extremity strength deficits</td>
<td>Hip manual muscle testing; Single leg squat</td>
<td>Plank progression; Single leg balance with perturbation; Standing ABD; Step downs</td>
</tr>
<tr>
<td>Abnormal Stride/Early Cocking</td>
<td>Shortened stride</td>
<td>Decreased lead leg hamstring tightness or stance leg hip flexor or rotator tightness</td>
<td>Flexibility testing of the hamstrings, hip flexors, and deep rotators</td>
<td>Stretching of the hamstrings, hip flexors, and deep rotators; Explosive side to side plyometrics</td>
</tr>
<tr>
<td>Long stride</td>
<td>Fatigue and overexertion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excessive internally rotated foot</td>
<td>Reduced lead hip ER of motion and/or stance hip IR range of motion</td>
<td></td>
<td></td>
<td>Hip joint mobilizations</td>
</tr>
<tr>
<td>Externally rotated foot</td>
<td>Decreased lead leg hamstring tightness or stance leg hip flexor or rotator tightness, decreased balance</td>
<td>Flexibility testing of the hamstrings, hip flexors, and deep rotators; single leg squat</td>
<td></td>
<td>Stretching of the hamstrings, hip flexors, and deep rotators; Single leg balance with perturbations</td>
</tr>
<tr>
<td>Short stride angle</td>
<td>Global decrease in hip flexibility</td>
<td>Flexibility testing of the hip flexors, deep rotators, iliotibial band, and hamstrings</td>
<td></td>
<td>Stretching of the hip flexors, deep rotators, iliotibial band, and hamstrings</td>
</tr>
<tr>
<td>Decreased arm ABD</td>
<td>Reduced strength and endurance of the scapular stabilizers</td>
<td>Manual muscle testing of the shoulder and scapular muscles; Shoulder Endurance Test</td>
<td></td>
<td>Rotator cuff strengthening; Proprioceptive neuromuscular facilitation exercises; Closed chain upper extremity plyometrics</td>
</tr>
<tr>
<td>Abnormal Late Cocking</td>
<td>Poor positioning of the humeral head in the glenoid, poor upward rotation of the scapular, upper extremity positioned posterior to the scapular plane</td>
<td>Reduced strength of the glenohumeral musculature and scapular stabilizers</td>
<td>Manual muscle testing of the shoulder and scapular muscles; Shoulder Endurance Test</td>
<td>Rotator cuff strengthening; Proprioceptive neuromuscular facilitation exercises; Closed chain upper extremity plyometrics</td>
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<td>Reduced lumbopelvic stability</td>
<td>Manual muscle testing of hip ABD, extension, and ER; Single leg squat</td>
<td>Abdominal and hip strengthening exercises; Plank progression; Single leg squat; Step downs</td>
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<tr>
<td>Abnormal Acceleration</td>
<td>Forward trunk posture</td>
<td>Poor trunk control</td>
<td>Manual muscle testing of hip ABD, extension, and ER; Single leg squat</td>
<td>Abdominal and hip strengthening exercises; Plank progression</td>
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### UPPER EXTREMITY STATIC SCREENING

**GLENOHUMERAL RANGE OF MOTION (ROM)**

An assessment of shoulder ROM should be performed, paying special attention to total shoulder ROM and GIRD. Shoulder ROM deficits may affect the movement system by causing abnormalities in the stride/early cocking, late cocking, acceleration, and deceleration throwing phases. An increased risk of upper extremity injury has been shown to occur in professional athletes with an internal rotation deficit between 15 and 25 degrees on the dominant versus non-dominant shoulder or a total range of motion deficit greater than five degrees on the dominant versus non-dominant shoulder.48,49 These deficits should be considered risk factors regardless of age as they result in extreme torque and force through the shoulder, especially in the setting poor eccentric control of the posterior musculature during the deceleration phase.25,48–50 Shoulder IR and ER ROM should be measured in supine with the humerus in 90 degrees of abduction. If these deficits are present along with an observed movement system dysfunction during throwing, a prevention program should focus on regaining ROM within the parameters described above by targeting joint capsule mobility, muscle/tendon extensibility with the goal of minimizing future injury.51

