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ABSTRACT
The rehabilitation process is driven by the manipulation of training variables that elicit specific adaptations in order to meet established goals. Periodization is an overall concept of training that deals with the division of the training process into specific phases. Programming is the manipulation of the variables within these phases (sets, repetitions, load) that are needed to bring about the specific adaptations desired within that particular period. The current body of literature is very limited when it comes to how these variables are best combined in an injured population since most of the periodization research has been done in a healthy population. This manuscript explores what is currently understood about periodization, gives clinical guidelines for implementation, and provides the sports physical therapist with a framework to apply these principles in designing rehabilitation programs.

Keywords: periodization, sports rehabilitation, strength and conditioning, sports physical therapy, progressive overload, strength, power

Level of Evidence: 5
INTRODUCTION

Restoration of strength is arguably the most vital aspect of a rehabilitation plan and is a central tenet of strength and conditioning programs. Strength is the foundation from which all other physical qualities of performance like power, speed, and agility are developed. Without proper strength development, these qualities cannot be optimized.

Sports physical therapists design programs that include several components including endurance, flexibility, proprioception/kinesthesia, balance, joint and soft tissue mobility, speed, and power.1 These programs often follow a logical sequence to not only promote optimal healing, but also to restore peak performance. A significant challenge for sports physical therapists is designing optimal training programs that facilitate neural and muscular adaptations while being mindful of biologic healing constraints and safety for the athlete.1 Unfortunately, most strength training research to date on program design has been conducted on healthy, trained and/or untrained adults,1-35 while only two studies have been loosely based on rehabilitation.36,37 Unfortunately, few studies have examined the effect of periodization approaches in adolescent athletic populations.38

Periodization is one way for the sports physical therapist to approach the design of resistance training programs. Periodization is defined as the planned manipulation of training variables (load, sets, and repetitions) in order to maximize training adaptations and to prevent the onset of overtraining syndrome.1,30 It appears from the strength training literature that is available that periodization is usually needed for maximal strength gains to occur,20,31,40-44 although evidence stating otherwise exists.4,24,45 Periodized training is a safe method of training for older adults, as well as those in pain.5,46 Periodization has been shown improve training adaptations but the most effective periodization approach for muscular strength development for a wide variety of populations is yet to be determined.48

The classic understanding of periodization is attributed to Selye’s General Adaptation Syndrome (GAS), the template from which the original concept of periodization was derived.47 In summary, GAS effectively states that systems will adapt to any stressors they might experience in an attempt to meet the demands of these stressors.47,48 According to Selye this is accomplished through a process of three phases. Initial reaction to the stressor is termed the alarm/reaction phase where the athlete may experience stiffness, soreness, or a small drop in performance from fatigue after the training session. The second phase was termed the resistance phase and is where the body responds to the stressor by adapting to the new stress with less soreness, stiffness, more tolerance to activity, and improved performance. This is considered to occur at a level greater than that demanded by the stressor and was termed “supercompensation”. The final phase occurs if the stressor goes on longer than the organism can adapt, and exhaustion results, whereby the athlete may experience staleness in training or deal with symptoms of overtraining.47 In contrast to Selye, the fitness-fatigue model looks at periodization as a balancing act between fitness and fatigue.49 An individual’s level of preparedness is thus a result of the interaction between their level of fitness and the amount of fatigue.49 This idea has significant implications for programming if preparedness can be optimized by methodical improvements in fitness while minimizing the resulting fatigue.49 For the neuromuscular system to adapt maximally to the training load or stress, volume and intensity alterations are necessary.1 Increased demands cause the neuromuscular system to adapt by increasing muscular performance but there is also a concurrent increase in the physical, mental, and metabolic cost of recovery. Without concomitant changes in overload, the system has no need to adapt to stressors. Therefore, no further adaptations are needed and increases in the desired outcome will eventually stop.20,50 On the other hand, if load is too high, the physiological costs will be too great and the physical readiness for training of the athlete will be comprised. A periodized program helps avoid these issues because the load on the neuromuscular system is varied in order to drive adaptation while minimizing fatigue.

Periodization may also be beneficial due to adding variation to workouts by manipulating sets, repetitions, exercise order, number of exercises, resistance, rest periods, type of contractions, or training frequency.1,40,48 Another added benefit is the avoidance of training plateaus or boredom.1,20,50 The reader is referred to Table 1 for a summary of training parameters to address specific training goals.
The purpose of this commentary is threefold. First, a review of various periodization models will be provided, and a discussion about the potential pros and cons of each approach will be explored. A secondary purpose is to provide a sample program or structural framework of the various approaches described herein for the sports physical therapist to implement into a rehabilitation or strength and conditioning program. Finally, a review of programming for maximization of strength and power will be discussed as these two variables are most critical not only for the recovering athlete but also for healthy trained or untrained athletes.

LINEAR PERIODIZATION

The “classic” or “linear” periodization (LP) model is based on changing exercise volume and load across several predictable mesocycles. Classical periodization was originally discussed by Russian scientist Leo Matveyev and further expanded upon by Stone and Bompa. The program is broken down into distinct blocks that are named based on time frames. Planning that spans over a 12-month period is referred to as a macrocycle, and two subdivisions are the mesocycle (3-4 months) and the microcycle (1-4 weeks). Most rehabilitation protocols follow this model. After pain and swelling have subsided, the sports physical therapist typically follows a systematic progression of range of motion, strength, power, and speed with progression to each phase depending on achievement of specific goals in the previous phase. In an athlete recovering from an anterior cruciate ligament (ACL) reconstruction, the mesocycle from months three through six may be strength and power focused, but individual mesocycles may reflect different training loads in one to two weeks of training. There are a number of potential advantages of utilizing a linear approach. First of all, repetition and loading schemes are predictable for both the athlete and the sports physical therapist because they are ultimately determined by what phase the athlete is in. Each phase typically focuses on only one training parameter. Secondly, the linear model helps ensure that each training parameter (strength, power, speed) is addressed in step-wise progression.

Advancement to other training methods is dependent upon successful completion of training in the previous phase. With declining reimbursement as well as allowable visits for physical therapy, another possible advantage of the linear model is that it provides the patient a predictable sequence of loading and repetitions that they can follow when doing supervised independent home exercise programs. Effectively, the linear program helps take the “guesswork” out of loading and repetitions schemes.

There are also several potential disadvantages to the linear program. The linear program was originally devised as a training model for preparing for one peak competition per year in Olympic weightlifters. For athletes that play several sports or athletes that have multiple competitions in a season, this may not be optimal as an athlete’s tolerance to loading may ebb and flow based on injuries or frequency/intensity of competition. Another potential disadvantage is that maintenance of specific training parameters is difficult once an athlete transitions to another phase. For example, an athlete may have a six-week strength phase, but once they transition to the power phase, there may be a decline in strength since the loading and repetition schemes for the power phase are not well-aligned with strength development. Unfortunately, all of these potential advantages and disadvantages are speculative at this time. The reader is referred to Table 2 for a one-week sample program of lower extremity strengthening utilizing linear periodization.

Author’s note: For all sample programs, 2-3 “core” lifts (total body lifts i.e. squat, deadlift, and power clean central to athletic development) will be used to illustrate how program design would occur. Such sample programs are not meant to be all-inclusive and could include many other exercises (i.e. lunges, step-ups, calf raises) that may be added in order to provide a comprehensive program for the athlete.
**NON-LINEAR/UNDULATING**

The other main model is the non-linear or “undulating” periodization model, first proposed by Poliquin.\(^5\) While undulating periodization has been used, the term “non-linear” has become more favorable. Non-linear periodization (NP) is based on the concept that volume and load are altered more frequently (daily, weekly, biweekly) in order to allow the neuromuscular system longer periods of recovery as lighter loads are performed more often.\(^1\) In the NP model, there are more frequent changes in stimuli. These more frequent changes may be highly conducive to strength gains.\(^1,5\)

There are many potential advantages to the NP approach, although no definitive conclusions can be made at this time. First of all, the weekly fluctuations in training loads may lead to better neuromuscular adaptations compared to the LP approach, as loads are more unpredictable. Secondly, the NP program accounts for the need for modifications in the training program based on an athlete’s recovery from competition or from a previous workout/training session. Additionally, in the NP model, several training parameters may be addressed at the same time. Therefore, an athlete may address power and strength within the same week. Finally, due to the concurrent nature of the training, the detraining effects that occur in a LP approach might be avoided.

Like LP, there are a few potential disadvantages for the NP approach. Particularly in the recovering athlete, the athlete may not be appropriate for lifts focusing on power development, like the clean and snatch, if an appropriate strength base has yet to be achieved or established. Therefore, a “power” session may not be indicated. Finally, the NP program may not allow each performance characteristic to be optimally developed due to focus on several parameters at once. Again, definitive conclusions cannot be made at this time about the advantages or disadvantages to the NP approach.

The reader is referred to Table 3 for a one-week sample program of NP.

**Evidence-Based Update: LP vs. NP**

A recent meta-analysis and systematic review by Harries et al found that there were no differences in the effectiveness of linear vs. undulating periodization on upper-body or lower-body strength in healthy trained and untrained subjects.\(^3\) Possible explanations include the short-term nature of studies and the previous training history of participants. The results sug-

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**Table 3. Non-Linear Periodization**

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Sets/reps</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workout 1</td>
<td>Zone 3</td>
<td></td>
</tr>
<tr>
<td>Hang Clean</td>
<td>3x3</td>
<td>80% 1RM</td>
</tr>
<tr>
<td>Back Squat</td>
<td>4x5</td>
<td>80% 1RM</td>
</tr>
<tr>
<td>Workout 2</td>
<td>Zone 1/2</td>
<td></td>
</tr>
<tr>
<td>Hang Snatch</td>
<td>3x5</td>
<td>50% 1RM</td>
</tr>
<tr>
<td>Front Squat</td>
<td>3x12</td>
<td>50% 1RM</td>
</tr>
<tr>
<td>Leg Press</td>
<td>3x12</td>
<td>50% 1RM</td>
</tr>
<tr>
<td>Workout 3</td>
<td>Zone 2</td>
<td></td>
</tr>
<tr>
<td>Deadlift</td>
<td>3x8</td>
<td>70% 1RM</td>
</tr>
<tr>
<td>Back Squat</td>
<td>3x8</td>
<td>70% 1RM</td>
</tr>
<tr>
<td>Leg Press</td>
<td>3x8</td>
<td>70% 1RM</td>
</tr>
</tbody>
</table>

RM= repetition maximum
gest that novelty or training variety are important for stimulating further strength development. Based on available data, it appears that daily program manipulation is more beneficial than non-periodized training for eliciting strength gains.

To date, most authors have found only minimal differences in strength and power measures between LP and NP. Recent studies by Franchini et al in judo athletes, Miranda et al in resistance trained men training with the leg press and bench press, de Lima et al in young, sedentary women, Prestes et al in previously trained females, Baker and Buford et al in trained males, Rhea et al and Rhea et al in untrained men and women, and Hoffman et al in American football players determined that neither LP or NP were superior. Although there were subtle differences in outcome measures studied, but these differences were not statistically significant. No definitive conclusions can be made at this time as to which method is preferred.

**BLOCK PERIODIZATION**

Block periodization is an approach to the periodization of strength that has experienced a renewed interest of late. Block periodization involves highly concentrated, specialized workloads. Each step in the training cycle has a large volume of exercises focused on specific, targeted training abilities to ensure maximum adaptation. The rationale for block periodization is that traditional models often account for only one “peak” per year, while many athletes have numerous competitions throughout the year (basketball, soccer, baseball, etc). The LP model increases basic qualities, but these tend to decline during the competitive season. The block system allows for these qualities to be maintained throughout the year. This is known as the *long-lasting delayed training effect* – retention of changes even after the cessation of training. Issurin has proposed that power and strength can be maintained for up to 30 days while peak performance can be maintained for 5-8 days. Furthermore, the “classic” models, like LP and NP, have time devoted to endurance, strength, power, and speed, regardless of the sport. In the block approach, if an athlete doesn’t require endurance for their sport, it is not a focus of training. Similarly, the block approach would not include balance, strength, and agility in one training block – they would be performed separately with a specific focus. Another example of differences in the block approach is the concept of “complex training,” whereby a strength exercise is followed by a biomechanically similar plyometric exercise (i.e. back squat followed by a squat jump). Because these exercises comprise two different training modalities (strength and power), they would not be performed simultaneously. On the contrary, complex training would be used in an LP or NP programs. Another difference is that the block program is broken down into 2-4 week blocks, while the linear and non-linear models have at least four-week phases. In other words, an athlete may do strength, power, and peaking within four weeks while it may be several months before each phase is completed in the LP or NP because they are of longer duration.

The block approach is divided into three distinct phases. The *accumulation phase* builds work capacity. Compared to the other two phases, there is a higher volume of exercises performed at 50-70% of 1RM, composed of general movements. Typically, this phase may last from 2-6 weeks, based on how long the athlete has till the competitive season, as well as their training history. Untrained athletes would require more time in this phase. The second phase is the *transmutation phase*. In this phase, specific exercises with greater loads, comprising 75-90% of 1RM are performed. Accommodating resistance, like the use of chains or elastic bands with squats, may be used to promote a strength overload. Finally, the *realization phase* is comprised of even more specific movements than the transmutation phase with loads at 90% of 1RM or greater. For example, accommodating resistance in not typically used in this phase. Instead, athletes will perform >90% 1RM squats, deadlift, bench press, cleans, etc. In some cases, there is a week of reduced loading and volume following the realization phase to allow recovery due to the high-intensities utilized within the realization phase.

**Evidence-Based Update: Block Periodization**

There are a few studies that have utilized the block approach compared to other approaches. To the authors’ knowledge, only one study by Bartolomei et al did not support the block model when compared to an NP program with regard to strength, power, and hypertrophy in recreationally-trained women. Another study by Bartolomei et al found there were no differences between the block and
a more traditional LP program on upper and lower body strength in trained athletes. Compared to the LP approach block training was found to be a superior method of training by Ronnstad et al61 in a group of cyclists for VO2max and power output, Ronnstad and others62 in a group of elite cross country skiers for peak power and maximal oxygen uptake, and by Breil and coauthors63 in elite junior alpine skiers. Interestingly, two studies found that the block program lead to greater improvements in strength per volume of load when compared to other programs.60,64 In other words, the block program was more efficient in training effectiveness.

In summary, block periodization is showing some promise when compared to more common approaches like LP and NP. The positive results may be partially explained by the fact that the block periodization studies were short in duration and the intensity was high. The intensity seemed to be a direct correlate to performance. Furthermore, it appears that the block program was indeed better for athletes who have multiple events per year (cycling, skiing, track, etc). More research is needed before definitive conclusions can be made. See Table 4 for a generalized four-week block program and Table 5 for more specific training parameters (sets, repetitions, load).

**Programming for Strength and Conditioning**

The periodization schemes laid out previously define methods of sequencing the training process over time. In turn, the creation of the specific program within the selected periodization scheme drives the desired adaptations. This process is built around the principles of overload, variation, and specificity. Overload is described as a stimulus of sufficient strength, duration, and frequency as such that it forces an organism to adapt.65 Variation describes the manipulation of training variables that changes the overload stimulus. These variables are traditionally considered to be the exercise type, the order performed, the intensity (percentage of repetition maximum) prescribed, as well as the sets, repetitions and rest periods assigned. Specificity can be approached via a bioenergetics or metabolic and/ or mechanical perspective. Siff and Verkoshansky laid out a number of considerations for addressing mechanical specificity such as looking at the movement’s amplitude and direction, the dynamics of the effort, the rates of force development, and contraction types.66

When viewed from a bioenergetics perspective, a task analysis must be performed and the identified demands on the energy systems should be reflected in the programming. A growing body of literature exists specific to the energy system demands of sport. For example, researchers have found that the physiologic demands in American football include 7-10 seconds of maximal effort followed by 20-60 seconds of recovery.8 When specific research is unavailable...

**Table 4. Block Periodization - General Structure**

<table>
<thead>
<tr>
<th>Week 1</th>
<th>Sets/reps</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push Press</td>
<td>3x10</td>
<td>50% 1RM</td>
</tr>
<tr>
<td>Back/Front Squats</td>
<td>3x12</td>
<td>50% 1RM</td>
</tr>
<tr>
<td>Leg Press/Hack Squat</td>
<td>3x12</td>
<td>50% 1RM</td>
</tr>
<tr>
<td>Step Ups</td>
<td>2x12</td>
<td>50% 1RM</td>
</tr>
<tr>
<td>Lunges</td>
<td>2x8 ea</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week 2</th>
<th>Sets/reps</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push Press</td>
<td>3x8</td>
<td>60% 1RM</td>
</tr>
<tr>
<td>Back/Front Squats</td>
<td>3x10</td>
<td>60% 1RM</td>
</tr>
<tr>
<td>Leg Press/Hack Squat</td>
<td>3x10</td>
<td>60% 1RM</td>
</tr>
<tr>
<td>Trap Bar Deadlift</td>
<td>3x8</td>
<td>60% 1RM</td>
</tr>
</tbody>
</table>

**Week 3-4: Transmutation Phase. Increased loading**

<table>
<thead>
<tr>
<th>Week 3</th>
<th>Sets/reps</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hang Clean/Hang Snatch</td>
<td>3x4</td>
<td>75% 1RM</td>
</tr>
<tr>
<td>Back/Front Squat</td>
<td>3x6</td>
<td>80% 1RM</td>
</tr>
<tr>
<td>Deadlift/Trap Bar Deadlift</td>
<td>3x6</td>
<td>80% 1RM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Week 4</th>
<th>Sets/reps</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hang Clean</td>
<td>4x3</td>
<td>85% 1RM</td>
</tr>
<tr>
<td>Back/Front Squats with accommodating resistance</td>
<td>4x6</td>
<td>75% 1RM with bands</td>
</tr>
</tbody>
</table>

**Week 5: Realization Phase. Peak power. Intensity can be based on sport demands**

| Hang Clean Squats (Front or Back) | 4x2 | 90% 1RM |
| Alternative Lifts: Deadlifts, Hang Snatch | 4x5 | 90% 1RM – complete as fast as possible |

**Week 6: Restoration Phase. Reduced loading to follow high intensity work**

Choose several exercises <50% 1RM. Emphasize total body workouts with light loads and high repetitions.

*After this 6-week block, the athlete repeats each phase.*

RM= repetition maximum
able to describe physiologic demands of a sport, a demands analysis must be performed in order to determine the specific needs of the athlete. The rehabilitation programming should be structured to prepare the athlete for the metabolic demands of their specific sport.