**GLENOHUMERAL STRENGTH**

Appropriate strength ratios between agonist and antagonist muscles surrounding the shoulder complex, specifically the internal and external rotators, and the scapula are crucial in maintaining dynamic glenohumeral joint stability during overhead activities.52 Strength deficits of the muscles around the glenohumeral joint may cause movement system abnormalities in the stride/early cocking, late cocking, acceleration, and deceleration phases of throwing. Strength measurements should be taken as unilateral ratios between IR and ERs, side-to-side comparisons, as well as strength in relation to body weight. Deficits in these strength ratios have been shown to increase the risk of shoulder pain in baseball players.53,54 Hand-held dynamometry can be utilized as high concurrent validity has been demonstrated when comparing the measurements with the standard isokinetic measurements.55–57 Normative values for these measures have been previously described by Wilk et al.48,58 and are as follows: ER/IR ratio 72-76%, ER torque to body weight ratio 18-23%, IR torque to body weight 26-32%, side-to-side comparison of ER and IRs 95-100% and 110-115%, respectively. In order to monitor for potential injury risk, these strength measures should be performed during pre-season training and repeated throughout the season. With identification of strength deficits along with an observed movement system dysfunction during throwing, exercise can be prescribed in a prophylactic manner with the goal of minimizing future injury.

### UPPER EXTREMITY FUNCTIONAL TESTING

Along with static strength measurements, functional test-
ing should be utilized. Several upper extremity functional tests have been described in the literature to help clinicians understand how each segment of the upper extremity interacts with one another. Additionally, functional testing provides the clinician with objective measurements regarding limb asymmetries and sport-specific movements that directly related to glenohumeral and scapular strength.

**UPPER EXTREMITY CLOSED CHAIN FUNCTIONAL TESTING**

While overhead throwing is an open chain activity, assessment of shoulder girdle performance in the closed chain will provide useful information on the function of the dynamic stabilizers. With deficits in closed chain performance coupled with a movement system dysfunction, closed chain rehabilitation exercises can be utilized to improve joint approximation and co-contraction in order to train the dynamic stabilizers as well as stimulate mechanoreceptors and improve proprioception.\(^{59}\) Deficits in functional stability of the shoulder girdle can lead to abnormal stride/early cocking, late cocking, acceleration, and deceleration phases. The Closed Kinetic Chain Upper Extremity Stability Test (CKCUEST) is a quantitative test to measure function and stability of the elbow, shoulder, and shoulder girdle. To perform this test, the subject begins in a traditional push-up position for males and a modified-push up position for females. While keeping one hand on the ground, the subject touches the ground on their opposite side and the number of touches over a 15-second period is recorded.\(^{59,60}\) There is evidence that the CKCUEST is valid, reliable, and responsive test with established normative values.\(^{61-64}\) It has been suggested that the CKCUEST can be utilized as a screening test as athletes who sustained an in-season injury had a significantly lower number of touches at the beginning of the season compared to athletes who did not sustain an injury.\(^{65}\)

A second closed chain functional test is the Upper Quarter Y-Balance test (YBT-UQ) which assesses the ability to reach with one upper extremity while maintaining stability on the other, taking the individual outside of their comfortable base of support. The YBT-UQ is most related to dynamic tasks involving core stability and upper extremity performance, which includes throwing.\(^{66}\) The subject is asked to perform a maximal reach in three different directions, medially, inferolaterally, and superiolaterally.\(^{67}\) To score this test, the sum of the three reach directions is divided by the upper extremity limb length and multiplied by 100. Gorman et al.\(^{67}\) found the YBT-UQ to be reliable for measuring upper extremity reach distance in a closed chain position in active adults. Unlike the CKCUEST, this test is able to utilize the non-injured upper extremity as "normal" which is beneficial for use with throwers as it allows for identification of side-to-side differences in functional performance.\(^{66}\)

**UPPER EXTREMITY OPEN CHAIN FUNCTIONAL TESTING**

Open chain functional tests should also be utilized when assessing throwers as throwing is an open chain activity. An commonly utilized open chain functional test is the seated single-arm-shot-put (SSASP) test, which replicates activities requiring a short burst of maximal pushing activity by the upper extremity.\(^{68}\) The subject sits with their back against a wall with their knees bent to 90 degrees. The subject is then asked to push the ball, not throw it, as far as possible while keeping their head and scapula against the wall and the contralateral arm in their lap. A 2.72kg (6 pound) medicine ball is utilized during this test. Two practice attempts are given, one at 75% effort and the other at 100% effort, followed by three maximal-effort attempts. The distance from the wall to the spot where the ball contacts the floor is measured and the results are averaged together. A study by Chmielewski et al.\(^{69}\) examined different normalization methods and recommend allometric scaling with the exponent 0.35 (cm/kg\(^{0.35}\)) be utilized to remove the influence of body mass on the results of this test. Additionally, the authors note that better performance should be expected on the dominant limb than the non-dominant limb and asymmetry up to 10% may be acceptable.\(^{69}\) Previous research has shown this test has excellent test-retest reliability and reflects upper extremity strength in healthy individuals.