**Load**
Without monitoring and adaptation the most elegant program can quickly become irrelevant. Furthermore, the sports physical therapist has the added challenge of dealing with the healing process. While adherence to a consistent approach will drive adaptation, structured variability is also necessary within this framework to ensure relevance on any given day. Because of this, a method of programming that is modifiable based on relevant feedback is important. One such method is autoregulation, a modification of the daily adjusted progressive resistive exercise (DAPRE) system that allows for a more flexible application than more traditional approaches.\(^{68,69}\) This modified protocol is a zone-based approach built around a focus on strength/power, strength/hypertrophy, and hypertrophy (Table 6). This approach has been applied successfully in both rehabilitation and performance based settings and has been shown to actually outperform more standard methods of periodization in some cases.\(^{70}\) The use of Rating of Perceived Exertion (RPE) has been shown to be a reliable measure of session intensity as well as specific exercise intensity within a training session.\(^{71-73}\) The use of RPE offers a significant

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<tr>
<th>Phase</th>
<th>Objectives</th>
<th>Example Exercise Sequence</th>
<th>Intensities</th>
<th>Sets x Reps</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Capacity/Tissue Healing</strong></td>
<td>Build work capacity &amp; general fitness. Promote Healing.</td>
<td>6-8 exercises selected based on ability to perform w/o damage to healing tissue but still impose metabolic load</td>
<td>Zone 1 or lower end of 2 at 6-7 RPE</td>
<td>2-3 sets x 10-15 reps; Rest ~2 min between circuits</td>
<td>2-4 weeks</td>
</tr>
<tr>
<td><strong>Accumulation</strong></td>
<td>Continue to build work capacity with more specific emphasis (Hypertrophy is a potential goal)</td>
<td>2-3 core lifts with 3-5 accessory lifts</td>
<td>Zone 2 strength; Zone 1 power</td>
<td>Core exercises 8-12 reps for 25-35 total reps</td>
<td>3-4 weeks</td>
</tr>
<tr>
<td><strong>Transmutation</strong></td>
<td>Focus on specific emphasis with specialized work to address main limitations. Maintain aerobic base.</td>
<td>1-2 main lifts, 1-2 specialized lifts and 3-4 accessory lifts; Cardiac work 2-3 days/week</td>
<td>Zone 3 strength; Zone 2/3 power</td>
<td>4-6 reps per set for 12-24 total reps</td>
<td>2-4 weeks</td>
</tr>
<tr>
<td><strong>Realization</strong></td>
<td>Bring everything together and emphasize power and max strength work.</td>
<td>1 main exercise each day; 1-2 accessory exercise; maintain Cardiac Workouts</td>
<td>Zone 4 strength and power work</td>
<td>1-4 reps per set for 8-15 total reps</td>
<td>2 weeks</td>
</tr>
<tr>
<td><strong>Restoration</strong></td>
<td>Choose several exercises &lt;50% 1RM. Emphasize total body workouts with light loads and high repetitions.</td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Table 5. Block Periodization – Detailed Description**

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advantage for the rehabilitation professional since it allows for monitoring intensity without establishing a true one-repetition maximum (1RM), which is often contraindicated due to stages of healing. Other models exist to estimate 1RM without actually lifting a true 1RM such as the Oddvar Holten Curve and other models by Baechle et al which are used to establish an estimated 1RM based off of submaximal loads taken to failure.

Velocity based training is another within-session method of monitoring that has grown increasingly popular as the technology for monitoring repetition velocity in the clinic or gym has become available. Research at this point is still emerging but a few practical models have been developed that determine intensity based on the velocity of the bar during the lift and the end of the set being based on a predetermined decrease in velocity. When applied systematically this approach allows for immediate feedback, fatigue control, prediction and monitoring of biomotor changes, and a guide to the training process. To the authors' knowledge, velocity-based training has not been studied in rehabilitative literature to date.

### Strength

Strength should be considered fundamental to all other aspects of training and forms the foundation of most successful return to play (RTP) approaches. Strength is defined as the ability to produce force and is traditionally measured with a single repetition maximum (RM) or by taking a percentage of RM to failure with the RM calculated based on a percentage table. Strength is closely correlated with the capacity to rapidly produce high levels of force and as a result maximal force development should be the initial emphasis with those presenting with lower levels of strength. The mechanism proposed for this increase in force as a result of strength work has been attributed to increased muscle cross-sectional area and changes in neural drive. Exercise intensity or load is commonly accepted as one of the critical components for achieving strength based adaptations. This is fairly well supported in the literature and the common recommendation of loads approximately >80% of RM in trained individuals should build the foundation of most programming for strength.

Optimal dosage has been debated, but the evidence to date supports multiple sets over single sets with up to 46% greater strength gains and 40% increase in hypertrophy seen when comparing multiple set to single set approaches in trained and untrained healthy individuals. Peterson also found that three to four sets per exercise with approximately eight sets per muscle group elicited the greatest pre/

<table>
<thead>
<tr>
<th>Zones</th>
<th>Goal</th>
<th>Rep Range</th>
<th>Sets</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>Strength/Power</td>
<td>3RM</td>
<td>Warmup</td>
<td>&lt;50% of RM</td>
</tr>
<tr>
<td>Zone 2</td>
<td>Strength/Hypertrophy</td>
<td>6RM</td>
<td>1</td>
<td>50% of RM</td>
</tr>
<tr>
<td>Zone 3</td>
<td>Hypertrophy</td>
<td>10RM</td>
<td>2</td>
<td>75% of RM</td>
</tr>
</tbody>
</table>

**Final Set Adjustment**

| 4+ reps below RM/RPE, reduce load 2.5-5kg | 3 | Reps to failure at RM |
| 2-3 reps below RM/RPE, reduce load by 0-2.5kg | 4 | Adjusted reps to failure based on final set adjustment |
| 1 rep above/below or RM/RPE goal, keep the same load | |
| 2-3 reps above RM/RPE, add 2.5-5kg | |
| 4+ reps above RM/RPE, add 5-7.5kg | |

RM= repetition maximum  RPE= rating of perceived exertion
post effect sizes (standardized mean differences) in strength. When multiple sets are not an option, single set training taken to failure is still of a sufficient stimulus to elicit significant changes in strength and hypertrophy.

This brief review of strength principles highlighted some of the considerations that the sports rehabilitation professional must consider when programming within any of the periodization schemes. Practical recommendations for strength training loads are presented in Table 7.

**Power**

Many aspects of sport and daily life require the ability to produce relatively high levels of force in a brief period of time. This characteristic is commonly described as power although there are some concerns that this term may not be as accurate as the biomechanical term, impulse. For the purpose of this paper the term will be used in its commonly accepted definition. Power is defined as the rate at which work is performed and is the product of force and velocity. As a result it becomes apparent that the ability to apply high levels of force in a brief period of time and to contract at high velocities are vital components of its development. The importance of power development in the rehabilitation environment ranges from fall risk reduction in the elderly to returning an athlete to sport post anterior cruciate ligament reconstruction. In athletics the ability to produce high power outputs with a high rate of force development has been proposed by Stone et al to be a critical aspect of success in many sports. As such an understanding of power development and its integration into a periodization approach is important.

Power development can be subdivided into a focus on muscular strength, rate of force development, and maximal force at high velocities of movement. There are excellent arguments for a high load approach (50-70% of one repetition maximum 1RM) as well as for a low load approach (<50% [1RM]) in exclusion but a “mixed methods approach” combining both appears to be the most beneficial. This approach to training for power has been suggested as optimal since it combines heavy resistance training with higher velocity work in order to develop power production across the entire force/velocity spectrum. The result is more relevant adaptations when compared with strength training or ballistic exercise alone. For the novice trainee, focused strength development alone is often sufficient for power development without the addition of any specific work and in general, a stronger individual responds better to the addition of specific power-based exercises than a weaker counterpart. It should be noted that all guidelines are general and acceptable levels of strength prior to initiation of power work is dependent on the individual and the demands of their task. Regardless of the specifics, maximal strength levels constrain the upper limits of maximal power output. The ability to generate force rapidly is of little use if the level of force generated is below a necessary threshold and thus adequate strength levels form the foundation of maximal neuromuscular power development.

Cormie et al randomized individuals into groups based on their squat 1RM to body mass ratio. They found that the stronger individuals displayed greater power production initially and also a trend towards a greater effect size when compared to the weaker group although both groups improved at a similar magnitude and displayed similar adaptive abilities when exposed to lower extremity ballistic (plyometric) power training. As a result, the authors concluded that there is potential benefit to develop-
ing strength initially before performing a focused ballistic program. In addition, they advise regarding the importance of maintaining strength throughout a power-specific training phase since decreases in maximal strength are theorized to result in a decreased ability to adapt to ballistic training.

There is a paucity of data with regard to power development or training in the upper body, but the same trend for stronger athletes to respond better to ballistic work compared to their weaker counterparts has also been seen. Young et al. found that athletes with a lower bench press repetition maximum benefited more from strength work, however, those with higher relative strength also benefit from the inclusion of ballistic work. Mangine et al. took a group of 17 resistance-trained men and compared combined ballistic and heavy resistance work with a group that only performed heavy resistance training. Their findings indicated that the addition of ballistic exercise increased power when compared to strength training alone.

**Training for Power**

Ballistic training, which includes techniques such as jump squats, medicine ball throws, and box jumps has been argued to impact the high velocity area of the force velocity curve. This is in contrast to power work done with heavier loads, such as the Olympic lifts, which will have a greater effect on the higher force aspect of this relationship. These exercises also differ from more traditional strength exercises in that they allow for acceleration throughout the entire movement, versus something like the bench press where up to 52% of the exercise duration is deceleration.

The concept of optimal load training indicates that training loads should be chosen to allow for maximal power output as this is the most effective means of further power development. Neglecting higher load work can be problematic however since training power at higher loads results in higher power outputs at heavier loads which is very important in sports such as American football or rugby. Optimal power development across the entire force velocity profile therefore requires training across the full spectrum of loads and velocities. While training with the intent to move explosively is very important a majority of the research demonstrates velocity-specific adaptations to training. Thus, all exercises should be performed as rapidly as possible regardless of the actual speed of exercise. Table 8 gives some general recommendations for power training intensity zones based on various exercises commonly used for power development.

**Conclusions and Directions for Future Research**

At this time, the research on periodization is limited, not only in the rehabilitation literature but also in strength and conditioning. The block model has not yet been studied in rehabilitation literature. Further, previous papers have shown that there is clear benefit to periodization over non-periodized programs, but there is no conclusive evidence that LP or NP is superior to the other. Likewise, block periodization has not been established as the definitive approach, but early studies show some promise with training improvements. Clearly, there is potential to use these various models for more “long term” rehabilitation programs, such as labral repairs of the hip and shoulder, rotator cuff repairs, ulnar collateral ligament reconstructions, or anterior cruciate ligament reconstructions, to see if recovery time can be improved or clinical testing methods for performance can be optimized. Additionally, use of these periodization models has not been utilized in interval sport programs. Truly, this is a relatively unexplored area of

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Optimal Power Load (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jump Squat</strong></td>
<td>0% of 1RM</td>
</tr>
<tr>
<td><strong>Power Clean</strong></td>
<td>80% of 1RM (50-90%)</td>
</tr>
<tr>
<td><strong>Squat</strong></td>
<td>56% of 1RM (42-71%)</td>
</tr>
<tr>
<td><strong>Bench Press Throw</strong></td>
<td>30-45% of 1RM (46-62% in highly trained athletes)</td>
</tr>
</tbody>
</table>

RM= repetition maximum
research and there are vast opportunities for studies to be conducted, all with the goal of maximizing long-term athletic rehabilitation, development, and performance.

REFERENCES


ABSTRACT

Injuries to the muscle and/or associated tendon(s) are common clinical entities treated by sports physical therapists and other rehabilitation professionals. Therapeutic exercise is a primary treatment modality for muscle and/or tendon injuries; however, the therapeutic exercise strategies should not be applied in a "one-size-fits-all approach". To optimize an athlete's rehabilitation or performance, one must be able to construct resistance training programs accounting for the type of injury, the stage of healing, the functional and architectural requirements for the muscle and tendon, and the long-term goals for that patient. The purpose of this clinical commentary is to review the muscular and tendinous adaptations associated with strength training, link training adaptations and resistance training principles for the athlete recovering from an injury, and illustrate the application of evidence-based resistance training for patients with a tendinopathy.

Key Words: Muscle, resistance training, therapeutic exercise, tendon

Level of Evidence: 5
INTRODUCTION
Sports physical therapists frequently prescribe therapeutic exercises (TE) in order to facilitate an athlete's recovery after acute injury or surgery.\textsuperscript{1,4} TE strategies should not be applied in a "one-size-fits-all approach". To optimize an athlete's rehabilitation or performance, one must be able to construct resistance training programs (or apply an evidence-based TE program when available) accounting for the type of injury, the stage of healing, the functional and architectural requirements for the muscle and tendon, and the long-term goals for that patient. Increasing muscular strength, muscular endurance, and muscular power is at the core of improving health and reducing the risk of injury in healthy athletes and athletic individuals.\textsuperscript{1,4}

In order to optimize an athlete's rehabilitation or performance, a physical therapist must be able to construct resistance training programs applying evidence-based principles of exercise prescription. The purpose of this clinical commentary is to present the muscular and tendinous adaptations associated with strength training, link training adaptations and resistance training principles for the athlete recovering from an injury, and illustrate the application of evidence-based resistance training for a patient with a tendinopathy.

MUSCULAR AND TENDINOUS ADAPTATION TO RESISTANCE TRAINING
Performing resistance training exercises will cause muscular and tendinous adaptations in patients and healthy athletes.\textsuperscript{2,15-16} These training adaptations can be advantageous for helping an athlete recover from an injury or surgery and/or to improve aspects of athletic performance. Increases in strength associated with prolonged resistance training occur due to a combination of neural and morphologic adaptations.\textsuperscript{2,17-22} The focus of this commentary will be on the morphologic adaptations of the muscle and tendon; however, it is important for physical therapists to appreciate that immediate gains in strength may be the result of neural adaptations.\textsuperscript{2,17-22}

Physiological Cross-Sectional Area (PCSA)
A key morphologic adaptation associated with increases in strength due to resistance training is the increase in physiological cross-sectional area (PCSA) of skeletal muscle. Increases in PCSA can be observed via diagnostic imaging including magnetic resonance imaging [MRI], diagnostic ultrasound, and computerized tomography, as early as two months after initiating a training program.\textsuperscript{2,20-24} MRI is considered the gold standard for measuring changes in PCSA.\textsuperscript{23} Diagnostic imaging is routinely utilized in research to assess changes in PCSA; however, utilization of imaging techniques is financially prohibitive in most clinical situations. In addition, strength gains experienced by patients during the early phases of a rehabilitation program are likely the result of neural adaptations with subsequent strength gains associated with muscular hypertrophy occurring one to two months after initiating training.\textsuperscript{1,2,21,22} Physical therapists, and other rehabilitation clinicians, should instead assess force production with traditional clinical tests (e.g., manual muscle testing, dynamometry) or with functional performance tests. A measure of a muscle's cross-sectional area could be determined with a girth measurement using a tape measure; however, this anthropometric measure can only provide a comparison to the uninjured side (e.g., thigh, calf, upper arm, chest) and cannot provide a measure of an individual muscle nor provide the clinician with an indication of either strength or functional performance.

Increases in PCSA plateaus at some point between six months to one-year after initiating a training program.\textsuperscript{2,23} Muscular hypertrophy occurs in both genders; however, muscular hypertrophy in women is typically lower. Strength gains and increases in cross-sectional area in females occur at 80% of those seen in their male counterparts.\textsuperscript{25-27} Lower circulatory androgens and androgen receptor content in females may explain the lower propensity for increases in PCSA as compared to that seen in males.\textsuperscript{28} PCSA decreases across the lifespan; however, aging adults who perform resistance training exercises can experience an increase in PCSA. Fiatarone et al found PCSA increases in the thigh in nonagenarians after 12 weeks of resistance training.\textsuperscript{29} The potential to experience increases in PCSA, and thus increases in muscular strength, may help to reduce risk of musculoskeletal injury and/or improve function.\textsuperscript{29-31}

Hypertrophy
The muscle fiber, or myofibril, is comprised of thousands of sarcomeres. The sarcomere, which is the functional unit of the muscle, consists of several
proteins that are involved in the contraction of skeletal muscles. Hypertrophy of muscle fibers is considered the primary mechanism associated with increases in PCSA due to resistance training. During resistance training, microdamage to the architecture of the muscle occurs. This “damage” to the muscle stimulates activity and proliferation of satellite cells. Satellite cells, precursors to myofibers, are located between the sarcolemma and the basal lamina. Satellite cells can contribute their nuclei to a myofibril; this addition of the nuclei can aid synthesis of contractile proteins. Addition of new actin and myosin contractile proteins increases the PCSA of the muscle. Satellite cells may also fuse existing cells to each other to create new myofibrils.

A proposed second mode of muscular hypertrophy is known as sarcoplasmic hypertrophy. Sarcoplasmic hypertrophy is the result of increases in fluid and noncontractile components that comprise muscle. This form of hypertrophy, which has been observed in bodybuilders, may be the result of a specific training stimulus. Researchers have found that bodybuilders have higher glycogen content levels than individuals who primarily perform exercises to enhance muscular power. Differences in muscle bulk due to changes in noncontractile elements of the muscle in bodybuilders may be due to changes in training strategies. For example, bodybuilders may perform 6 to 12 repetitions per set with training loads ranging from 67 to 85 percent of their 1-repetition max (RM) lift whereas recommended training volumes and loads to enhance power are one to three repetitions performed at 75 percent or higher of one’s 1-RM.

Resistance training appears to have a greater effect on increasing PCSA in the muscles of the upper extremity than those in the lower extremity. There are two potential explanations for this observation. First, the muscles of the lower extremities (LE) may experience a lower level of PCSA gains in response to a new resistance training program because many of the LE muscles are consistently under load in weight-bearing positions. Additionally, the loads during resistance training of the LE may not be high enough to cause increases in PCSA. Second, the upper extremity muscles have higher concentrations of androgen receptors.

Researchers have observed, via biopsy studies of the UE and LE muscles, increases in fiber area with both Type I and Type II fibers experiencing hypertrophy in response to resistance training. Initial adaptations to resistance training (during the first one to two months after initiating a program) occur due to hypertrophy primarily of Type II fibers. Of potential clinical interest to physical therapists is the finding that Type II fibers, in injured individuals or in those who have reduced or altogether stopped their training program, atrophy quicker than Type I fibers. Type I muscle fibers also hypertrophy in response to resistance training programs; however, increases in fiber size are usually observed in studies when researchers perform assessments 2 or more months after initiation of a training program.

Given the right stimulus, most characteristics of the musculotendinous unit including fiber type, fiber length and diameter; tendon length, distribution, and architecture; and the glycolytic/oxidative pathways change. It is well established that muscle fiber transformation can take place with specialized training stimuli. For example, regardless of muscle or species (both animal and human), many researchers have demonstrated muscle fiber transformation from Type II (fast twitch) to Type I (slow twitch). This fast-to-slow fiber transformation is generally described as a complete change of the fast twitch fiber both histochemically and biochemically without any actual differences in the slow twitch fibers that did not convert. Additionally, the process of transformation is not merely a loss of fast twitch fibers but a change in the amount of metabolic enzymes and sarcoplasmic reticulum available for use and interestingly, both adapt much more easily than the contractile proteins. Resistance training may cause ruptures of the Z-disk followed by subsequent longitudinal division of the muscle fiber. This response has been observed in animal studies, and is postulated to also occur in humans. Training also leads to increases in the size of myofibrils as well as increases in myosin filaments on the periphery of each fibril.

Hyperplasia, which is a term describing an increase in the total number of muscle fibers, has also been proposed as a potential mechanism associated with increases in muscular size. However, evidence to
support this mechanism is lacking. Current thought is any contribution to PCSA via hyperplasia is minimal if at all.2,61,62

Tendinous Adaptations
Increases in tendon stiffness in response to resistance training have been identified in both animal and human studies.63-66 Stiffness describes a mechanical property of the tendon. Stiffness is the force required to stretch a tendon per a unit of distance. Increased stiffness can impact the ability of the muscle to rapidly generate force. In addition, tendons respond to chronic resistance training by increasing total number of collagen fibrils, increasing the diameter of collagen fibrils, and increasing in fibril packing density.67-71

GENERAL CELLULAR EVENTS ASSOCIATED WITH AN INJURY OF A MUSCLE AND TENDON
After a soft tissue injury to a muscle and/or tendon, a series of cellular events occur as part of the healing process (Table 1).72 Appreciating the events that occur during the healing process should influence the type of exercises prescribed by the rehabilitation professional.

The Acute Stage
Onset of an inflammatory response occurs the moment of an acute injury. The function of the inflammatory response is to halt of the progression of cellular injury, initiate the body’s healing process, and to protect the area from further injury.72 The onset of an acute injury is marked by the classic inflammatory signs: rubor (redness), tumor (swelling), calor (warmth or heat), and dolor (pain).72 The swelling associated with the acute inflammatory process is a result of spread of exudate (the plasma and serum proteins) from the damaged vessels in the region of injury. The function of the exudate is to initiate repair at the site of the injury. A negative consequence associated with swelling is the onset and/or increase pain due to the pressure applied to free nerve endings.72

The cellular events associated with the acute injury stage can last up to six days. Appropriate treatment

Table 1. General Cellular Events Associated with a Muscle and/or Tendon Injury*2

<table>
<thead>
<tr>
<th>Time Frame After Injury</th>
<th>Cellular Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>First 48 hours</td>
<td>- Initial vasoconstriction and coagulation upon rupture of blood and lymphatic vessels</td>
</tr>
<tr>
<td></td>
<td>- Immediate swelling at injury site caused by cellular components (e.g., exudate) leaking from the blood and lymphatic vessels leaking into wound area</td>
</tr>
<tr>
<td></td>
<td>- Clot formation</td>
</tr>
<tr>
<td></td>
<td>- Hallmark signs associated with an acute injury: redness, warmth, pain, and swelling</td>
</tr>
<tr>
<td></td>
<td>- Chemical mediators attracted to the site to control the inflammatory process</td>
</tr>
<tr>
<td></td>
<td>- Vasodilation occurs shortly thereafter the initial injury</td>
</tr>
<tr>
<td></td>
<td>- Phagocytosis (removal injured/dead cellular material)</td>
</tr>
<tr>
<td>Day 2 to 4</td>
<td>- Reduction in inflammation</td>
</tr>
<tr>
<td></td>
<td>- Reabsorption of clot</td>
</tr>
<tr>
<td></td>
<td>- Increase in granulation tissue (fibroblasts, myofibroblasts, and capillaries)</td>
</tr>
<tr>
<td></td>
<td>- Angiogenesis</td>
</tr>
<tr>
<td>Day 4 to 21</td>
<td>- Scar formation</td>
</tr>
<tr>
<td></td>
<td>- Production of collagen, elastin, and ground substance</td>
</tr>
<tr>
<td></td>
<td>- Growth of scar ceases at the end of the phase</td>
</tr>
<tr>
<td>Day 21 to 60</td>
<td>- Scar remodeling</td>
</tr>
<tr>
<td></td>
<td>- Collagen thickens and strengthens</td>
</tr>
</tbody>
</table>
prescription is key to facilitating the progression of healing from the acute to subacute stages. Delaying treatment may fail to modulate a patient’s pain experience whereas aggressive treatment may increase a patient’s pain experience or further damage the injured region. Appropriate forms of treatment for an acutely injured region include protection or rest, modalities (e.g., cryotherapy), gentle range of motion exercises, and possibly gentle isometric strengthening exercises (Table 2).

### The Subacute Phase

The subacute phase of healing begins as early as the third day after trauma/injury and lasts for up to 21 days. New capillary growth, known as angiogenesis, occurs in the injured area early in this stage. Also, fibroblasts synthesize new collagen to replace the damaged tissue. Collagen is the primary structural protein of soft tissue structures. This newly formed collagen is weak and thin and is oriented haphazardly. It is clinically relevant to appreciate the structural integrity of the newly repaired collagen tissue. Aggressive or unsupervised treatments may damage this structurally weak tissue and delay healing. Common practice during the early part of the subacute phase is to have a patient continue range of motion exercises in order to restore any remaining deficits, initiate gentle, pain-free stretching, and initiate either isometric or low-load, high-repetition exercises. A key to successful rehabilitation is to not have the patient perform exercises that provoke or increase pain (Note: there are instance when a patient should experience an increase in pain during exercise. Specifically, this relates to rehabilitation of tendinosis conditions). For example, a clinician may prescribe two sets of 15 repetitions of a short arc quad exercise for a patient with anterior knee pain. The exercise should be terminated if the patient begins to experience symptoms during the performance of the repetitions (the clinician would document how many sets and reps that the patient was able to perform and how much weight was utilized).

### The Chronic Stage (Maturation and Remodeling Stage)

The term chronic is sometimes used in reference to the final stage of healing (e.g., the maturation and remodeling stage) or as a descriptor of one’s medical condition state (e.g., chronic low back pain or chronic pain due to arthritis). The chronic stage of healing is the final stage of healing that begins around day 21 and continues up to 12 months after injury. During this stage of healing collagen is remodeled in response to applied forces. Progression of the exercise program will increase tensile strength of the tissue. Patients are typically able to initiate functional strengthening (e.g., squats, lunges) followed by plyometric or power training exercises.

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**Table 2. Summary of Healing Response and Appropriate Conservative Rehabilitation Treatments**

<table>
<thead>
<tr>
<th>The Acute Stage (Inflammatory response) 1-6 days post-injury</th>
<th>The Subacute Stage (Repair and Healing Phase) Begins as early as day 3</th>
<th>Chronic Stage (Maturation and Remodeling Stage) Begins about 3 weeks post-injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exudate (plasma and serum pr-) leaks out of damaged vessels into surrounding tissue They function to repair damaged site, but can cause significant swelling Swelling → stress to free nerve endings → pain</td>
<td>Fibroblast activity: synthesize new collagen, the collagen is formed and oriented in a haphazard fashion. Collagen is structurally thin and weak Overstressing/aggressive therapy may reinjure tissue Not stressing tissue may allow adhesions to form</td>
<td>Collagen is remodeled along lines of applied stress Applying appropriate volume of stress to healing tissue will help to facilitate functional orientation of collagen and increase tensile strength capability</td>
</tr>
<tr>
<td>Treatments: Modalities, gentle ROM, isometric strengthening</td>
<td>Treatments: initiate strengthening, continue ROM progression</td>
<td>Treatments: strengthening, functional strengthening, progress to plyometrics or power training as appropriate</td>
</tr>
</tbody>
</table>
PATHOANATOMICAL CHANGES ASSOCIATED WITH SKELETAL MUSCLE AND TENDON INJURY

Muscle Injury
Features of a strain injury of a muscle include tearing of the fibers, muscular weakness, functional loss, swelling, and pain. Strain injuries are classified as 1st, 2nd, or 3rd degree strains (Table 3). First degree strains are minor injuries associated with tearing of less than one-half of the fibers, minor pain and weakness, little to no loss of function, and little to no swelling. Second degree strains are associated with tearing of approximately one-half of the fibers, moderate pain and muscular weakness, a moderate degree of functional loss, and visible swelling. A third degree injury is associated with a complete tear or rupture, of the muscle or tendon, significant loss of function, significant muscular weakness, and swelling. An individual who has experienced a third-degree strain may not experience pain if an innervating sensory nerve has been damaged.

Often, injury results in immobilization and it may have an unpredictable effect on muscle size, length, and strength. Position of immobilization effects sarcomeres. When a muscle is immobilized at a longer length it will experience an increase in its number of sarcomeres in series whereas immobilization of a muscle in a shorter length will cause a decrease in the number of sarcomeres in series. Researchers have found that not all muscles respond in a similar fashion to immobilization. For example, when the quadriceps was immobilized for 10 weeks, the PCSA of rectus femoris was least affected, and conversely, the PCSA of the vastus medialis was affected the most. Fiber type alone does not help explain some of these differences in atrophy. The vastus medialis (VM) has a similar percent of Type I (slow twitch) fibers as the rectus femoris and yet atrophied more. Similarly, the VM’s Type II fibers atrophied more than those Type II fibers of the vastus lateralis. Most muscles are comprised of similar levels of Type I and Type II fibers with some variation among studies. In general, there is either a 40%-60% split (Type I:II) or 60%-40% split (Type I:II). Muscles with a higher percentage of Type I fibers have slower twitch characteristics as well as a decreased capacity for force generation, function as postural stabilization muscles, and function predominantly in endurance-type activities. Conversely, muscles with a higher concentration of Type II fibers have more fast twitch characteristics, are able to generate greater amounts of force, and function predominantly in shorter burst activities. With specific endurance training, it is possible to increase the percentage of Type I fibers. However, it is not

| Table 3. Pathoanatomical Changes Associated with Muscle and Tendon Injury: 1st, 2nd, and 3rd Degree Strains |
|--------------------------------------------------|----------------|----------------|
| Degree of Muscle Damage                          | 1st Degree     | 2nd Degree     | 3rd Degree     |
| Muscle Weakness                                  | Tear of a few muscle & tendon fibers | Tear of approximately half of the muscle fibers | Tear (rupture) of the entire muscle |
| Loss of Function                                 | Minor          | Moderate (significant) | Major          |
| Pain                                             | None to minor  | Moderate       | Major          |
| Swelling                                         | Minimal to none| Noticeable degree of Swelling | Significant degree of Swelling |
clear if training causes an increase in the percentage Type II fibers in strength and power athletes. Table 4 lists a few of the major muscles and their Type I fiber proportions.

As previously mentioned, the long held belief about the specificity of training is true. As an example, endurance training signals the satellite cells to produce Type I muscle fibers. Since some muscle fiber conversion (Type II-to-Type I) takes place during training, rehabilitation and training experts need to keep this in mind. For example, excessive endurance training for a sprinter may result in a fast-to-slow conversion of muscle fibers. Similarly, too many repetitions for a strength and power athlete may also result in muscle type conversion from fast-to-slow. Table 5 provides general training guidelines for muscles based on fiber type.

Tendon Injury
Tendons are fibrous connective tissues that are anatomically oriented between muscle and bone. The tendon helps to facilitate joint movement and stability via the tension generated by the muscle. Tendons also store energy that may be used for later movement. For example, the Achilles tendon may store as much as 34% of the total ankle power. Tendons consist of fibroblasts and an extracellular matrix. The fibroblasts synthesize the components of the extracellular matrix including the ground substance, collagen fibers, and elastin. The collagen fibers are key to providing tensile strength to the tendon. The parallel arrangement of the collagen fibers provides strength to the tendon allowing it to experience large tensile forces without sustaining injury. When a tendon experiences strain levels that overload the tissue’s tensile capabilities microtrauma or macrotrauma will result. Typically, strength training rarely leads to a tendon injury. However, in a diseased state, a tendon is at risk of injury or reinjury if the tendon is overloaded. Clinicians are advised to prescribe training loads for patients with a tendon injury (or for that matter any musculoskeletal injury) that do not reproduce symptoms.

Tendons are largely comprised of Type I collagen and once lengthened provide a high degree of tensile strength. They also act parallel with the viscoelastic component of the muscle storing energy for later use. Significant variations exist in the stiffness properties of tendons and this stiffness can affect the force-velocity characteristics of a muscle. As an example, if a tendon is too compliant (lacks stiffness) it will result in a reduced ability of the muscle to generate force. The property of a tendon is dependent on its stress and strain characteristics where stress is defined as force divided by cross-sectional area and strain is defined as the change in length divided by its resting length. Young’s Modulus helps describe the relationship between stress and

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**Table 4. Muscle Groups and Type I Fiber Contribution**

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Type I Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotator Cuff (Supraspinatus, Infraspinatus,</td>
<td>Type I: 44% range 38% in</td>
</tr>
<tr>
<td>Teres Minor, Subscapularis)</td>
<td>subscapularis – 54% in</td>
</tr>
<tr>
<td>Deltoid</td>
<td>Type I: 47 – 74%</td>
</tr>
<tr>
<td>Gluteus Maximus</td>
<td>Type I: 52-60%</td>
</tr>
<tr>
<td>Rectus Femoris</td>
<td>Type I: 30 – &lt;50%</td>
</tr>
<tr>
<td>Vastus Lateralis, Medialis, Intermedius</td>
<td>Type I: 44 – 64%</td>
</tr>
<tr>
<td>Hamstrings (Semitendinosus, Semimembranosus, Biceps Femoris)</td>
<td>Type I: 44 – 67%</td>
</tr>
<tr>
<td>Gastrocnemius</td>
<td>Type I: 44-65%</td>
</tr>
<tr>
<td>Soleus</td>
<td>Type I: ~70%</td>
</tr>
<tr>
<td>Multifidus</td>
<td>Type I: ~65%</td>
</tr>
</tbody>
</table>

**Table 5. General Training Guidelines for Selective Hypertrophy of Muscle Fibers**

<table>
<thead>
<tr>
<th>Muscle Fiber Type</th>
<th>Training Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I Muscle Fibers</td>
<td>Low resistance, volume, and aerobic exercise</td>
</tr>
<tr>
<td>Type II Muscle Fibers</td>
<td>High intensity / low volume training programs (e.g., power training)</td>
</tr>
</tbody>
</table>
strain. For example, a stiff tendon can accept high loads (stress) and experience very low deformation (strain). Some evidence exists suggesting that tendon stiffness and hypertrophy increases following resistance training.\textsuperscript{66,69,87,88}

Tendons are at risk for overuse, traumatic, and degenerative injury.\textsuperscript{86,89,90} Because of the anatomical relationship between the tendon and skeletal muscle, sometimes both structures are injured simultaneously. However, there are a number of injuries that are specific to the tendon itself (Table 6). It is important for clinicians to distinguish the difference between an acute, inflammatory tendon injury and a chronic, degenerative injury. Acute injuries of the tendon include peritenonitis, tenosynovitis, and tenovaginitis (Table 6). Therapists will be unable to clinically distinguish between the different types of an acute tendon injury; diagnosis would require medical studies not available to PTs. Clinical diagnosis of a tendinosis may also pose challenges for a PT. A patient who presents with a tendinosis may report experiencing pain for a prolonged period of time and not be able to describe a specific mechanism of injury. For example in a patient with a suspected Achilles tendinosis (see Appendix), the therapist must use their clinical judgment to determine if inflammation is present. Although the symptoms may be similar, palpation may reveal whether the enlarged area has inflammatory signs including redness and swelling. Another differentiating test is range of motion. If swelling is a result of inflammation, the swelling will not move with the tendon, whereas an enlarged or thickened region in the tendon will move as the tendon moves in a patient with a tendinosis. Results from rehabilitation studies suggest that individuals with a tendinosis (chronic, degenerative) benefit from intense, eccentric exercise based programs whereas those with a tendinitis (acute, overuse) benefit from a gradual, conservative therapeutic program.\textsuperscript{90}

### Table 6. Tendon Injury Classifications

<table>
<thead>
<tr>
<th>Injury Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tendinitis</td>
<td>Acute, inflammatory injury</td>
</tr>
<tr>
<td></td>
<td>Examples</td>
</tr>
<tr>
<td></td>
<td>Peritenonitis – inflammation of the peritenon</td>
</tr>
<tr>
<td></td>
<td>Tenosynovitis – inflammation of the synovial membrane</td>
</tr>
<tr>
<td></td>
<td>Tenovaginitis – inflamed, thickened tendon sheath</td>
</tr>
<tr>
<td>Tendinosis</td>
<td>Chronic, degenerative injury not associated with an inflammatory process. Degenerative changes result from microtrauma or age.</td>
</tr>
</tbody>
</table>

Case Example: Therapeutic Exercise for Achilles Tendinosis

Although skeletal muscle may be one of the most adaptable materials in the body, if the cumulative mechanical or metabolic loads on the muscle fiber are too high, the tissue will “break”. Simply stated, injury is a result of the body’s failure to adapt and muscle overtraining continues to be the number one reason for injury.

Documented injury rate among recreational runners range between 25-65\%.\textsuperscript{91-93} Midportion Achilles tendinopathy is among the most common injuries, with the incidence in recreational and elite runners ranging between 6-18\%.\textsuperscript{89,90,94} The challenge is that up to 29\% of patients with Achilles tendinopathy do not respond to conservative treatment and may require surgical intervention.\textsuperscript{95,96} Interestingly, as high as 45\% of non-athletic patients’ with Achilles tendinopathy may not respond to current eccentric protocols.\textsuperscript{96}

As stated above, tendinosis is a chronic degeneration and is associated with a conversion of Type I and a higher percentage of Type III collagen fibers resulting in a structurally altered tendon. There are no inflammatory markers and the tendon often demonstrates neovascularization. The overwhelming current evidence-based conservative treatment for Achilles tendinosis that shows favorable results in many randomized controlled studies and in systematic reviews, is an eccentric training program.\textsuperscript{90,97-99} Although the exact mechanism by which eccentric exercise affects tendon is unclear it is thought that the eccentric exercise encourages tissue repair and remodeling.\textsuperscript{100} Recently, van der Plas et al reported that 46 patients with Achilles tendinopathy at the five-year follow-up
demonstrated significant increases in the VISA-A but with continued minimal pain. Additionally, Beyer et al recently published an article on the benefits of a heavy slow resistance training protocol compared to current eccentric protocols and demonstrated positive results.