More recently, the Shoulder Endurance Test (SET) has been developed as a measure muscle endurance capacity and mimic overhead sporting activities. Assessment of muscular endurance is important in pitchers as fatigue is a common risk factor for shoulder injury and athletes with a history of shoulder pain demonstrate more fatigue than their healthy counterparts.\(^{70}\) To perform this test, the subject stands barefoot with their back against a wall and the non-testing hand placed on their spine near the 4-5\(^{th}\) lumbar vertebrae. The foot opposite of the testing arm is placed forward in a staggered stance position. The testing arm is placed in 90 degrees of forward flexion holding a 1-m long TheraBand fixed at shoulder height. The subject is then asked to pull the TheraBand to a 90-90 position of abduction and external rotation at a cadence given by a metronome. The subject performs as many repetitions as possible until fatigue. Fatigue is defined as the inability to keep the pace of the metronome, inability to reach the ending position after two verbal cues, or a verbal report of the inability to continue. The verbal report of fatigue is standardized by using a Borg rating of perceived exertion scale where fatigue was reported at a level exceeding 14 out of 20.\(^{71}\) Test-retest reliability has been demonstrated to be high (ICC=0.93) for the dominant upper extremity in overhead athletes. Relative reliability in both sedentary individuals and overhead athletes has been shown to be high to very high and the test is able to assess overhead functionality as well as side-to-side differences in muscle endurance. While this test may be utilized to assess shoulder endurance, the SET demonstrates a weak correlation between isometric shoulder rotational strength and therefore should be utilized in conjunction with strength testing as outlined above.\(^{71}\)

**LOWER EXTREMITY SCREENING**

**HIP RANGE OF MOTION**

Normal hip rotational ROM is crucial to allow for appropriate energy transfer from the lower extremity to the upper
extremity during pitching. Hip range of motion deficits may affect the movement system by causing abnormalities in the stride/early cocking and deceleration throwing phases. Reduced lead hip rotational ROM results in decreased stride length and reduced force production whereas increase in lead rotational hip ROM results in a lag between early trunk rotation and the pitching shoulder. In both of these scenarios, the pitcher compensates with increased shoulder ER putting both the glenohumeral and elbow joints at risk for injury.\textsuperscript{33,72,73} Saito et al.\textsuperscript{75} reported lead and trail leg limitations of hip flexion ROM and internal rotation at 90 degrees of hip flexion were risk factors for elbow injuries adolescent baseball players. In elite young baseball players, Sekiguchi et al.\textsuperscript{74} found a decrease in hip IR ROM on the stride leg was significantly associated with elbow or shoulder pain (38.5 degrees vs. 43.7 degrees, \( p = .002 \)). In high school baseball players, Hamano et al.\textsuperscript{73} reported a hip ER ROM deficit on the dominant side (lag leg) was significantly decreased in injured versus non-injured players (injured vs non-injured: 15.8 + 3.6 vs 15.4 + 3.3, \( p = .04 \)). Assessing specifically hip flexion, internal rotation, and external rotation, should be of particular interest during pre-season screening examinations of youth and young adult baseball players because of the known importance of these motions for normal mechanics. Since appropriate hip ROM values have not been well established, these static measures, obtained through traditional goniometry, should be correlated to findings of the throwing movement system assessment.

**LUMBOPELVIC STRENGTH**

Special attention should be given to pre-season lumbo pelvic strength as weakness of the hip abductors leads to a poor energy transfer in the kinetic chain and consequently increased stress through the upper extremity.\textsuperscript{76} Lumbo pelvic strength deficits may affect the movement system by causing abnormalities during the wind-up, late cocking, and acceleration throwing phases. The hip abductors, specifically the gluteus medius and gluteus maximus, are active throughout the throwing motion. On the lead leg, they work to decelerate the knee, provide a stable base, and absorb force from deceleration and follow through phases.\textsuperscript{77} On the trail leg, the abductors stabilize the pelvis and provide balance from wind-up to early cocking.\textsuperscript{78} Weakness through the hip abductors may result in knee valgus, a trunk lean, pelvic drop, or a reduction in balance resulting in upper extremity compensations.\textsuperscript{79} With identification of static strength deficits, obtained through standard manual muscle testing, along with an observed movement system dysfunction during throwing, lumbo pelvic strengthening exercises can be prescribed in a prophylactic manner with the goal of minimizing future injury.