CONCLUSION
This commentary has reviewed morphologic changes in the human muscle and tendon associated with resistance training. Sports physical therapists prescribe therapeutic exercises in order to address deficits associated with injury as well as design and implement training programs to reduce the risk of injury and to enhance sports performance. When possible, sports physical therapists should utilize evidence-based programs in the rehabilitation of musculoskeletal sports injuries. The provided case example illustrates the application of the concepts in this commentary applied to treatment for Achilles tendinosis.

REFERENCES


ABSTRACT

As knowledge regarding rehabilitation science continues to increase, exercise programs following musculoskeletal athletic injury continue to evolve. Rehabilitation programs have drastically changed, especially in the terminal phases of rehabilitation, which include performance enhancement, development of power, and a safe return to activity. Plyometric exercise has become an integral component of late phase rehabilitation as the patient nears return to activity. Among the numerous types of available exercises, plyometrics assist in the development of power, a foundation from which the athlete can refine the skills of their sport. Therefore, the purpose of this clinical commentary is to provide an overview of plyometrics including: definition, phases, the physiological, mechanical and neurophysiological basis of plyometrics, and to describe clinical guidelines and contraindications for implementing plyometric programs.

Keywords: Amortization, plyometric, rehabilitation, stretch shortening cycle

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INTRODUCTION: AN OVERVIEW OF PLYOMETRICS

There are as many strength and conditioning programs as there are individual clinicians developing the programs. Rehabilitation programs have dramatically changed over the past several years. Regardless of the purpose of the program, whether it is used in the terminal phases of rehabilitation, for strength and conditioning, or for performance enhancement, plyometric exercise should play an integral part of the program. An important part of performance-based rehabilitation programs is the development of power often addressed by using plyometric exercises. Sports physical therapists strive to prevent injuries, rehabilitate injuries in a timely manner in order to rapidly return athletes back to activity, improve the strength and conditioning of athletes, and facilitate the specificity of sports performance. Because of this there is an increasing demand to progress performance as quickly as possible. Plyometrics may be incorporated as an integral component of an exercise program that can produce all the aforementioned outcomes. As tremendous forces are imposed on the extremities during sports and athletics, there is a huge demand to develop power during the performance phase of rehabilitation. The concepts of specificity of rehabilitation and the SAID (Specific Adaptation to Imposed Demands) principle imply the need for periodization programs to be incorporated in the terminal phases of rehabilitation, as well as conditioning and performance programs. Of the numerous types of available exercises, plyometrics assist in the development of power, a foundation from which the athlete can refine the skills of their sport. Therefore, the purpose of this clinical commentary is to provide an overview of plyometrics including: definition, phases, the physiological mechanical and neurophysiological basis of plyometrics, and to describe clinical guidelines and contraindications for implementing plyometric programs.

PHASES OF PLYOMETRICS

Why should plyometric exercises even be used for rehabilitation or performance enhancement in sports? Both lower extremity (LE) and upper extremity (UE) sports use the plyometric concept as part of functional movement patterns and skill when performing the sport. Plyometric training utilizes the stretch-shortening cycle (SSC) by using a lengthening movement (eccentric) which is quickly followed by a shortening movement (concentric).2-16

Eccentric Pre-Stretch

The eccentric pre-stretch phase has also been described as the readiness, pre-loading, pre-setting, preparatory, facilitatory, readiness, potentiation, counter-force, or counter-movement phase. The eccentric pre-stretch phase of a plyometric activity stretches the muscle spindle of the muscle-tendon unit and the non-contractile tissue within the muscle (series elastic components [SEC] and parallel elastic components [PEC]). This stimulation of the components of the muscle is often referred to as the neurophysiological-biomechanical response. Several researchers17-24 have demonstrated this eccentric pre-stretch will enhance the resultant concentric muscle contraction. The pre-stretch phase is predicated on three stretch variables: magnitude of the stretch, rate of the stretch, and duration of the stretch.15-21 Manipulating any of these variables will have a significant effect on the amount of energy stored during the eccentric pre-stretch motion.

Amortization Phase (Time to Rebound)

The term amortization has been developed to describe the time from the cessation of the eccentric pre-stretch to the onset of the concentric muscle action. Authors of this manuscript prefer to use the term “time to rebound”. This phase is also frequently referred to as the electro-mechanical delay phase of plyometrics. The amortization phase is the time delay between overcoming the negative work of the eccentric pre-stretch to generating the force production and accelerating the muscle contraction and the elastic recoil in the direction of the plyometric movement pattern.15-21 This phase is the key to the performance of plyometrics, because the shorter the amortization phase the more effective and powerful is the plyometric movement because the stored energy is used efficiently in the transition. If the amortization phase is delayed, the stored energy is wasted as heat, the stretch reflex is not activated and the resultant positive work of the concentric contraction is not as effective.27 One of the primary goals of plyometric training is to decrease the time to rebound phase.

Concentric Shortening Phase

The concentric phase can also be referred to as the resultant power production performance phase. This
phase has also been described as the facilitated or enhancement phase of plyometrics. These terms actually describe what happens during the plyometric activity. This final phase of the plyometric movement results from many interactions including the biomechanical response that utilizes the elastic properties of the pre-stretched muscles.

The blending of these three phases to perform a plyometric movement is used to enhance the muscle's power performance. Designing the periodization programs and execution of the actual plyometric drills described later in this article is what makes these exercises so effective in performance enhancement.

**EXAMPLES OF PLYOMETRICS IN ATHLETICS**

This rapid deceleration-acceleration produces an explosive reaction that increases both speed and power of the limb during athletic activities. This explosive reaction facilitates the production of maximal force in the shortest amount of time. Plyometric training is often considered the missing link between strength and return to performance. An example of the SSC is illustrated during the overhead pitching motion. When the pitcher goes into the late cocking position, the muscle spindle and the PEC and SEC of the shoulder internal rotator muscles are pre-stretched, in order to enhance the acceleration phase of the pitching motion. The necessity of plyometrics for the shoulder complex can be illustrated in the context of the incredible demands placed on the shoulder with different sporting activities. For example, overhead throwing produces angular velocities that exceed 5000-7000 degrees per second, which makes the SSC necessary to help generate the forces required. With a short amortization phase, the time from the cessation of the eccentric pre stretch to the onset of the concentric muscle action, the SSC permits stretching (eccentric lengthening) to contribute to the maximal explosive shortening (concentric contraction).

The follow through phase of the throwing motion actually generates the highest electromyographic (EMG) activity of the posterior shoulder complex as well as the core stabilizers and the scapulo-thoracic muscles. Volleyball players and tennis players use an abbreviated cocking motion to strike the ball, but still use the SSC during their functional tasks. Baseball or softball pitching motions are movements with a controlled plyometric movement, whereas the volleyball and tennis motions are usually reactive movement patterns, which occur more quickly. The other common overhead activity is swimming which actually involves more repetitions in the overhead position than most other sports; however, swimming involves minimal ballistic plyometric movements.

There are many examples of plyometric activities in the lower extremities, such as running, jumping and kicking. The angular velocities of the knee have been recorded at around 1,000 degrees/second. With each foot contact, there is an eccentric stretch followed by the concentric shortening contraction. Jumping, cutting and pivoting activities occur in almost all sports and each has plyometric demands, thus the concept of power development is the key for many activities of daily living, work related activities, recreational, and competitive sports.

Realizing the fast angular velocities and tremendous forces required in various activities of daily living and sporting activities, illustrates the need for plyometric training in preparing the patient or athlete for return back to their activities. Rehabilitation and conditioning programs are designed to return patients and athletes back to their respective activities as safely and quickly as possible based on functional specific activities. Plyometric exercises should play a critical role in this important role to develop power for performance.

**DEFINITION**

Plyometrics have been used for many decades in the Russian and eastern European training of track and field athletes. Verkhoshanski, a well-known track and field coach in Russia, began the concept that he referred to as shock training or jump training. However, former Purdue University women's track coach Fred Wilt first coined the actual term plyometrics in 1975. The word plyometrics is actually a derivation from the Greek words *plythein* or *plyo*, which means to increase and *metric*, which means to measure. Consequently, the purpose of plyometrics may be thought of as “to increase the..."
measurement." Typically the measurement is sports performance outcomes demonstrated in testing or competition such as throwing, serving velocity, jump height or sprint speed. 47-49

**SCIENTIFIC FOUNDATION FOR THE APPLICATION OF PLYOMETRICS**

**Physiologic Basis**

The contractile component of the actin and myosin cross bridges with the sarcomere plays an important role in motor control and force development during plyometrics. The plyometric movement uses the pre-stretch of the muscle-tendon unit physiological length-tension curve in order to enhance the ability of the muscle fibers to generate more tension and resultant force production. 15,27 Biomechanically "priming" the muscle is supported by the work of Elfman.50 The Elftman proposal simply states that the force production of muscle is arranged in a predictable hierarchy. This orderly format is that eccentric muscle contractions create the most force, followed by isometric contractions and then concentric contractions. Concentric muscle contractions therefore, are actually the weakest of the three modes of muscle actions. However, plyometrics create the greatest forces during the concentric power production phase. It is for this reason that the eccentric pre-stretch and the short amortization phases are so critical for the optimum power development in a muscle.

However, whenever an eccentric muscle action occurs, there is concern for the development of delayed onset muscle soreness (DOMS).14,15,57 DOMS will always occur in the skeletal muscles following an unaccustomed eccentric exercise. When a maximal eccentric muscle action occurs, it generates 10-40 percent more force than concentric contractions. The reason it generates more force is because during the eccentric muscle action the SEC and PEC are being stretched which generates more force (than during concentric), which in turn causes microtrauma to the connective tissue. The microtrauma to the SEC and PEC releases hydroxyproline which creates a noxious stimulus to the muscles and that creates the participants perception of the DOMS response.52-57 Therefore, it is important to inform the athlete when starting a plyometric program they will experience a DOMS response.15 It is critical to explain to the athlete that DOMS is a self-limiting conditioning and usually resolves in approximately 7-10 days. If the participant is a highly trained athlete, due to a repeated bout effect, they will not usually experience a DOMS response.58 The education of athletes about DOMS is important when implementing plyometrics into the terminal phases of a rehabilitation program or into a performance enhancement program.

Rapid voluntary contractions of skeletal musculature are achieved via selective recruitment of motor units. It is generally accepted that recruitment of muscle fibers follows an orderly pattern or sequence termed the size principle. Slow twitch (ST) fibers are typically recruited at sub-maximal intensity efforts, and then as the intensity increases, the fast twitch (FT) IIa fibers are recruited at approximately 30 percent up to about 80 percent of maximal intensity. At approximately 70-80 percent intensity, the fast twitch IIa, IIB fibers are then recruited. Thus, plyometrics need to be performed with high intensity efforts, above 80 percent, to recruit the fast twitch fibers that are crucial to power development. FT muscle fibers respond better to high-speed small amplitude pre-stretch, therefore, specificity of rehabilitation and performance enhancement via specific exercises, intensity, sets and reps, are important in the design and execution of specific exercises. 15,26,59,60

Lovering61 performed muscle biopsies of the rotator cuff and found the muscles to be comprised of approximately 55-60 percent FT fibers. Furthermore, Irlenbusch62 performed muscle biopsies of the rotator cuff in patients with rotator cuff injuries and found that the FT fibers were most affected. Consequently, when trying to selectively activate FT fibers in rehabilitation or performance enhancement the therapist needs to perform activities to recruit the FT muscle fibers. There are generally three ways to recruit FT fibers: 1) maximum intensity effort, 2) electrical stimulation, and 3) fast movement patterns like plyometric exercises.

**Mechanical Basis**

Muscles function in various sporting activities as force production generators, and eccentric decelerators/shock absorbers primarily due to the active and elastic properties within the muscles.65 These elastic proper-
ties form the mechanical basis of muscle mechanics and are due to the three structural components within the muscles: contractile components (CC), SEC, and PEC. All three of these components interact with one another to produce force output. The mechanical behavior of the SEC is a major contributor in the plyometric action. Increased force generation during the concentric phase of the plyometric movement occurs from the mechanical elastic issue loading. During the pre-stretch motion, potential kinetic energy is stored in the SEC. This stored energy then contributes to the concentric force production as the muscle returns to its normal length. This is referred to the rebound force response. The SEC acts like a spring, where the energy release will be greater with higher forces. This effect of plyometric exercises is attributed to the elastic recoil of the elastic (PEC, SEC) tissues. The SEC accounts for 70-75 percent of the concentric force increases of muscle thereby making the plyometric training very efficient.

Neurophysiological Basis
The proprioceptors of the body include the muscle spindle, the Golgi tendon organ (GTO), and the mechanoreceptors located in joint capsules and ligaments. Stimulation of these receptors can cause facilitation, inhibition, and modulation of both agonist and antagonistic muscles. When the muscle spindle is stretched, there is an increase in afferent nerve firing. The strength of the signal that is sent to the spinal cord from the muscle spindle is dependent on the rate of the applied stretch. The faster the rate of the stretch, the stronger the neurological signal sent from the muscle spindle, and as a result, the greater the efferent muscle contraction (the shortening cycle of the plyometric movement). The other mechanoreceptor that plays a significant role in the plyometric stretch-shorten cycle is the GTO. The function of the GTO is to act as a protective reflex preventing over-contraction or too much tension in the muscle. Thus, the GTO assists with modulating forces during plyometric exercises. Consequently, the purpose of plyometric training is to increase the excitability of the neurologic receptors for improved reactivity of the neuromuscular system while desensitizing the GTO. Explosive plyometric exercises may improve the neural efficiency through enhancement of neuromuscular coordination. Therefore, plyometric training increases neuromuscular performance by increasing the set speed in which the muscles may act. Ultimately this mechanism results in the enhancement of the neurologic system to allow neuromuscular coordination to become more automatic.

THEORETICAL TRAINING BENEFITS OF PLYOMETRIC EXERCISES
The potential and theoretical training benefits of plyometric exercises for the upper and lower extremities include, but are not limited to the following concepts: ability to increase average power and velocity; increased peak force and velocity of acceleration; increased time for force development; energy storage in the SEC; the ability for heightened levels of muscle activation; and the ability to evoke stretch reflexes.

By desensitizing the GTO, plyometric exercises allow muscles to generate force by having the musculoskeletal system tolerate increased workloads without the GTO firing. Plyometrics increase neuromuscular coordination by training the nervous system and making movements more automatic during activity (training effect). This is known as reinforcing a motor pattern and creating automation of activity, which improves neural efficiency and increases neuromuscular performance. The increase in performance often occurs without a concomitant increase in morphological changes within the muscle. This training effect of the neural system predominates in the first six to eight weeks of any training program, and then after several additional weeks, hypertrophic changes of the muscles begin to occur.

CLINICAL GUIDELINES WHEN BEGINNING A PLYOMETRIC PROGRAM
As a plyometric training program is initiated, there are some general considerations and guidelines that should be considered. The age of the patient or participant, the injury history, the type of injury, appropriate warmups before beginning the actual plyometric drills, foundational strength, and resistance training experience.

Although there are some empirically based guidelines for initiating plyometrics in the LE, there are no scientific or evidence-based guidelines that serve
as criteria for beginning an UE plyometric training program in a rehabilitation setting. Specific recommendations will be made for a testing hierarchy for initiating both UE or LE plyometrics in the following sections. Davies and Matheson indicate clinicians should make the training specific to the individual goals of each patient. The authors of this manuscript believe that each specific movement pattern involved in the activity should be trained initially in isolation to work each kinematic chain link, allowing the sports activity to be dissected into smaller components and trained with isolated movements first. Then, smaller components can be integrated back into a total coordinated movement pattern. If a muscle cannot function normally in an isolated pattern, then it cannot function normally in an integrated pattern. The authors of this manuscript feel that plyometric training should be preceded by and coincide with other forms of resistance and flexibility training until and adequate base (foundation) of strength and flexibility has been established. Plyometric exercises need to be integrated into the totality of the rehabilitation or conditioning program. One way to design the program is through the application via the periodization model.

PERIODIZATION PROGRAM AND TRAINING COMPONENTS

Periodized training, in essence, is a training program that changes the workouts at regular intervals of time. For a full review of periodization training readers should refer to the paper by Lorenz as a part of this special issue. The plyometric program should use the principles of progression and overload. This can be accomplished by manipulating the volume dosage (reps, sets, weight, etc.) of many different variables. The quality of the work is more important with plyometrics than the quantity of the work. In order to recruit the fast twitch fibers, the intensity of the work should be performed at high levels of intensity 80-100% maximum volitional contraction (MVC). Additionally the rate of the muscle stretch is more important than the length of the stretch. During the training session, if the quality of the movement performance deteriorates and is not able to be performed correctly, then the athlete is probably experiencing fatigue and the plyometric portion of the exercise session should be terminated. Based on

the rest, recovery and reparative phase following high intensity resistive plyometric exercises, there should be increased recovery time when compared to other types of exercise. Although no evidence exists regarding the optimum rest period between high intensity plyometric workouts, the authors recommend 48-72 hours between sessions.

CLINICAL GUIDELINES FROM THE LITERATURE

There is no consensus in the published literature on the specific criteria, parameters, guidelines, specific exercises, or principles of progression that should be used during plyometric training. Most of the recommendations are empirically based upon Level 5 evidence with minimal scientific research supporting any of the recommendations. For example, Chu recommends the typical plyometric exercise program using a medicine ball should follow the concept of periodization with training occurring in the following order: preseason general body conditioning, beginning of a season sport-specific conditioning, and in-season sport specific maintenance. Wilk, et al disagrees and recommends plyometrics be used only in the first and second preparation phases of training according to the periodization model.

DESIGNING A PLYOMETRIC PROGRAM: TRAINING VARIABLES TO CONSIDER

Neuromuscular Overload: Applied Loads and Distances

With plyometric exercises, neuromuscular overload usually takes the form of a rapid change of direction of a limb or the entire body without external loads. The amount of total work in repetitions, sets, etc., and/or the range of motion (ROM) the athlete moves through both contribute to the total overload amount.