**LOWER EXTREMITY FUNCTIONAL TESTING**

The single leg squat test has been shown to be a valid in assessing dynamic lower extremity control and hip muscle function.\textsuperscript{79,80} A study by Wasserberger et al.\textsuperscript{81} found the single leg squat to be a useful assessment tool in adolescent athletes, as single leg squat mechanics were related to stride knee mechanics. Minimizing knee valgus during the throwing motion, especially of the stride knee, may result in better transfer up the kinetic chain and a reduction in both upper and lower extremity injuries. When assessing a single-leg squat, the clinician should pay careful attention to the position of the trunk, pelvis, and knee. With identification of poor mechanics during the single leg squat coupled with an observed movement system dysfunction during throwing, exercises to improve strength and functional performance of the lumbo pelvic musculature can be prescribed.

**DISCUSSION**

The demands of throwing on the upper extremity lead to frequent injuries of both the shoulder and elbow in youth and young adult baseball players. Given the time lost from participation due to injury, pre-season screening examinations should be performed to assess for risk factors that may result in upper extremity injury. Additionally, an assessment of the throwing motion should be performed to screen for any movement system dysfunctions that may occur during each of the five phases. When possible, objective findings during the screening examinations should be compared to a throwing assessment to facilitate optimal performance.

Upper extremity screening should include as assessment of glenohumeral range of motion and strength. When an IR ROM deficit is identified, posterior glides of the glenohumeral joint and posterior capsule stretching are recommended. If deficits in ER strength are observed, infraspinatus and teres minor strengthening should be prescribed with special attention to strengthening exercises that mimic the overhead throwing motion (Figure 1).
At least one functional assessment of the upper extremity should also be utilized during screening for upper extremity kinetic chain performance. Poor performance on any of the upper extremity functional testing should be compared to findings of shoulder strength and ROM screens as well as the throwing assessment to ensure appropriate prescription of exercise. For example, decreased shoulder ER strength and poor performance on the SET may result in an abnormal late cocking movement system dysfunction. In this case, scapular endurance exercises as well as shoulder ER strengthening in abduction may be prescribed (Figure 2).

The lower extremity should also be screened for hip range of motion deficits as well as deficits in lumbopelvic strength. Hip flexion, internal rotation, and external rotation ROM deficits can be addressed with inferior, posterior, and anterior hip joint mobilizations, respectively (Figure 3). Appropriate muscle stretching should be prescribed to complement hip joint mobilizations with the goal regaining appropriate ROM and improving of any movement system dysfunctions identified that relate to limited hip ROM.

Manual muscle testing of the hip abductors, hip extensors, hip external rotators, and abdominals can be used to screen for strength deficits of the lumbopelvic stabilizers. In order to assess functional performance of the lower extremity kinetic chain and core, a single leg squat test is recommended. Deficits in hip muscle strength and lower extremity neuromuscular control can be addressed with exercises that emphasis movements that closely resemble the phases of the throwing motion. For example, weakness of the hip abductors and poor control during single leg squat may result in an observed abnormal wind-up movement system dysfunction. In this case, perturbations during single leg balance drills would challenge both balance and hip abductor strengthening in a position that mimics the wind-up phase (Figure 4).

CONCLUSION

Shoulder and elbow injuries in overhead athletes, especially throwers, are increasingly common and result in lost participation time. Throwing requires the shoulder, elbow, trunk, and lower extremities to withstand large forces at extreme ranges of motion. An adequate evaluation of the movement system as it relates to the throwing motion can provide insight into abnormal throwing mechanics and provide rationale for selecting appropriate interventions to address identified impairments that may lead to injury. This review presents a recommended movement system evaluation that can be utilized during both pre-season and in-season to assess for modifiable injury risk factors in youth and young adult baseball players.

Screening procedures can provide rationale for selecting potential interventions to address the identified impairments that are potential risk factors for throwing injuries.
Figure 4a. Hip abductor strengthening mimicking wide up (left) and stride (right)

Figure 4b. Single leg balance with perturbations
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Lifting Techniques: Why Are We Not Using Evidence To Optimize Movement?

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Keywords: optimize movement, lifting technique, semi-squat lift, squat lift, stoop lift

Lifting something off the ground is an essential task and lifting is a documented risk factor for low back pain (LBP). The standard lifting techniques are stoop (lifting with your back), squat (lifting with your legs), and semi-squat (midway between stoop and squat). Most clinicians believe the squat technique is optimal; however, training on squat lifting does not prevent LBP and utilizing greater lumbar flexion (i.e. stoop) when lifting is not a risk factor for LBP. The disconnect between what occurs in clinical practice and what the evidence suggests has resulted in ongoing debate. Clinicians must ask the right questions in order to apply the evidence appropriately. A proposed clinical framework of calm tissue down, build tissue up, improve work capacity can be used to determine which lifting technique is optimal for a patient at any given time. When applying this clinical framework, clinicians should consider metabolic, biomechanical, physical stress tolerance, and pain factors in order to address the movement system. For example, stoop lifting is more metabolically efficient and less challenging to the cardiopulmonary system. There may be few biomechanical differences in spinal postures and gross loads on the lumbar spine between stoop, squat, and semi-squat lifting; however, each lift has distinct kinematic patterns that affects muscle activation patterns, and ultimately the movement system. Clinicians must find the optimal dosage of physical stress to address all aspects of the movement system to minimize the risk of injury. There is no universal consensus on the optimal lifting technique which will satisfy every situation; however, there may be a lifting technique that optimizes movement to achieve a specific outcome. The calm tissue down, build tissue up, improve work capacity framework offers an approach to determine the best lifting technique for an individual patient at any given time.

Level of Evidence

5

PROBLEM

Lifting something off the ground is an essential task that is required for most individuals to maintain their independence and is also required of athletes for training and performance purposes. Lifting is also a documented risk factor for low back pain (LBP). Therefore, it is essential that physical therapists provide lifting education and interventions for our patients. The standard lifting techniques: stoop, squat, and semi-squat (Figure 1) are well-described in the literature. The stoop technique can be quantified as <45° knee flexion and ~90° of trunk flexion, corresponding with a layman’s description of lifting with your back. The squat technique can be quantified as ~135° knee flexion and <30° trunk flexion, corresponding with a layman’s description of lifting with your legs. The semi-squat technique uses a posture midway between the stoop and squat lifts, which quantitatively can be described as ~90° knee flexion and ~45° trunk flexion.

Although 75% of physiotherapists, 91% of manual handling advisors, and 88% of osteopaths believe that the squat technique is the safest way to lift, many recreational and competitive athletes utilize the stoop and semi-squat lifting
techniques during training. The squat technique is the most commonly advised lifting technique by health care providers\textsuperscript{5}, however, it has been shown that training on squat lifting does not prevent LBP\textsuperscript{6} and utilizing greater lumbar flexion during lifting (i.e. stoop lifting) is not a risk factor for LBP onset, persistence, or recurrence.\textsuperscript{7} There is clearly a disconnect between what occurs in clinical practice and what the evidence suggests related to lifting.

The squat technique is generally accepted to be the optimal lifting technique,\textsuperscript{2–5} but are we really practicing in an evidence-based manner when making this determination? It seems that the answer to the question of "what is the optimal lifting technique" is that "it depends." The authors suggest a more appropriate, alternative question that should be asked: "which lifting technique optimizes movement to complete the task as hand?" The purpose of this clinical suggestion is to propose the calm tissue down, build tissue up, improve work capacity framework that can be used to determine the optimal lifting technique for a patient.

**SOLUTION**

The clinical framework of calm tissue down, build tissue up, improve work capacity is the integration of a concept introduced by Greg Lehman, a physiotherapist and chiropractor, and integrated with the Physical Stress Theory.\textsuperscript{8} One of the primary goals of rehabilitation professionals should be to optimize patients' movement.\textsuperscript{9} Optimizing movement can occur by modulating pain (calm tissue down) to allow for greater options of movement, increasing tissue strength, hypertrophy, neuromuscular activation, power, and/or endurance (build tissue up) to raise the threshold for injury, or increase the total amount of work the body can perform with respect to the muscular and cardiopulmonary systems (improve work capacity). There is an abundance of research and data on lifting, yet clinicians struggle applying the evidence. The calm tissue down, build tissue up, improve work capacity framework can be applied to lifting, in order to utilize evidence appropriately to optimize movement. The American Physical Therapy Association defines the Movement System as a collection of systems that interact to move the body or its component parts.\textsuperscript{9} Since human movement is a complex behavior within a specific context,\textsuperscript{9} the authors consider four primary movement factors when applying this framework: 1) metabolic, 2) biomechanical, 3) physical stress tolerance, and 4) pain.