Spatial Overload: Range of Motion

Movements can have the effects of overload from the standpoint of ROM. The ROM can be performed throughout a larger range via an exaggerated movement pattern. The concept is to employ the muscle activation and stretch reflex within a specific ROM. As previously described, the reflex mechanisms help facilitate the movement pattern to enhance the force production.
Temporal Overload: Timing
Temporal overload can be accomplished by concentrating on executing the movement as rapidly and intensely as possible. The temporal overload, or keeping the time to rebound (amortization phase) as short as possible, is one of the keys to performing plyometric exercises for increased power production. A shorter time to rebound and electro-mechanical delay allows for effective force transmission from the eccentric pre-stretch to the concentric power performance phase of the plyometric movement.

Intensity
Intensity is the actual percentage of effort required by the athlete to perform the activity. In plyometrics, the type of exercise performed controls the intensity. Plyometric exercises can come in many forms and intensities. Some activities such as bilateral jumping to a box are lower level plyometrics while others such as single leg jumps from a box are intense. These variables must be considered when designing conditioning or rehabilitation programs.

Volume
Volume is the total work performed in a single work session or cycle (periodization). In the case of plyometric training, volume is often measured by calculating the load, counting the number of repetitions, sets, etc. of the specific activity (number of throws, jumps, etc.) Fifty foot contacts during a training session would be considered low volume, while 200+ would be considered high volume. Volume should be increased in a progressive manner to decrease risk of injury or overtraining.

Frequency
Frequency is the number of exercise sessions that take place during the training or rehabilitation cycle.

Recovery
Recovery is important to prevent injuries, overtraining and to determine the primary emphasis of the plyometric program. Because of the intense demands on the body with plyometric training, longer recovery periods between sets may be appropriate. There is limited research on the optimum recovery times, but recovery between training sessions is usually 48 to 72 hours between exercise bouts with plyometrics is recommended.

Specificity
Specificity in a plyometric program should be designed dependent upon the athletes sport and position whenever possible to enhance the specific goals of the program and to replicate the athletes given sport specific activities. Specificity in plyometric training could include motions, angular velocities, loads, metabolic demands, etc.

CONTRAINDICATIONS FOR PERFORMING PLYOMETRIC EXERCISES
Examples of contraindications for using plyometrics include, but are not limited to: pain, inflammation, acute or sub-acute sprains, acute or sub-acute strains, joint instability, and soft tissue limitations based on postoperative conditions. However, probably the most significant contraindication to plyometrics is when the athlete does not have the foundational strength or training base upon which a plyometric program can be built. If an athlete does not meet the minimum criteria in regards to foundational strength or training base that have been delineated, then the coordination and motor control may not be present to progress the subject or patient to high demand plyometric exercises.

LOWER EXTREMITY PLYOMETRIC EXERCISE
Competitive sports and recreational activities often require athletic movements that combine both strength and speed to create the byproduct known as power. For years, numerous clinicians including strength and conditioning specialists, performance enhancement coaches, and athletic trainers have sought ways to increase power in order to enhance performance. More recently sports physical therapists have begun to utilize these techniques to prevent injuries and improve performance during rehabilitation.¹ In an effort to return athletes to play at the highest levels, rehabilitation professionals also have come to rely on the use of plyometric exercises. In the LE, plyometric exercises are often performed through jumping, bounding, and hopping.

EVIDENCE FOR LOWER EXTREMITY PLYOMETRIC EXERCISE
There are numerous studies that have established the effectiveness of plyometric exercises in improving power and performance in the lower extremities.
Evidence for the use of plyometric exercises in the LEs is available with regard to enhancement of performance in uninjured subjects and also in those with injury or previous injury. Numerous authors have described increased jump height, sprint time reduction, improved running economy and improved joint position sense and postural control as a result of LE plyometric training.

**JUMP HEIGHT**
Multiple authors have demonstrate that plyometric training programs can increase maximal vertical jump height. These studies included various jump training programs ranging from six to 24 weeks, including pre-pubertal, pubertal, and adult athletes. A variety of jump training tests have been measured to evaluate improved vertical jump height including squat jumps (Figure 1), split squat jumps (Figure 2), bounding (Figure 3), countermovement jumps with and without arm swings, and drop jumps (Figure 4). More advanced techniques include tuck jumps (Figure 5), depth jumps (Figure 6), and single-leg hops (Figure 7). To achieve improved jump heights training has been anywhere from one to five sessions per week or tallied as total training sessions from six to greater than 25 sessions. Volume of jump training has ranged from 400-1700 jumps. Despite the large variety of variables that have been manipulated within these studies, improved vertical jump performance is a consistent outcome after plyometric training.

**SPRINT SPEED**
Plyometric training of the LEs been shown to increase sprinting speed or velocity. Sprinting velocity is important for sports requiring quick bursts of speed or repetitive change of direction. This is valuable for sports like soccer, handball, volleyball and tennis. These studies included various forms of plyometric training ranging from three to 12 weeks in duration. Weekly dosage ranged from once per week to four times per week at most. Volume of greater than 80 jumps per session seem to result in the greatest benefit. One consistent finding is that sprint performance improvement was not found to be significantly greater when plyometric exercises are performed combined with other types of exercises (such as plyometrics + weight training) as compared
Figure 3. Lateral bounding

Figure 4. Tuck jumps

Figure 5. Jumping to box

Figure 6. Depth jumps
improved force dispersal resulting in less torque applied directly to the knee.\textsuperscript{93,148} Váczi\textsuperscript{149} and colleagues demonstrated the effectiveness of plyometrics in enhancing the components inherent in soccer performance such as strength, power, and agility.

**LOWER EXTREMITY PLYOMETRIC IMPLEMENTATION**

Not everyone in rehabilitation and sports require plyometric exercises. Based on the principles of training specificity, exercise, training and rehabilitation should as closely match the ultimate performance as possible.\textsuperscript{150,151} Therefore, only those patients or subjects that need explosive powerful movements for their recreational or competitive athletic activities really need to train using plyometric exercises. These types of activities generally occur at faster speeds, incur higher forces, and involve multiple planes of movement. Because general traditional exercises are not matched to the actual demands of sports performance it has been suggested that plyometric exercises can bridge the gap between rehabilitation and sports specific activities.\textsuperscript{152}

**BASIC LOWER EXTREMITY PLYOMETRIC PRE-TRAINING REQUIREMENTS (TABLE 1)**

Pending the athlete's present physiologic level (healthy, injured), plyometric activities may or may not be even indicated. General contraindications for plyometric training has been described earlier in this manuscript, however, specific relative contraindications to the LE include joint pathology such as cartilage and ligament injury, arthritis, bone bruises and muscle tendon injuries until tissue healing has occurred enough to allow the tissue to tolerate repetitive, rapid high compressive and shear forces that occur during lower extremity plyometric exercise. Before initiating a plyometric exercise program, there should be a systematic functional testing algorithm developed to screen the subject or patient for the ability to participate with LE plyometrics.\textsuperscript{153-158} The athlete must have an adequate strength base to safely perform these higher level exercises. These criteria include full ROM, as well as adequate base level of strength, endurance and neuromuscular control to properly perform plyometric exercise without symptoms or risk of injury. This article will describe several tests and methods that can be used.
LOWER EXTREMITY PLYOMETRIC PROGRESSION

Because of the amount of stress created in even lower level plyometric activities, many exercises are not appropriate for early phases of rehabilitation or those individuals who may be deconditioned.161 Certainly before initiating higher level jump training, lower level plyometric or plyometric type activities can be used to test the athlete’s tolerance. A progression of plyometric intensity is always prudent, especially in those returning to activity from previous injury. Plyometric drills should be progressed from low – medium – high. Generally two legged drills are a good starting point for low to medium intensity drills. Forward, backward and lateral step ups and downs from progressively increasing heights are a good first step and provide low intensity stimulus in a plyometric fashion. Controlled testing of limbs can be performed by using shuffling, and carioca drills to determine readiness to advance loading. Vertical jumping and horizontal and medial to lateral bounding are a few other ways as are running and jogging in place. Running and jogging require the athlete to individually load each limb to full body weight. Table 2 describes examples of parameters that can be manipulated when designing plyometric activities and progressions for plyometric training programs. All of the variables listed need to be considered and designing and when executing a plyometric program.

General progressions of plyometric exercises for rehabilitation and conditioning are illustrated in Table 3. Additionally, progressing from general to very specific plyometric exercises can be performed.

Another important concept in plyometric progression is volume of exercise. During LE plyometric exercise and training this is typically achieved through total foot contacts. Recommended total foot contacts for various levels of athletes have been recommended by Chmielewski and colleagues1 (Table 4). Furthermore, volume via foot contacts can also be determined based on general exercise intensity (Table 5). Examples of the progression of LE plyometric exercises are divided into beginner, intermediate and advanced categories for stratification into a hierarchy of training stress in Table 6.

Table 1. Suggested testing algorithm for preparation for plyometric training

<table>
<thead>
<tr>
<th>Tests &amp; Methods</th>
<th>Specific Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pain</td>
<td>None in lower extremities</td>
</tr>
<tr>
<td>ROM</td>
<td>Full ROM of all joints</td>
</tr>
<tr>
<td>Swelling</td>
<td>None</td>
</tr>
<tr>
<td>Balance-Eyes open</td>
<td>30 seconds</td>
</tr>
<tr>
<td>Balance-Eyes closed</td>
<td>30 seconds</td>
</tr>
<tr>
<td>Muscle strength</td>
<td>20% bilateral comparison</td>
</tr>
<tr>
<td>Muscle endurance</td>
<td>20% bilateral comparison</td>
</tr>
<tr>
<td>Neuromuscular control</td>
<td>Qualitatively good movement patterns with no compensations</td>
</tr>
<tr>
<td>Single-leg half squat</td>
<td>No pain and good qualitative movement patterns</td>
</tr>
<tr>
<td>Free weight squat: 1.5 to 2.5 times body mass</td>
<td>No pain and good qualitative movement patterns</td>
</tr>
<tr>
<td>Squat 60% of body mass 5 times within 5 seconds</td>
<td>No pain and good qualitative movement patterns</td>
</tr>
<tr>
<td>Lower level plyometric drills</td>
<td>No pain and good qualitative movement patterns</td>
</tr>
</tbody>
</table>

to determine readiness but it must be remembered that there is never a good substitute for sound, practical clinical judgment during assessment of any athletic patient, healthy or injured. This is especially important because guidelines for initiating plyometric exercises during rehabilitation and in general healthy population have been not clearly described. Ability to perform a 30-second single leg stance with eyes open and closed has been recommended by Voight and Tippett158 before initiating a LE plyometric program. Voight and Draovitch160 also describe assessment of a single-leg half-squat that can additionally be evaluated. Wathen suggests LE plyometric activity should be initiated only after achieving minimum strength levels including the ability to perform a full, free-weight squat 1.5 to 2.5 times body mass and/or squat 60% of body mass five times within five seconds. If strength is not adequate to perform these tests it is recommended that the athlete continue to work on adequate technique and strength training and delay plyometric activity until an adequate strength base is met.36
### Table 2. Parameters that can be manipulated when designing training progressions for plyometric programs

<table>
<thead>
<tr>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetitions</td>
</tr>
<tr>
<td>Sets</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Rest intervals (Recovery)</td>
</tr>
<tr>
<td>Intensity (Sub-maximal during the orientation or beginning phases or training, although maximal intensity plyometrics are most effective)</td>
</tr>
<tr>
<td>Duration</td>
</tr>
<tr>
<td>Pattern</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Progression</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Resistance implement (body weight, external weight vest, weights, etc.)</td>
</tr>
<tr>
<td>Position of patient</td>
</tr>
<tr>
<td>Quality of the movement patterns</td>
</tr>
<tr>
<td>Body parts involved in the activity (isolated joint movements vs multi-joint movements)</td>
</tr>
<tr>
<td>Effects of fatigue</td>
</tr>
</tbody>
</table>

### Table 3. Examples of a progressions for a lower extremity and upper extremity plyometric training program

<table>
<thead>
<tr>
<th>Warm-ups</th>
</tr>
</thead>
<tbody>
<tr>
<td>General or systemic</td>
</tr>
<tr>
<td>Specific joint related</td>
</tr>
<tr>
<td>Lower extremity (LE)/Upper extremity (UE) plyometrics</td>
</tr>
<tr>
<td>Trunk (core) stability plyometrics</td>
</tr>
<tr>
<td>Trunk flexion/extension</td>
</tr>
<tr>
<td>Trunk lateral flexions</td>
</tr>
<tr>
<td>Trunk rotations</td>
</tr>
<tr>
<td>Trunk PNF functional patterns</td>
</tr>
<tr>
<td>Total pattern plyometrics</td>
</tr>
<tr>
<td>Sport specific simulations</td>
</tr>
<tr>
<td>Jumping activities/shoulder complex activities</td>
</tr>
<tr>
<td>Bounding activities/combination glenohumeral and scapulothoracic joints</td>
</tr>
<tr>
<td>Isolated plyometrics of the primary joint</td>
</tr>
<tr>
<td>Examples include single leg hops, prone drops</td>
</tr>
</tbody>
</table>

### Table 4. Plyometric exercise volume (foot contacts) based on athletic ability

<table>
<thead>
<tr>
<th>Athletic Ability</th>
<th>Beginner</th>
<th>Intermediate</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot Contacts</td>
<td>80-100</td>
<td>100-120</td>
<td>120-140</td>
</tr>
</tbody>
</table>

Data taken from: Chmielewski, Myer, Kauffman, Tillman

### Table 5. Plyometric exercise volume (foot contacts) based on exercise intensity

<table>
<thead>
<tr>
<th>Exercise Intensity</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
<th>Very High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot Contacts</td>
<td>400</td>
<td>350</td>
<td>300</td>
<td>200</td>
</tr>
</tbody>
</table>

Data taken from: Chmielewski, Myer, Kauffman, Tillman
TECHNIQUE
A major consideration when training with plyometric exercise is the need to closely monitor technique. Acquisition or reacquisition of skill should occur to ensure biomechanical safety. Improper technique should not be allowed, as faulty motor patterns should not be reinforced. It could be the athlete's poor motor control that has caused problems to begin with.\textsuperscript{162,163} Feedback to poor performance or technique should be given immediately and continuously to increase awareness of faulty mechanics that might put the athlete at risk of injury or re-injury. Feedback can be given through verbally addressing the fault or through visual means from either a mirror or video camera recordings. Just because the athlete is able to initially perform the techniques perfectly, the clinician should not assume they have enough endurance to continue their flawless performance. When technique declines the clinician should immediately stop the activity. The goal should be for the athlete to be able to increase the volume via number of repetitions or exercises while still maintaining excellent technique.

UE PLYOMETRICS
Scientific Research Supporting UE Plyometrics
Despite the large number of studies on LE plyometrics described earlier, few studies address plyometric training and the UE: five intervention studies, three descriptive studies, three case studies and one descriptive EMG study. Many clinicians and practitioners assume that the UEs will respond to plyometric training in a similar fashion as the LEs. The authors assert that external force applied during the eccentric preload phase could need to be reduced due to the smaller mass of the UEs and the high potential for iatrogenically causing an injury to the shoulder complex from overloading the structures in an unaccustomed position.

McEvoy and Newton\textsuperscript{164} have demonstrated that medicine ball plyometric training increased throwing velocity. Heiderscheit et al\textsuperscript{165} studied untrained subjects performing plyometric training for eight weeks, however, there were no significant improvements in any outcome measures. Fortun et al\textsuperscript{166} replicated the Heiderscheidt study using trained subjects and found improvements in most of the outcome measures, including improvements of isolated shoulder power of internal rotators measured with isokinetics and improvement in a throwing performance test. Using plyometric training, Swanik et al,\textsuperscript{167} demonstrated improvements in swimmers proprioception, kinesthesia, and muscle performance characteristics. Schulte-Edelmann et al\textsuperscript{168} performed shoulder and arm retro-plyos did not see increases in shoulder outcome measures, however, the elbow extensors did improve in isokinetic power testing. Carter et al\textsuperscript{169} used a high volume Ballistic 6 plyometric training program with a DI baseball team and found selected improvements in isokinetic shoulder power. Carter et al based his training program on the work of Pretz.\textsuperscript{170, 171} Gelen et al\textsuperscript{172} demonstrated that high volume UE plyometric activities benefit the service speed of elite junior tennis players. Fernandez-Fernandez et al\textsuperscript{173} using an UE plyometric training program improved shoulder ROM and increased the tennis serve velocity. Chelly et al performed an eight-week in season plyometric training program on elite adolescent handball players and found that the participants increased their ball throwing velocity.

<table>
<thead>
<tr>
<th>Beginner</th>
<th>Intermediate</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squat jumps</td>
<td>Jump and reach</td>
<td>Depth jumps</td>
</tr>
<tr>
<td>Split squat jumps</td>
<td>Medial and lateral</td>
<td>Box jumps</td>
</tr>
<tr>
<td>Bilateral mini</td>
<td>Anterior and posterior</td>
<td>Single leg hops</td>
</tr>
<tr>
<td>Skipping</td>
<td>Double leg tuck jumps</td>
<td>Single leg tuck jumps</td>
</tr>
<tr>
<td>Lateral bounding</td>
<td>Pike jumps</td>
<td>Drop jump to second box</td>
</tr>
<tr>
<td>Ankle bounces</td>
<td>Jumping to box</td>
<td>Squat depth jump</td>
</tr>
<tr>
<td>Shuffling</td>
<td>Zigzag jumps</td>
<td></td>
</tr>
<tr>
<td>In place jumps</td>
<td>Side to side push off jumps</td>
<td></td>
</tr>
<tr>
<td>Single leg push off box</td>
<td>Step from box</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Examples of progression of plyometric activities for the lower extremity
CLINICAL GUIDELINES WHEN BEGINNING AN UE PLYOMETRIC PROGRAM

As a plyometric training program for the UE is initiated, there are some general considerations and guidelines that should be considered. Davies indicated since there are no real guidelines for criteria to begin a plyometric training program for the shoulder, the clinician should make the training specific to the individual goals of each patient. For best results, the training program should be individualized as much as possible to the athlete and his or her sport to develop the best motor performance pattern through neuromuscular dynamic stability.

Plyometric training for the UE should always be preceded by and coincide with other forms of resistance and flexibility training until an adequate base (foundation) of strength and flexibility has been established. Plyometric exercises need to be integrated into the totality of the rehabilitation or conditioning program. One way to design the program is through the application via the periodization model described earlier in the manuscript.