**METABOLIC**

Energy consumption, ventilation, and heart rate are all higher during squat and semi-squat lifting when compared to stoop lifting.\textsuperscript{2,10} In other words, the stoop technique is more metabolically efficient and energy sparing, which is likely the reason many individuals use the stoop as their default lifting technique.\textsuperscript{2} If a goal is to improve work capacity, the patient's intended type of work must be considered. Does the patient require energy conservation for repetitive submaximal lifting and work productivity? If so, the stoop technique would be a more optimal movement as it is more energy efficient, less challenging to the cardiopulmonary system, and has been shown to be a quicker technique.\textsuperscript{2}

**BIOMECHANICAL**

During lifting, the lumbar spine is subjected to high loads; however, it is not clear if loads differ between lifting techniques.\textsuperscript{2,11} It appears that joint positions, the size and weight of the load lifted, and the biomechanical models used to estimate forces affect the calculated loads on the spine.\textsuperscript{2,11} It has also been shown that the lumbar spine experiences significant amounts of flexion, even when subjects attempt to keep a "neutral" spine,\textsuperscript{12} suggesting there may be very little difference in spinal postures between the stoop and squat techniques. Even with the unclear difference in the gross loads placed on the lumbar spine,\textsuperscript{2,11} as indicated by estimated moments acting on the spine, and unclear differences in spinal postures between the lifting techniques, evidence suggests subjects with LBP, when
asked to lift, utilize the squat technique, indicating the squat technique may feel less stressful. Looking collectively at the overall loads on the spine and the relative load sharing between active and passive spinal structures, there is evidence to support the utilization of semi-squat lifting.

It is clear that the kinematic patterns for the stoop, squat, and semi-squat techniques are different. The most obvious difference is that stoop lifting requires greatest trunk flexion, the squat lift requires greater tibiofemoral flexion, and the semi-squat lift is a blend of squat and stoop lifts. These kinematic differences will affect muscle activation patterns, power generation abilities, and joint stress. If the goal is to optimize movement by building tissue up, the therapist needs to consider prescribing the lifting technique that produces the desired muscle activity and power generation in the targeted tissue(s). The squat technique is optimal for quadriceps muscle activation, while the stoop technique is optimal for hamstring and lumbar extensor muscle activation. If the goal is to optimize movement by calming tissue down, the therapist should prescribe the lifting technique that incorporates kinematic patterns that do not excessively load tissues that may not be able to currently handle the stress. Based on what is known on the effects of different kinematic patterns on lifting, athletes and fitness populations need to ensure they utilize a lifting technique that accomplishes their desired outcome. Specific kinematic patterns used during a lift can help to protect painful tissue, help to strengthen specific tissue, and can ultimately help create an advantage when lifting heavy loads.

The amount of weight someone is able to lift is influenced by their lifting technique. There is strong evidence suggesting individuals self-select a maximum acceptable weight for the semi-squat and stoop lifts that is greater than the squat lift; however, the strength capacity of each lifting technique is very similar. A recent study looked at the effect of three different lumbar postures while lifting with the knees in 45° of flexion on lumbar extensor strength, which is a technique that would fall somewhere between the stoop and semi-squat lifting techniques. The three different lumbar postures included full extension (lordotic), mid-range (flat back), and fully flexed. It was found that lumbar extensor moments and neuromuscular efficiency was greatest when lifting with fully flexed lumbar spines and changes in lumbar spine posture did not influence hip or knee moments. These findings suggest that lifting with your legs while keeping your back straight (squat lifting) may not be an efficient way to lift heavy loads.

PHYSICAL STRESS TOLERANCE

Changes in the relative level of physical stress on the body will cause predictable adaptive responses in biological tissue. Tissue will atrophy under decreased stress, be maintained when stress is unchanged, and will hypertrophy under increased stress. Increased stress will also provide an opportunity for development of increased strength, neuromuscular activation, power, and/or endurance. Tissue will become injured if exposed to stress beyond its physical capacity.

There is a common belief among clinicians that stoop technique leads to intervertebral disc herniations, which is a primary reason clinicians oppose stoop lifting. While herniations are associated with spinal compressive loads in flexion (i.e. stoop lifting), there is a high percentage of asymptomatic individuals with herniations and spontaneous regression of herniated disc tissue can occur. In line with other tissues, such as bone and muscle, specific types of loading appear to be beneficial to the intervertebral disc and will result in hypertrophy (build tissue up) or spontaneous regression of disc material. Intervertebral discs act as shock-absorbing cushions between vertebrae, and, if compressed or degenerative, may lose flexibility and load bearing ability. It is unknown if intervertebral disc hypertrophy is clinically relevant or protective; however, hypertrophy appears to be possible in the intervertebral disc. It is currently unknown what mode of stress or dosage is optimal for intervertebral disc hypertrophy. If a clinician’s goal is to optimize movement by building tissue up, then physical stress levels that overload the tissue are required. However, excessively high levels of physical stress may result in injury. Therefore, it is the clinician’s job to find the optimal dosage of physical stress to ensure hypertrophy and minimize the risk of injury, and impact the movement system, even in those with intervertebral disc pathologies.

When considering modification of a patient’s lifting technique, clinicians must consider whether it was the technique itself or the inadequate dosage of physical stress that led to injury. Changing the patient’s preferred lifting technique may change the physical stress patterns on their body, decreasing stress in some areas while increasing stress to other areas which could result in pain in other areas.

PAIN

Pain is a perception and one of the ways the brain lets us know that it perceives a threat. If a patient has pain with lifting, should the clinician permanently change the way the patient lifts or utilize an alternative lifting technique as an intervention until symptoms resolve? If a patient is in pain, sometimes the goal is to give that perceived threat a break (calm tissue down). Recognizing that pain is complex and interrelated with many other variables, the challenge clinicians have is determining when they should be calming tissue down, building tissue up, or improving work capacity to optimize movement. With an acute injury and intense pain, the clinical focus should be to protect the tissue by decreasing the physical stress, as the tissue is likely not prepared to handle load and is at risk for further injury. This can be accomplished by educating a patient on alternate lifting techniques that can be utilized in the presence of pain. An alternate lifting technique as a temporary desensitizer can be used to calm tissue down prior to building tissue up. Even in cases of chronic pain, alternate lifting techniques can be used to teach the patient that they can control their pain and positively affect overall movement tolerance.
DISCUSSION

The conflicting evidence regarding lifting techniques implies that there is no universal consensus on the optimal lifting technique; however, there may be a lifting technique that optimizes movement to complete the task at hand. A lifting technique should be specific to a patient’s desired outcome and tailored to improve their unique function (Figure 2). Clinicians need to consider why they would promote one lifting technique over another, at any given time. The following clinical examples highlight the application of this clinical framework.

In CrossFit, the athlete that completes a workout in the shortest time “wins” that workout. Depending on the specifics of a CrossFit workout, the athlete will require varying degrees of strength, neuromuscular activation, power, and endurance. Similar to a track athlete completing a mile run as quickly as possible, CrossFit athletes complete many workouts as fast as they can. An example of a CrossFit workout might be completing 21 deadlift repetitions, 21 handstand push-up repetitions, 15 deadlift repetitions, 15 handstand push-up repetitions, 9 deadlift repetitions, and 9 handstand push-up repetitions, as fast as possible. The deadlift exercise requires lifting a barbell off the ground until the athlete is standing erect. The goal is to complete the deadlifts as quickly as possible, while also conserving as much energy as possible, in order to complete the handstand push-ups quickly, which would ultimately lead to a faster time and improve the athlete’s chances of winning. A lifting technique that resembles the stoop technique may be most optimal for this athlete, as the stoop lift is more energy efficient, less challenging to the cardiopulmonary system, and has been shown to be a quicker technique. Lumbar extensor moments and neuromuscular efficiency when deadlifting is greater when the lumbar spine is flexed, providing another potential benefit of stoop lifting for this athlete.

Patellofemoral pain has an annual prevalence in the general population of over 22% and over 35% in professional male cyclists. The incidence rates for patellofemoral pain in adolescent amateur athletes is between 5.1% - 14.9%. Due to the high incidence and prevalence rates for patellofemoral pain and poor long term prognosis, optimizing treatment in these patients should be a priority. Patellofemoral joint reaction forces are partially explained by the knee flexion angle; as knee flexion increases in a closed chain environment, the patellofemoral compressive load is increased. However, quadriceps strengthening exercises should be included in the management of patients with patellofemoral pain. Those patients with high levels of patellofemoral pain may benefit from stoop lifting, where the knee flexion angle is minimal and remains relatively static, while those patients with resolving or lower pain may benefit from squat lifting for optimal quadriceps activation.