CRITERION-BASED RECOMMENDATIONS FOR INITIATING AN UE PLYOMETRIC PROGRAM

The authors utilize a quantitative and qualitative functional testing algorithm as a way to measure improvement, so the patient’s progression can be managed through a rehabilitation program. As an example, soft tissue healing times must be respected following the injury or surgery, the patient must not have any pain from the site of the injury or surgery, the swelling must be absent or minimal, the ROM should be within normal limits (WNL) based on a bilateral comparison and relative to normative data, proprioceptive tests need to be WNL based on a bilateral comparison and relative to normative data, manual muscle testing must be at least a 4/5 for the muscles mostly involved with the injury/surgery whereas all synergistic muscles must be 5/5, negative neurological tests, special tests should be normal without signs or symptoms, isokinetic testing should be 80% of peak torque in a bilateral comparison, the closed kinetic chain upper extremity stability test (CKCUEST) score should be within 20% of normative data for the overhead athlete.

DESIGNING AN UE PLYOMETRIC PROGRAM

There are numerous considerations when designing a UE plyometric program. The following aspects can be manipulated when initiating an UE plyometric program: components of the program, ROM progressions, CKC and OKC plyometric exercises, general progressions, perturbation guidelines, examples of general plyometric exercises for the athlete, specific plyometric exercises for the overhead athlete, specific guidelines for volume dosage, and examples of progressions for core stability and the overhead athlete.

When beginning an UE plyometric program following an injury or surgery, and the patient meets the criteria to initiate the program, oftentimes the plyometric program will begin by limiting the ROM using a bolster so the patient can start working on power development in a shortened ROM without compromising healing structures. Then the patient's arm can be progressed through the ROM as appropriate. Table 7 and Figures 8 through 10 offer examples of the ROM progression.

UE Plyometric exercises can be performed in both the closed kinetic chain (CKC) and open kinetic chain (OKC) positions of the UE. As an example, CKC UE plyos can be initiated in a partial weight bearing position by performing wall plyo push-ups (Figure 11) and then progressed to full weight bearing plyo push-ups, depth drop plyo push-ups, and clap push-ups (Figure 12). Moreover, the UE plyos...
listed and seen in Figures 13-15. Additionally, progressing from general to very specific plyometric exercises can be performed.

Perturbation training can utilize many variables, and when performed in an alternating agonist/antagonistic movement patterns, actually mimics a plyometric motion with each perturbation. Examples of ways to perform and progress the perturbation plyo training guidelines are listed in Table 9.

Progressions for training the shoulder complex from general to specific are listed in Table 10 and illustrated in Figures 16-24.

If the patient is an athlete who participates in overhand throwing sports, then plyometric drills that may enhance the throwing motion due to the SAID principle are recommended. Examples of some sport

<table>
<thead>
<tr>
<th>Table 7. Range of motion progression following an injury or surgery and the initiation of plyometric exercises.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited range of motion (short-arc exercises) using a bolster (Figure 8)</td>
</tr>
<tr>
<td>Limited range of motion (short-arc exercises) using table as a support (Figure 9)</td>
</tr>
<tr>
<td>Full range of motion (full-arc exercises) with patients arm off the side of the table (Figure 10)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 8. Example of progression of upper extremity plyometric exercises from CKC to OKC positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed kinetic chain (CKC) exercises-wall plyo push-ups (Figure 11)</td>
</tr>
<tr>
<td>Closed kinetic chain (CKC) exercises-plyo push-ups (Figure 12)</td>
</tr>
<tr>
<td>Open kinetic chain (OKC) exercises – multiple joints</td>
</tr>
<tr>
<td>Open kinetic chain exercises – isolated joint activity with assistance (Shoulder Horn)</td>
</tr>
<tr>
<td>Open kinetic chain exercises – isolated joint activity without assistance</td>
</tr>
</tbody>
</table>

Figure 8. Limited range of motion (short-arc exercises) using a bolster

Figure 9. Limited range of motion (short-arc exercise) using table as support

can be performed in an OKC position using a progression outlined in Table 8.

General progressions of UE plyometric exercises for rehabilitation and conditioning are illustrated in Table 3. Examples of core plyometric exercises are
Figure 11. Closed kinetic chain (CKC) exercises-wall plyo push-ups

Figure 12. Closed kinetic chain (CKC) exercises-plyo push-ups

Figure 13. Trunk flexion

Figure 14. Trunk rotations

Figure 15. Prone ER drops
specific overhand throwing plyometric exercises are listed in Table 11 and Figure 22.

Based on the references\textsuperscript{79,191,192} the following guidelines for volume dosage are recommended when designing a plyometric program for the shoulder (Table 12).
Table 13 demonstrates a hierarchy of UE plyometric exercises ranging from low level intensity for the beginner through intermediate to advanced or maximum intensity exertion.

SUMMARY
The purpose of this clinical commentary was to provide an overview of plyometric exercises including historical information, definitions, phases of plyometrics, and the scientific foundation for the application of plyometrics. The physiological, mechanical and neurophysiological basis of plyometrics has also been described with supporting evidence regarding its effectiveness. The theoretical basis for the use plyometrics and clinical guidelines for designing plyometric programs have been listed, with evidence support as available.
Figure 21. 90°/90° Baseball throw (90° GH abduction/90° GH ER)

Figure 22. Retro-Plyos (reverse throw) for plyometric eccentric decelerations

Figure 23. Wrist flexor flips

Figure 24. Wrist extensor flips
Suggestions regarding the use of plyometrics for training of the LE and UE are presented, and contraindications and empirically based suggestions for criteria to begin a plyometric program are included. Acknowledging the lack of evidence in this realm, recommendations for the volume dosage for plyometric training and a hierarchy of plyometric exercises progression are provided.

<table>
<thead>
<tr>
<th>Table 12. Specific guidelines for volume dosage for an upper extremity plyometric program</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recommended Parameters</strong></td>
</tr>
<tr>
<td>Reps</td>
</tr>
<tr>
<td>Sets</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Rest Intervals</td>
</tr>
<tr>
<td>Intensity</td>
</tr>
<tr>
<td>Duration</td>
</tr>
<tr>
<td>Pattern</td>
</tr>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Progression</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 13. Examples of progression of plyometric exercises for core stability and the upper extremity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beginner</strong></td>
</tr>
<tr>
<td>Wall dribbling-2 arms</td>
</tr>
<tr>
<td>Half twists</td>
</tr>
<tr>
<td>Full twists</td>
</tr>
<tr>
<td>Clap wall pushups</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
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<td></td>
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</table>
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145. Saez de Villarreal E, Requena B, Izquierdo M, Gonzalez-Badillo JJ. Enhancing sprint and strength performance: combined versus maximal power,


ABSTRACT
Rolling is a movement pattern seldom used by physical therapists for assessment and intervention with adult clientele with normal neurologic function. Rolling, as an adult motor skill, combines the use of the upper extremities, core, and lower extremities in a coordinated manner to move from one posture to another. Rolling is accomplished from prone to supine and supine to prone, although the method by which it is performed varies among adults. Assessment of rolling for both the ability to complete the task and bilateral symmetry may be beneficial for use with athletes who perform rotationally-biased sports such as golf, throwing, tennis, and twisting sports such as dance, gymnastics, and figure skating. When stability-based dysfunction exists, the rolling patterns can be used as intervention techniques, and have the ability to affect dysfunction of the upper quarter, core, and lower quarter. By applying proprioceptive neuromuscular facilitation (PNF) principles, the therapist may assist patients and clients who are unable to complete a rolling pattern. Examples given in the article include distraction/elongation, compression, and manual contacts to facilitate proper rolling. The authors assert that therapeutic use of the developmental pattern of rolling with techniques derived from PNF can be creatively and effectively utilized in musculoskeletal rehabilitation. Preliminary results from an exploration of the mechanism by which rolling may impact stability is presented, and available updated evidence is provided. The purpose of this clinical commentary is to describe techniques for testing, assessment, and treatment of dysfunction, using case examples that incorporate rolling.

Keywords: Developmental sequence, rolling, neuromuscular sequencing

Level of Evidence: 5
INTRODUCTION
As humans develop from small, relatively immobile infants at birth into fully developed, amazingly mobile adults, they pass through many predictable patterns of body control and movement. In motor development, these patterns can be described as both reflexive and intentional movements, both of which serve as developmental milestones. These concepts are familiar to the therapists who treat pediatric clientele with neurodevelopmental diagnoses. Many therapists who treat adult patients and clients may fail to remember the principles of developmental postures and their sequence. In settings where patients with orthopedic and sports injuries predominate, the therapist can easily become focused on discrete local problems (or impairments) and miss the global effects (functional limitations) that impairments create. In mature movement strategies/motor programs, the presence of developmental skills are not readily identifiable, but may in fact be a part of movement. An example of this principle is the movement of rolling. Although most adults do not consider the act of rolling to be an important part of complex movement skills, rolling may be a novel method to assess for, and subsequently intervene, with inefficient movements that involve rotation of the trunk and body, weight shifting in the lower body, and coordinated movements of the head, neck, and upper body.

The developmental milestones through which humans progress are related to developmental postures. Human infants are initially able to exist in sidelying, prone, or supine and are unable to move between these positions without assistance. These postures offer the infant the greatest amount of support/contact from the supporting surface, and are the beginning of the developmental sequence and the development of whole-body motor control. As the infant matures, head control is achieved by four months of age leading to the ability to transition from one posture to the other, also known as rolling. The movement of rolling requires that an infant begin by moving one of their hips to their opposite shoulder in a diagonal manner. Rolling is defined as “moving from supine to prone or from prone to supine position”, and involves some aspect of axial rotation. Rotational movements are described as a form of a righting reaction because, as the head rotates, the remainder of the body twists or rotates to become realigned with the head. Rolling can be initiated either by the upper extremity or the lower extremity, each pattern producing the same functional outcome: movement from prone to supine or supine to prone. The development of rolling serves as the foundation for strength and neuromuscular integration from which other complex movements can build.

Typically an infant can perform basic log rolling, with the body moving as a unit at four to five months of age, moving from prone to supine at four months of age, followed by moving from supine to prone (although the order varies in infants). Finally, segmental or “automatic” rolling occurs at six to eight months of age, which involves deliberate, organized progressive rotation of segments of the body. Some children actually use multiple consecutive rolls as a method of locomotion across a floor. Adults use a form of rolling that is segmental, but has also been described as “deliberate.” Richter and colleagues described adult rolling, and found that normal adults use a variety of movement strategies to roll, most likely related to the flexibility and strength (or lack thereof) of the individual performing the movement. Several of the movement patterns described by Richter et al were similar to the original patterns of rolling movement described by Voss et al in their original text on proprioceptive neuromuscular facilitation (PNF). Contemporary practice of PNF continues to incorporate rotational movements of the trunk that resemble rolling, in multiple patterns. The variability of movement patterns used by adults to roll gives therapists multiple options to use when training or retraining adults in the task of rolling.

Although the skill of rolling is an early developmental task that continues to be used throughout a lifetime, rolling may become altered or uncoordinated due to muscular weakness, stiffness or tightness of structures, or lack of stability in the core muscles. Several potential dysfunctions and assessments for these problems that affect rolling in adults will be subsequently addressed in detail. Adults often use inefficient strategies to complete the task of rolling, some of which are compensatory and disorganized, serving to perpetuate the dysfunction(s) associated with the movement. The authors assert that when rolling is asymmetrical, the client demonstrates an alteration in optimal patterning (symmetry), which can
help the clinician visualize the interplay between the local (impairment level) problem and the global effect (functional limitation).

Developmentally important positions, such as kneeling and quadruped, are useful for the analysis of complex motor patterns. While these two postures are commonly used by the sports physical therapist in interventions for orthopedic pathology to address muscular strength, core control, balance, and coordination, rolling is often overlooked. Although this clinical commentary addresses the movement of rolling, other developmental postures are important to the examination and training of athletes whose sports involve the use of rotation (tennis, golf, swimming, baseball).

Once a human utilizes upright postures for completion of motor tasks, rolling becomes less important for movement or access to the environment and, thus, is used less. Adults generally only use rolling to transition from prone to supine, as if turning over in bed. Most adults do not consciously make use of rolling in everyday mobility tasks, training and exercise routines, or as a part of more difficult rotational movements/skills. Rolling is a good choice for assessment and training because rolling is not commonly practiced. Therefore, compensation and incorrect performance can be easily observed. Rolling can be used as both a functional activity and an exercise for the entire body. It is the assertion of the authors of this clinical commentary that many physical therapists should consider the use of rolling as an assessment and rehabilitation technique.

The Relationship of Rolling to Rotation
Frequently, even highly functional patients demonstrate dysfunctional sequencing or poor coordination during active rotational movements that are part of their functional demands/tasks. Rolling patterns can easily illuminate rotational stability-based movement pattern dysfunction, especially when comparing between sides. It should be noted that stability-based movement dysfunction is usually a problem with neuromuscular sequencing and stabilization rather than a deficiency in strength of a prime mover. Theoretically, a person should be able to roll (rotate) equally easily to both the right and the left. Frequently athletes have a typical pattern or habitual “good side” for rotational activities. Consider the gymnast, thrower, or golfer; each of whom rotates to the same direction repeatedly, according to the demands of their sport. Examples include the twisting and spinning motions used during tumbling, the unidirectional rotation used during the throwing motion, and the same side rotational motions that comprise the golf swing. In each of these examples, the athlete has a preferential side, and a pattern of rotation (e.g. always to the left in a right handed thrower or golfer) which is typical for the performance of their sport, and may have asymmetry in rolling to the opposite side.

The Relationship of Rolling to Other Movement Tasks
Although described in relationship to rotational tasks and movements, rolling is not only related to rotational tasks. The rolling patterns can function as a basic assessment of the ability to shift weight, cross midline, and coordinate movements of the extremities and the core. Abnormalities of the rolling patterns frequently expose proximal to distal and distal to proximal sequencing errors or proprioceptive inefficiency that may present during general motor tasks. Finally, many adults have lost the ability to utilize the innate relationship of the eyes, head, neck, and shoulders to positively affect coordinated movements.

Rolling as Assessment
As indicated previously, many high level tasks are often performed in a prescribed and unilateral motion. Even though a task or sport specific skill may be demonstrated by patients and clients at high levels, the fundamental task of rolling should not be altered when compared bilaterally. Whether rolling is initiated by the upper or lower extremities, the state of optimal muscle recruitment, coordination, and function is reached when symmetry is present. For example, a right handed thrower should be able to complete all four variations of rolling, with equal ease regardless of direction. If during assessment the different rolling tasks are not symmetrical and equal, the clinician should consider that foundational stability or neuromuscular coordination may be compromised.

Rolling tasks occur about diagonal axes. Figures 3a and 3b depict the two diagonals that comprise the axes of movement used by humans during the task of rolling. These graphics also demonstrate the starting positions for supine to prone rolling and prone to
supine rolling movements, respectively. Typically, the axis for rolling does not involve the extremity that leads the movement.

Because rolling precedes other locomotion activities in the developmental postures of infants and children, it can be used as a discriminatory test that uses regression to a basic developmental task in order to locate and identify dysfunction in the form of poor coordination and stability. Without a doubt, mobility, core stability, controlled mobility, and properly sequenced loading of the segments of the body are required to perform these rolling tests correctly. Assessment of necessary precursor abilities should always precede common measurements of function, which include strength, endurance, balance, and gait. Simply stated, movement quality appraisal should precede movement quantity appraisal.

Several neurophysiologic principles of PNF can be applied to the assessment and enhancement of the task of rolling. During treatment, the therapist may use visual, verbal, and tactile techniques to cue or resist the neck, trunk, or extremities to promote a maximal response from muscle groups used during rolling. These cues serve to enhance the quality of the skilled motion and to move the patient toward functional gains. Verbal cues will be described with each variant of rolling, as well as suggestions for visual and tactile cues to enhance overflow or irradiation.

Overflow or irradiation is defined as the increase in facilitation that alters the excitatory threshold level at the anterior horn cell. By facilitating the stronger portions of a pattern, the motor unit activation of the involved or weaker portions is enhanced, thereby strengthening the response of the involved segments. Normally, overflow occurs into those muscles that offer synergistic support for the prime movers used during a motor task. Overflow can occur from proximal to distal or vice versa. The increased peripheral feedback that occurs when more than the involved segment participates in the activity may enhance the ability to respond and to learn the motor task.

For example, when using an elastic addition to the body for axis elongation facilitation, the patient's upper extremity or lower extremity is placed and held in a traction or elongated position, thereby pre-activating the phasic Type II receptors and promoting stretch-ting of the synergistic trunk musculature. These elongated muscles provide a stable base upon which rolling occurs and utilize multiple segments to enhance motor learning. Conversely, joint approximation by compression of joint surfaces stimulates the static Type I receptors that facilitate the postural extensors and stabilizers. This technique, applied to the upper extremity or lower extremity which are a part of the rolling axis, can be used to improve the performance of a person having difficulty with the rolling task.

Address Mobility Before Stability
It is important to remember that patients or clients who are being asked to perform the rolling patterns must have sufficient trunk, upper extremity, and lower extremity mobility. For example, if a patient or client cannot roll it may simply be due to a mobility impairment in the thoracic spine. A mobility problem should not be addressed by a stability exercise. So, continuing with this example, prior to any assessment of rolling, trunk range of motion must be screened. An example of a simple thoracic rotation motion screen is the use of the seated trunk rotation test. The seated trunk rotation test is designed to identify how much rotational mobility is present in the thoracolumbar spine. To pass this screen the patient must demonstrate sufficient mobility to ensure 45 degrees of rotation bilaterally. Johnson and Grindstaff described measurement of thoracic rotation in the seated, half kneeling, and quadruped (lumbar-locked) positions and found their measures to be reliable. Thus, any of these methods of measurement of rotation could be used for screening thoracic rotation mobility.

It is imperative that potentially contributory mobility problems are addressed prior to assessing the functional rolling motions. Figures 2a and 2b depict example interventions for a patient or client who fails the rotation screen secondary to diminished thoracic rotation. Note how the posteriorly tilted position of the pelvis in the quadruped position locks the lumbar spine in flexion, which allows for a targeted stretch of the thoracic spine. Once the rotation motion is equal bilaterally (patient can pass the rotation screen test) or has significantly progressed toward appropriate mobility, interventions for assisted rolling may begin, at which time rolling may be viewed as an adjunct exercise to encourage mobility.
The Rolling Patterns Described

Four different rolling tasks are described. Each description will include the axis of rotation, specific instructions for performance of the test, verbal cues, and potential tactile or resistance cues.

Supine to Prone Leading with the Upper Body
This pattern isolates shoulder flexion/horizontal adduction, which leads to trunk flexion/rotation, culminating in pelvic rotation/hip flexion that allows for completion of the roll. The patient lies supine with legs extended and slightly abducted; arms flexed overhead, also slightly abducted. Head is in neutral rotation (Refer to Figure 3a for the start position). When rolling to the left, the axis of rotation is formed by the upper extremity of the side that the individual is rolling towards and the lower extremity of the side the individual is rolling from, in this case, the left upper extremity and right lower extremity.

Ask patient to actively roll his or her body to the prone position starting with his or her left arm by reaching obliquely across body.

- The patient's head and neck should flex and turn toward the right axilla. Remember, the head and neck are connected to the core, therefore where the eyes, head, and neck lead the body will follow. (Figure 4) Facilitation of rolling from supine to prone from the cranial end of the body involves activation of the flexor chain: the neck, trunk, and hip flexors sequentially.
- The lower body should not contribute to the roll. Cue the patient to resist the temptation to push with the left lower extremity.

Figure 1. Seated rotation test used to screen thoracolumbar rotational mobility. Begin in a seated position, with knees and feet together, body upright and spine erect, arms holding a stick or dowel (placed behind the neck as shown). Ask the patient to rotate the trunk to the right and left as far as possible, and examine for symmetry. The stick offers a visual reference for the amount of rotation, and 45° is considered normal.

Figure 2. A. Example mobility technique for thoracic rotation. Note the pelvic position (posterior tilt, achieved by sitting on the heels) to ensure locking of the lumbar segments. Can be performed actively or the therapist can use an interlocked arm position as shown to assist the patient into end-range rotation. B. Example of self-assisted mobility exercise for thoracic motion, utilizing the CLX band (Hygenic Corporation, Akron, OH, USA).
The therapist can also give visual reference by placing his or her body on the side toward which the rotation is occurring, in this case, on the right side.

- Evaluate for quality, ease of movement, synergy, and ability to complete the roll.
- Repeat to the opposite side, leading with the right arm. Evaluate carefully for symmetry between the rolling to the right and rolling to the left.

**Verbal cueing:**

- Look with the eyes and head
- Reach arm across body and turn head into shoulder
- Elongate the axis:
  - Make the axis (left) leg long – “reach”
  - Make the axis (right) arm long – “reach”
  - Stay long through the axis
  - Verbal sequence: “Reach-lift arm-look into shoulder-roll”

**Tactile/resistance cueing to assist rolling:**

- Use proximal manual contacts to facilitate protraction of the scapula by the therapist positioning him or herself on the side toward which the patient is rolling, while cueing the patient to “pull your shoulder down toward your opposite hip.”
- Use distal manual contacts to approximate the upper extremity of the axis arm to facilitate elongation of the axis. For example, in an upper body driven roll led with the left upper extremity, offer manual approximation through the right upper extremity at the wrist/hand to encourage the response of elongation.
- Use an elastic device to cue the patient/client to elongate the axis either through the lower or upper body. For example, in an upper body driven roll led with the left upper extremity, place tubing on either the right distal upper extremity anchored lower on the body or on the left distal lower extremity to encourage the response of elongation.

**Prone to Supine Leading with Upper Body**

This pattern begins with isolated shoulder flexion, leading to trunk extension/rotation, culminating in pelvic rotation that allows for the completion of the roll. Patient lies prone with legs extended and
slightly abducted; arms flexed overhead, also slightly abducted as depicted in Figure 3b. When rolling toward the left side of the body, the axis of rotation is formed by upper extremity of the side that the individual is rolling from, or in this case the left upper extremity and right lower extremity, respectively.

Ask patient to actively roll his or her body to the supine position starting with his or her left arm only. The head should extend and rotate toward the leading arm, in this case the left. Remember, the head and neck are connected to the core, therefore, the head should follow the motion of the arm because where the head and neck lead the body will follow.

- During this form of the test, the lower body should not contribute to the roll.
- The body will always follow the head. Facilitation of rolling from prone to supine from the cranial end of the body, involves activation of the extensor chain: the eyes, neck, trunk, and hip extensors, sequentially.
- The therapist can also give visual/auditory reference by placing his or her body on the side toward which the rotation is occurring, in this case the left side. (Figure 5 demonstrates the therapist giving a cue while placed on the right side of the patient.)
- Evaluate for quality, ease of movement, synergy, and ability to complete the roll.
- Repeat to the opposite side leading with the right arm. Evaluate carefully for symmetry between rolling to the right and rolling to the left.

**Verbal cueing:**
- Lift arm and look up and over the opposite shoulder.
- Elongate the axis (see tactile cues below):
  - Make the axis (right) leg long – “reach”
  - Make the axis (left) arm long – “reach”
  - Stay long through the axis
- Verbal sequence: “Reach-lift arm-look over shoulder-roll”

**NOTE:** The following techniques are not used during the initial assessment, rather, these may be used when dysfunctional patterns of movement are identified. These facilitory techniques are intended to be used for short term assistance and then eliminated as soon as the technique is improved and perfected.
Tactile/resistance cueing to assist rolling:
- Use proximal manual contacts to facilitate retraction of the scapula by the therapist positioning him or herself on the side toward which the patient is rolling, using the verbal cue “lift and pull your shoulder blade down and in.” (Figure 6)
- Use manual contacts to approximate the upper extremity of the axis arm to facilitate elongation of the axis. For example, in an upper body driven roll led with the right upper extremity, offer manual approximation through the left upper extremity to encourage the response of elongation.
- Use an elastic device to cue the patient/client to elongate the axis either through the lower or upper body. For example, in an upper body driven roll led with the right upper extremity, place tubing on either the left distal upper extremity anchored lower on the body or on the right distal lower extremity to encourage the response of elongation.

Supine to Prone Leading with the Lower Body
This pattern isolates hip flexion, which leads to pelvic rotation/lumbar flexion, and culminates in trunk flexion/rotation to allow for completion of the roll. The patient lies supine on the ground with his or her legs extended and his or her arms flexed over his or her head on the ground. The head is in neutral rotation. (Refer to Figure 3a for start position.) Like the upper extremity initiated supine to prone roll, this task utilizes a flexed posture and is often easier than the prone to supine task. When rolling to the left, the axis of rotation is formed by the lower extremity of the side that the individual is rolling towards and the upper extremity of the side the individual is rolling from, or in this case the left lower extremity and right upper extremity, respectively.

Ask patient to actively roll his or her body to the prone position starting with the right leg only.
- Lead with right hip flexion followed by the adduction of the flexed leg.
- Do not allow the person to use the weight of the leg to drag the body into the roll, rather, keep the initiating leg low and reach across the body.
- The upper body should not contribute to the roll. During lower body initiated rolls, the head and neck play less of a role, and are therefore not cued.
- Evaluate for quality, ease of movement, synergy, and ability to complete the roll.
- Repeat to the opposite side, leading with the left lower extremity. Evaluate carefully for symmetry between rolling to the right and rolling to the left.

Verbal cueing:
- Elongate the axis:
  - Make the axis (right) leg long – “reach”
  - Make the axis (left) arm long – “reach”
  - Stay long through the axis
  - Verbal sequence: “Reach – lift leg across body roll”

NOTE: The following techniques are not used during the initial assessment, rather, may be used when dysfunctional patterns of movement are identified. These facilitory techniques are intended to be used for short term assistance and then eliminated as soon as technique is improved and perfected.

Tactile/resistance cueing to assist rolling:
- Use proximal manual contacts to facilitate protraction of the pelvis by the therapist positioning him or herself on the side toward which the patient is rolling, using the verbal cue “pull your pelvis up and forward.”
- Use distal manual contacts to approximate the lower extremity of the axis leg to facilitate elongation of the axis. For example, in a lower body driven roll led with the right lower extremity, offer manual approximation through the sole of the left foot to encourage the response of elongation.
• Use and elastic device to cue the patient to elongate the axis either through the lower body or through the upper body. For example, in a lower body driven roll led with the right lower extremity, place tubing on either the left distal lower extremity anchored higher on the body or on the right distal upper extremity to encourage the response of elongation.

Prone to Supine Leading with the Lower Body
This pattern begins with hip extension which initiates the roll and leads to pelvic rotation/lumbar extension and culminates in trunk extension/rotation, completing the roll. This pattern helps to identify weak gluteal muscles by isolating hip extension/lateral rotation. Patient lies prone with legs extended and slightly abducted; arms flexed overhead, also slightly abducted. Head is in neutral rotation. (Refer again to Figure 3b.) When rolling toward the left side of the body the axis of rotation is formed by the lower extremity of the side that the individual is rolling toward and the upper extremity of the side the individual is rolling from, or in this case the left lower extremity and right upper extremity, respectively.

Ask patient to actively roll his or her body to the supine position starting with the right leg only.

• Attempt to perform with a fully extended lower extremity, but if unable to complete the roll, the patient may flex the knee if needed in order to initiate the roll. Cue to extend at the hip and then at the knee.
• During this form of the test, the upper body should not contribute to the roll. During lower body initiated rolls the head and neck play less of a role, and are therefore not cued.
• Evaluate for quality, ease of movement, synergy, and ability to complete the roll.
• Repeat to the opposite side, leading with the left lower extremity. Evaluate carefully for symmetry between rolling to the right and rolling to the left.

Verbal cueing:
• Elongate the axis:
  - Make the axis (right) leg long – “reach”
  - Make the axis (left) arm long – “reach”
  - Stay long through the axis
  - Verbal sequence: “Reach – lift leg across body roll”

NOTE: The following techniques are not used during the initial assessment; rather, these may be used when dysfunctional patterns of movement are identified. These facilitory techniques are intended to be used for short term assistance and then eliminated as soon as the technique is improved and perfected.

Tactile/resistance cueing to assist rolling:
• Use proximal manual contacts to facilitate retraction of the pelvis by the therapist positioning him or herself on the side toward which the patient is rolling using the verbal cue “lift and pull your pelvis back” (Figure 7)
• Use distal manual contacts to approximate the lower extremity of the axis leg to facilitate elongation of the axis. For example, in a lower body driven roll led with the right lower extremity, offer manual approximation through the sole of the foot to encourage the response of elongation.
• Use an elastic device to cue the patient to elongate the axis either through the lower body or through the upper body. For example, in a lower body driven roll led with the right lower extremity, place tubing on either the left distal lower extremity anchored higher on the body or on the right distal upper extremity to encourage the response of elongation.
Dysfunctional Patterns of Rolling and Contributory Factors

Knowledge of typical functional movement patterns of the body enables the therapist to identify dysfunctional patterns of motion. As each of the four described rolling tasks are performed, the therapist should carefully observe and document the qualitative differences between upper and lower body initiated rolls and side to side differences. Outcomes that display less than optimal performance include: inability to complete the roll, use of inertia or swinging of the extremities to complete the roll, use of extremities not being tested during the roll, and pushing or bracing with the opposite lower or upper extremity in order to artificially supply stability during the attempt.² Many contributory factors may play a role in a patient's ability or inability to roll in a smooth, coordinated, and controlled manner. These factors include: strength of the pelvis and scapula (proximal links) and the extremities, length/stiffness of important muscle groups, and insufficient coordination of all the moving parts of the system.⁵,⁶,⁹ The ideal is for the individual to be able to segmentally roll easily and symmetrically while adjusting to various demands. Patients with many diagnoses may demonstrate difficulty with attempts to roll. Some examples of these diagnoses include: poor neuromuscular control and stability of the core muscles, low back pain of multiple origins, sacro-iliac pain/dysfunction, and various upper and lower extremity mobility or stability problems. The authors believe that one of the main reasons for dysfunctional rolling is inhibition of the local spine stabilizers (multifidus) and over activation of the larger global (prime mover) muscles of the erector spinae group. Activation patterns of the deep and superficial trunk muscles are altered in patients with recurrent low back pain as compared to uninjured normals. In fact, researchers have found that the activity of the lumbar multifidus muscles is delayed¹¹ and reduced¹² during postural and functional tasks in those with low back pain. Additionally, activity of the more superficial trunk muscles is often increased.¹³,¹⁴,¹⁵ These neuromuscular alterations could affect rolling as the lumbar multifidus muscles specifically contribute to the control and stability of intervertebral segments.¹⁶,¹⁷ If the multifidus muscles are delayed and/or inhibited and the larger more global muscles demonstrate increased activity, then changes to spinal loading and movement will occur.

The following examples illustrate the power of rolling as an assessment strategy.

Case Example-Upper Extremity

Consider the pitcher who has undergone a right rotator cuff repair and has progressed through the rehabilitation process, as prescribed by the therapist, regaining full active range of motion in all planes, manual muscle test scores for the muscles of the shoulder complex of 4+/5 or better, and functional abilities to perform all activities of daily living with 10 pounds at shoulder height without dysfunctional movement. He still complains of “fatigue and lack of endurance” with the initiation of a return to throwing program. When assessed using the rolling tasks, the patient was able to roll from supine to prone leading with each of the extremities, but was unable to roll from prone to supine when leading with the right upper extremity.²

Case Example-Lower Extremity

Consider the recreational soccer player who has undergone a partial medial menisectomy on the left knee. The patient has progressed well throughout the rehabilitation process and has full active and passive range of motion, normal manual muscle test scores of the lower quarter, and knee flexion/extension isokinetic scores that demonstrate less than 10% difference in peak torque when compared bilaterally to the uninjured lower extremity. The patient can perform a full, painfree functional squat and can jump and land without difficulty (single limb hop for a given distance is within 90% of uninvolved lower extremity). Functionally, this soccer player still has difficulty with performance of cutting and lateral movements. When assessed using the rolling tasks, the patient was able to perform all upper extremity initiated rolls without difficulty. Lower extremity initiated rolls by the right lower extremity were also achieved without difficulty. He was unable to roll from supine to prone to the right (initiating movement with the left lower extremity) and also was unable to roll prone to supine to the right (also initiating with the left lower extremity). The patient had difficulty crossing the midline of the body with the left lower extremity initiated rolling task.²
Although impairments had been addressed and quantitative performance tests were essentially symmetrical to the uninvolved extremity, qualitative performance assessment of rolling revealed a deficiency in each of the two case examples. This assessment indicated the inability to effectively coordinate, time, and sequence the movements of the extremities and the trunk during a lower level developmental task. Normal impairment measures and quantitative functional measures do not necessarily imply normal function.

In an attempt to study both the dysfunction present when unable to roll and the effects of the multifidus on rolling, the authors have been performing pilot research in the manner first proposed by Hodges. Using movement of the upper extremity as stimulus, timing of firing between the local stabilizers (multifidus) and the more global muscles of the erector spinae can be established. Single arm movements were used to evaluate preprogrammed activity of the trunk muscles as a component of feed-forward postural adjustments. To date, 15 volunteer subjects with no trunk mobility restriction (five with normal segmental rolling and 10 with dysfunctional rolling patterns) have been assessed. Subjects were screened for thoracic mobility in the same manner as outlined in this commentary. Once adequate mobility was established, electromyographic (EMG) activity of the lumbar multifidus was recorded using bipolar fine-wire electrodes. A fine-wire electrode was inserted via a hypodermic needle with ultrasound guidance into the multifidus muscle adjacent to the L5 spinous process on both sides in the manner established by Moseley and Hodges. For the multifidus muscle, the needle was inserted 3 cm lateral to the L5 spinous process until the needle reached the most medial aspect of the L5 lamina. In addition to the fine wire electrode, pairs of surface electrodes were placed over the lumbar erector spinae 5 cm lateral to the L2 spinous process and thoracic erector spinae 3 cm lateral to the T9 spinous process. Surface electrodes were also placed over the anterior and posterior deltoid muscles of the left arm to be used as an indicator of when arm movement took place. The data were collected with the subjects standing with their feet shoulder-width apart. They were instructed to remain relaxed before flexing or extending their left arm as fast as possible in response to visual cues triggered by the experimenter. A visual display indicated to the subject the direction of the arm movement to be performed. Ten repetitions of arm flexion and extension were completed in random order as in previous research. In addition to the baseline data, EMG activity was recorded during arm movement immediately after a single session of segmental rolling training.

Following the rapid arm movements, onsets of trunk and deltoid muscle EMG were visually identified. The onset of EMG was selected as the point at which EMG increased above baseline level. Onsets of trunk muscle EMG relative to the deltoid during rapid arm movements were compared between the control group with normal rolling and the dysfunctional rolling group. In the control group, activation of local stabilizer multifidus occurred before the more global erector spinae group. In the dysfunctional rolling group, the activation of the multifidus was delayed and occurred after the onset of the erector spinae group. Within the dysfunctional rolling group, EMG onsets during rapid arm movement tasks before and immediately after a single session of segmental rolling training or intervention were assessed. Following the rolling intervention, EMG activity in the multifidus occurred before the erector spinae group which was the same as the control group with normal rolling.

These preliminary findings demonstrate that in subjects with dysfunctional rolling, an abnormal strategy of spinal control may exist, with the global erector spinae muscles being activated before the local multifidus segmental stabilizers. Additionally, it appears that a single 15 minute session of assisted segmental rolling training was sufficient to induce earlier postural activation of the lumbar multifidus muscles while at the same time reduced the activity of the superficial trunk muscles during rapid arm movement testing. Additional research is being completed to continue to investigate the relationship between spinal muscular activity, rolling, and intervention.

**ROLLING AS AN INTERVENTION**

Rolling has thus far been described as an assessment. After the assessment is complete, the therapist must draw conclusions about bilateral symmetry and roll-
ing ability, as well as possible causes for less than optimal rolling. Motor training interventions that aim to achieve appropriate coordination between the local stabilizing function of the multifidus and the more global erector spinae group can be modified with exercise. Multiple interventions exist that can assist the patient or client to enhance the ability to roll, and thereby enhance core stability, rotational function, and overall function of the upper and lower extremities. Many alternate exercise postures and modifications to the task of rolling exist, each attempting to begin to elicit core control of the scapula and pelvis or trunk/spine or diminish the demands of the task. In order to achieve rolling, regression back to basic or lower demands must be considered. The infant initially learns how to perform rolling through trial and error. Thus, dysfunctional rolling in adults can be addressed by several methods that employ the principles of simplification (part to whole task training) and trial and error. One easy way to help initiate and facilitate rolling is to begin in the side lying position and allow gravity to assist with the task. As the patient gets better at activating and synchronizing the segmental rolling task, slowly lower them into the supine or prone positions depending upon the direction of the roll. This can be further simplified by lowering either the upper body or lower body first. An example of this would be having the patient supine while still elevating or supporting the pelvis as they lead with the upper body moving supine to prone. Another simple technique to facilitate rolling is to decrease the length of the lever arms. In the supine position, have the patient or client draw the knees towards the chest (in some methods called “egg rolling”) and hold them there. Now simply look to the right and/or the left with the head and neck, and allow the body to roll side to side. Properly integrated rolling builds from head and neck control. From this, add the task of reaching. Infants first learn how to roll through reaching as they investigate their environment. Having an established target will often encourage the infant to reach for the target and roll without intention. As adults, we sometimes need to regress to the use of a target or utilize the cue of reaching for something. Reaching with an extremity may also provide an elongation stimulus that can affect the stiffness of the core and proximal musculature.