A patient presents with a discogenic LBP, where their pain is reproduced with prolonged sitting, forward bending, and lifting anything heavier than 10 pounds. In an acute case, this patient would benefit from a lifting technique that prevents exacerbation of symptoms (calm tissue down), and in a chronic case, a lifting technique should be used that allows the patient to control or manage their symptoms while maintaining their independence (improving work capacity). Evidence suggests that patients with LBP prefer the squat technique, indicating that squat lifting may be best indicated for this patient while in the acute stage.

Evidence supports each technique in different scenarios; therefore, clinicians need to start asking alternative questions: How can movement be optimized by calming tissue down, building tissue up, or improving work capacity? This question cannot be answered without in depth, integrative knowledge of the movement system and its component elements.
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Return to Pre-injury Level of Play

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<th>With InternalBrace (in weeks)</th>
<th>Standard repair (in weeks)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13.3</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Postoperative management is patient-specific and dependent on the treating professional’s assessment. Individual results will vary and not all patients will experience the same postoperative activity level or outcomes.

The InternalBrace procedure gives patients the flexibility to move freely while protecting the primary repair by limiting abnormal or excessive lateral movement during the healing process.

Reference

InternalBrace surgical technique is intended only to support the primary repair and is not intended as a replacement for the standard of care using biologic augmentation in a primary repair. InternalBrace surgical technique is intended only for soft-tissue-to-bone fixation and is not cleared for bone-to-bone fixation.
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RESEARCH SHOWS THAT AQUATIC THERAPY ENHANCES REHAB OUTCOMES.

- Patients and athletes who walk in a HydroWorx pool are better equipped to transfer what they learn to land than their counterparts who engage in self-directed shallow water walking.

- Aquatic therapy is beneficial to achieve threshold-intensity training while lowering the stress on the joints that is caused by land running.

- The benefits of water therapy on the underwater treadmill included reduced soreness, body fat and inflammation while also improving muscle mass and strength performance.

- Clinical results show that athletes who participate in water rehabilitation and land-based post rehabilitation have better scores on postural sway, indicating better balance and fewer episodes of re-injury.

- Benefits of hydrotherapy exercises included a lean body mass increase with underwater treadmill training, with gain seen mainly in the legs.

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...to deliver functional outcomes faster.
The IFSPT and its sponsors, ATI and Hyperice, would like to congratulate the winners of the inaugural Research Symposium at the Orthopedic Summit, held December 11, 2021, at the Bellagio Resort in Las Vegas, Nevada.

First Place:
THE EFFECTS OF VERBAL CUES ON QUADRICEPS EMG ACTIVITY DURING A QUADRICEPS SETTING EXERCISE

Second Place:
THE EFFECTS OF CERVICAL SPINE POSITION ON SHOULDER ROTATION STRENGTH.
Giordano K, Oliver G

Third Place:
PRETIBIAL STRENGTH AND GAIT CHARACTERISTICS IN INDIVIDUALS WITH UNILATERAL PLANTAR FASCITIS VERSUS HEALTHY CONTROLS
Granado M, Lohman E, Gordon K, Daher N

THE EFFECTS OF DRY NEEDLING ON RUNNERS: A RANDOMIZED CONTROLLED TRIAL
Dewald M, Whitten B, Reynolds A, Semprini J

Honorable Mentions:
THE ROLE OF CORE BODY TEMPERATURE ON LACTATE PRODUCTION
Heller C, Grahn D, Cao V, Choi A

THE FATIGUE INDEX: AN OVERLOOKED COMPONENT OF CRITERIA FOR RETURN TO SPORT (RTS) FOLLOWING UPPER EXTREMITY INJURIES AND USING UPPER EXTREMITY FUNCTIONAL PERFORMANCE TESTS (UEFPT)
Davies GJ, Bargeron S, Connolly A, Hackmann K, Lane T, Riemann BL

THE EFFECT OF STRENGTH OR ENDURANCE TRAINING PROGRAMS ON STRENGTH AND ENDURANCEmeasures of the supraspinatus and infraspinatus

DOES HIGH MEDIAL ELBOW STRESS DURING PITCHING COMPROMISE THE DYNAMIC STABILIZERS OF THE ELBOW?
Mullaney MJ, McHugh MP