For a patient who is unable to complete the roll, the use of assistance in the form of a rolled airex mat or half foam roll behind the trunk or pelvis to place him or her in an easier starting position when rolling from supine to prone (Figure 10), referred to as assisted or facilitated rolling, can be used. Additionally, the quadruped posture can be used to recruit and facilitate underutilized proximal musculature such as the scapular posture and gluteal muscles (Figures 8 and 9).

Recall the patient that underwent a rotator cuff repair who demonstrated the inability to roll from prone to supine leading with the involved upper extremity. For this patient, an exercise progression might include the following:

- Assisted rolling in the side-lying position
- Resisted rolling with manual contact on the scapula (Figure 6)
- Axis elongation using manual contact or an elastic device applied to the uninvolved upper extremity Quadruped position stabilization for the scapula (Figure 8)

Early establishment of proper neuromuscular control or timing with rolling patterns is key whenever...
possible. If needed, exercises to encourage the use of the scapula in a facilitated, stabilized position, and then subsequent exercises progress to the recruitment of the scapular prime movers, which serve to facilitate coordinated upper extremity and trunk movement as well as to provide opportunities to cross the midline. Although the patient in this case had all of their impairments addressed (range of motion, manual muscle test, etc.), the qualitative assessment of the task of rolling revealed an alteration of timing and coordination between the involved upper extremity and the trunk. This examination of a lower level developmental task revealed another area for potential intervention. Rolling was an effective low-level functional intervention because of its requisite demands of timing and reflex stabilization between the extremities and trunk which serve to “reset” the timing and coordination necessary for higher level function, such as throwing.2

Next, return to the patient who underwent the partial medial meniscectomy of the left knee and was unable to roll from supine to prone or prone to supine when leading with the involved lower extremity. This patient might use a similar exercise progression, including the following:

- Assisted rolling in the side-lying position
- Proximal stabilization/manual contacts during rolling via pelvic resistance (Figure 7), (Note that this principle could also be applied to the supine to prone task by utilizing anterior pelvic contact.)
- The rolling task itself, facilitated with tubing in the form of the Starfish 1 drill for supine to prone (Figures 13A& B) and the Starfish 2 drill (Figures 14A & B)
- Bridging exercises for stabilization of the pelvis/gluteals, using a tubing loop for abduction resistance
- Quadruped stabilization of pelvis/gluteals, core, and scapula, using elastic resistance (Figure 9)
- Hip abduction with core stabilization might follow to address both proximal lower extremity strength and stability (through gluteus medius and minimus muscles) and core stability (Figure 11) or the side plank with abduction for same (Figure 12)

Once again, early establishment of proper neuromuscular control and timing with rolling patterns

Figure 9. Quadruped using the CLX band (Hygenic Corporation, Akron, OH, USA) for facilitation of pelvic, core, and scapular stabilizers.

Figure 10. Assisted rolling supine to prone, left upper extremity led. Note the use of a half foam roll behind the trunk for assistance.

Figure 11. Side lying hip abduction with core activation. During the exercise, the trunk is held stabilized in sidelying while the upper extremities perform and hold the lift pattern.
is key whenever possible. If needed, exercises to encourage the use of the pelvic and core muscles in a facilitated, stabilized position can be used, and then progress to the recruitment of the movements of the hip/pelvis to facilitate coordinated lower extremity and trunk movement, as well as to provide opportunities to cross the midline. Again, although the patient in this case had all of their impairments addressed (range of motion, manual muscle test, isokinetic scores, etc.), the qualitative assessment of the task of rolling revealed an alteration of timing and coordination between the involved lower extremity and the trunk. This examination of a lower level developmental task revealed another area for potential intervention. Rolling is an effective low-level functional intervention because of its requisite demands of timing and reflex stabilization between the extremities and trunk. The task of rolling serves to “reset” the timing and coordination necessary for higher level function, such as lower extremity movements that cross the midline and require high proprioceptive acuity.

In the two case examples, rolling was being used for its impact on neuromuscular timing and coordination of movement, as well as recruitment of important muscles of the proximal extremities and core. It is important that the patient be instructed to perform the tasks associated with rolling with precision and perfection. When attempting to determine dosage for the previously described exercises, it is important to dose below the threshold of the inappropriate motor pattern domination. If the patient has difficulty with more than one rolling pattern, begin with the component parts of the roll that are most dysfunctional. Select an exercise that is achievable for the patient
to the roll. As they progress into a higher-level developmental position, they may be able to perform quadruped stabilization with scapular movement without any resistance 18 times before a form break. Start with that number of repetitions, and have the patient attempt to perform two or more sets. Progress the quadruped exercise by adding elastic resistance, again determining the number of repetitions that can be performed with precision. Finally, the speed at which the exercise is being performed can be altered to mimic more functional motion demands.2 Learning the building blocks of a motor sequence and the control of the rolling movement is paramount to perfecting the task. The rolling task maximally challenges the core muscle stabilizers and extremities during a developmental, atypical movement. As motor learning occurs, the patient or client accomplishes the control and skilled use of a wide variety of muscles to accomplish the task of rolling. The authors of this article believe that rolling can facilitate enhanced use of the trunk, core musculature, and the extremities during many functional tasks.

CONCLUSION

The human body is built on and relies upon symmetry. A delicate balance of muscular length, strength, and
stability/mobility must be present during static postures and dynamic functional tasks. Side-to-side and anterior posterior movement balance are important to healthy, normal function. Without symmetry, a state of asymmetry occurs which may eventually lead to injury, imbalance, and dysfunction. Normal functional activities are rhythmic and reversing, which both establishes and depends upon balance and interaction between stabilizers, agonists, and antagonists. Often, athletes become “stuck” in patterns of movement that do not promote symmetry and reversal, such as tasks that require rotation in one direction. Determining alterations in symmetry or the inability to reverse a movement is the first step to successfully addressing dysfunction. Treatment must facilitate movement in both rotational directions in order to enhance normal functional movement and provide adequate postural responses to motion. Improvement of motor ability depends on motor learning, which can be enhanced by auditory, tactile, and visual stimuli. During intervention, specific developmental postures may be used to enhance the use of the head, neck, and trunk as important parts of the movement. The use of the skill of rolling as an assessment and intervention technique can serve as a possible method by which symmetry, reversal, and motor learning can be achieved.

REFERENCES
ABSTRACT

Purpose/Background: While the traditional clean and jerk maneuver implies simultaneous participation of a large number of muscle groups, the use of this exercise with some variations to enhance core muscle activity remains uninvestigated. The purpose of this study was to compare the muscle activity during clean and jerk lift when performed with a barbell, sandbag and a water bag at same absolute load.

Study Design: Descriptive, repeated-measures study

Methods: Twenty-one young fit male university students (age: 25 ± 2.66 years; height: 180.71 ± 5.42 cm; body mass: 80.32 ± 9.8 kg; body fat percentage: 12.41 ± 3.56 %) participated. Surface electromyographic (EMG) signals were recorded from the anterior deltoid (AD), external oblique (OBLIQ), lumbar erector spinae (LUMB), and gluteus medius (GM) and were expressed as a percentage of the maximum voluntary isometric contraction (MVIC).

Results: There were no significantly significant differences for AD muscle activity between conditions, whereas muscle activation values for OBLIQ (60%MVIC), GM (29%MVIC) and LUMB (85%MVIC) were significantly higher during the water bag power clean and jerk maneuver when compared with the other conditions.

Conclusions: The clean and jerk is an exercise that may be used to enhance core muscle activity. Performing the maneuver with water bags resulted in higher core muscle activity compared with sandbag and standard barbell versions

Level of Evidence: 3

Keywords: Muscle activation, olympic lift, resistance training, weight lifting
INTRODUCTION
The clean and jerk is an Olympic lift that involves multi-joint movements while using fast movement velocity, typically used by athletes to improve muscular power.1 Indeed, performance in the hang power clean has been correlated 20-m sprint, countermovement jump performance,2 and several strongman tests.3 As a result, power cleans are commonly used to assess and monitor the effectiveness of training programs, providing valuable power and strength information.4 The clean and jerk exercise involves complex and synchronized neural recruitment patterns. As the barbell is elevated successively higher above the base of support,5 simultaneous participation of a large number of muscle groups is required, balance disturbances occur, and thus a postural control challenge is provided. These facts suggest that the clean and jerk may be used to induce different muscle strength adaptations not only for athletic conditioning but also in the clinical setting. Significant positive associations have been found between the power clean and several core isometric endurance strength tests used in the clinical setting, such as trunk flexion (r = 0.396), back extension (r = 0.449), right flexion (r = 0.519) and left flexion (r = 0.460).6 However, there is only one study evaluating electromyographic (EMG) activity during the clean and jerk, and data were measured only during different static phases of the movement6 so results may differ when a dynamic condition is used for analysis of this movement. Moreover, the use of maximal speeds to perform the exercise can provide a greater increase in muscle activity compared with lower speeds7 and could provide high challenges for the activation of postural muscles.

The clean and jerk is commonly performed using a barbell. However, during the last decade, performance of classic multi-joint strength exercises with additional instability elements have become popular8 and have been studied with the purpose of understanding their use during rehabilitation.6,9 The number of alternative unstable devices is growing and their use is common at fitness facilities and physical therapy centers. For example, the use of bag implements (water or sand filled) as a resistance training element has increased over recent years.10 Sandbags or water bags may be used to perform different lifting movements and also to simulate contact and throws, requiring participation of a large number of muscles, facilitating specific adaptations in occupational tasks that require lifts and dragging objects or persons.10 However, the use of sandbags in the scientific literature and their effect on EMG measures during exercise remain uninvestigated. The disruptive and unpredictable forces that are provided by sandbags or water bags require continuous body stabilization, especially when high speeds are used.

Core strength is an important element in low back pain and rehabilitation,11 related to both muscle endurance and motor control.8 Wang et al9 found in their recent meta-analysis that core training had greater effectiveness than general exercise in decreasing pain and improving physical function in patients with chronic low back pain in the short term. Instability resistance training has the aim of stressing and reprogramming feed-forward and feedback systems and may be useful to induce greater core activity when high loads cannot be used in the presence of injury-susceptible joints or as a first step before using high loads in untrained people.8 Even low core muscular activity (EMG) values may provide an effective stimulus to promote motor control improvements and provide benefits in those with low back pain.8 Hence, the use of the clean and jerk in the stable version and performed with more unstable devices (e.g., sandbags and water bags) may be novel and good methods to enhance core muscle activity and improve core strength. The perturbations provided by the unstable versions of the clean and jerk may provide additional stimulus for muscle recruitment and benefits for core training in comparison with the traditional stable version. With this in mind, the purpose of this study was to compare muscle activity during the standard clean and jerk and the same exercise performed with a sandbag and a water bag. The authors hypothesized that unstable clean and jerk lifting (sandbag and water bag versions) would demonstrate greater core muscle activity compared with the corresponding barbell exercise using the same absolute load of 20 kg.

METHODS
Participants
Young fit male university students (n=21; age: 25 ± 2.66 years; height: 180.71 ± 5.42 cm; body mass:
80.32 ± 9.8 kg; body fat percentage: 12.41 ± 3.56 %) voluntarily participated in this study. Participants had a minimum of one year of resistance training experience, performing at least two sessions per week at moderate to vigorous intensity. In addition, participants had to be familiar with the clean and jerk exercise. None of the participants had musculoskeletal pain, neuromuscular disorders, or any form of joint or bone disease. All participants signed an institutional informed consent form before starting the protocol, and the institutions’ review board approved the study (H1421157445503). All procedures described in this section comply with the requirements listed in the 1975 Declaration of Helsinki and its amendment in 2008.

Procedures

Each participant took part in two sessions: familiarization and experimental sessions both at the same hour during the morning. The first session occurred 48-72 hours (hrs) before the data collection in the experimental session. Several restrictions were imposed on the volunteers: no food, drinks or stimulants (e.g. caffeine) to be consumed two hrs before the sessions and no physical activity more intense than daily activities 12 hrs before the exercises. They were instructed to sleep at least eight hrs the night before data collection.

During the familiarization session, height (IP0955, Invicta Plastics Limited, Leicester, England), body mass and body fat percentages (Tanita model BF-350) were obtained. An assistant researcher showed the proper clean and jerk technique, in accordance with the NSCA guidelines.12 Then, the participants were familiarized with the different conditions, movement amplitude, body position, and load that would later be used during data collection. Participants practiced the three exercises until they felt confident and the researcher was satisfied that proper form was achieved. The three different conditions (Figure 1, Figure 2, Figure 3) were performed with the same absolute load (i.e., 20 kg) since this was the maximal weight that could be achieved by either type of bag. The load of both bags was checked before starting each testing session.

The protocol started with a light warm-up, where each participant performed five minutes of mobility drills without ballistic movements and then performed five repetitions of traditional clean and jerk without additional load (i.e., only with a 10 kg barbell). The protocol continued with the preparation of participants’ skin, and followed by electrode placement, MVIC collection and exercise performance. Hair was removed from the skin overlying the muscles of interest, and the skin was then cleaned by rubbing with cotton dipped in alcohol for the subsequent electrode placement, positioned according to established recommendations13 on the anterior deltoid (AD), external oblique (OBLIQ), lumbar erector spinae (LUMB) and gluteus medius (GM), on the dominant side of the body. Pre-gelled bipolar silver/silver chloride surface electrodes (Blue Sensor M-00-S, Medicotest, Olstykke, Denmark) were placed with an interelectrode distance of 20 mm. The reference electrode was placed between the active electrodes, approximately 10 cm away from each muscle, according to the manufacturer’s specifications. All signals were acquired at a sampling frequency of 1 kHz, amplified and converted...
from analog to digital. All records of myoelectrical activity (in microvolts) were stored on a hard drive for later analysis. To acquire the surface EMG signals produced during exercise, an ME6000P8 (Mega Electronics, Ltd., Kuopio, Finland) biosignal conditioner was used. Prior to the exercise performance described below, two five second MVICs were performed for each muscle and the trial with the highest EMG was selected. Participants performed one practice trial to ensure that they understood the task. One minute of rest was given between each MVIC and verbal encouragement was provided to motivate all participants to achieve maximal muscle activation. Positions during the MVICs were based on standardized muscle testing procedures for the 1) AD,14 2005), 2) OBLIQ,15 3) LUMB,16 4) GM16 and were performed against a fixed immovable resistance (i.e., Smith machine). Specifically, 1) deltoid flexion at 90º in a seated position with erect posture and no back support, 2) a trunk curl up at 40º with arms on chest and pressing against the bar in an oblique direction with the participant lying on the bench, with the feet flat on the bench and the knees bent at 90º, 3) trunk extension with the participant lying on the bench and pelvis fixated, the trunk was extended against the bar, and 4) hip abduction at 30º against the bar with the participant positioned sidelying on their nondominant limb.

Participants performed the clean and jerk in accordance with established exercise technique guidelines.12 The upward movement of the bar was performed in one continuous motion without interruption as explosive as was possible. 1-second rate for descent to the clean and 1-second rate more for descent to the initial position was used before starting the subsequent repetition. Cadence of the descent movement was controlled with the use of a metronome set at 60 bpm (Ableton Live 6, Ableton AG, Berlin, Germany). Visual and verbal feedback was given to the participants in order to maintain the range of movement and hand distance during the data collection. Each participant performed three consecutive repetitions in the three conditions, with two minutes resting between exercises.
Data analysis
All raw EMG signals obtained during MVCs as well as during the exercises were digitally filtered using 1) high-pass filtering at 10 Hz, and 2) a moving root-mean-square (RMS) filter of 500 ms. For each individual muscle, peak RMS EMG of the three repetitions performed at each level was determined, and the average value of these three repetitions was then normalized to the maximal RMS EMG obtained during MVIC.

Statistical Analyses
A two-way repeated measures analysis of variance (Proc Mixed, SAS version 9, SAS Institute, Cary, NC) was used to determine if differences existed between exercises and muscles. Factors included in the model were Exercise (3 exercises) and muscle (4 muscles), as well as Exercise by muscle interaction. Normalized EMG was the dependent variable. Values are reported as least square means (SE) unless otherwise stated and p-values <0.05 were considered statistically significant.

RESULTS
AD muscle activity showed no statistically significant differences between conditions. OBLIQ (p<0.01), GM (p<0.05) and LUMB (p<0.05) muscle activation values were higher in the water bag clean and jerk when compared with the other conditions. Complete results and muscle activations values expressed as a %MVIC are represented in Table 1.

DISCUSSION
The main finding of the current study was that clean and jerk lifting with water bags provided greater core muscle activation than traditional barbell version or the sandbag version. This is the first study to compare the level of muscle activity during different variations of resistance offered during the clean and jerk lift. However, other multi-joint exercises on stable and unstable surfaces have been investigated. Willardson, Fontana and Bressel17 found the same OBLIQ muscle activation during the deadlift, vertical shoulder press and the squat when the exercises were performed with the same absolute load on a BOSU and on a stable surface. Same muscle activation patterns were found in some studies that used relative loads (loads previously measured for each of the different conditions). For instance, Saeterbakken & Fimland18 found the same OBLIQ muscle activity when participants performed a squat at a one-repetition maximum (RM) under different unstable/stable conditions. In another study with relative intensities (10RM), differences between the barbell shoulder press and the dumbbell counterpart (which the authors considered an unstable load) were nonexistent.19 However, when the barbell exercise was performed on a Swiss ball, decreased activation was found in comparison with the version performed on a bench, probably due to the higher force production that was found during the most stable conditions.19 In contrast to the unstable moving objects used during the present study (sandbag or the water bag), previ-
ously mentioned studies used unstable platforms or surfaces that served as a base upon which to perform the exercise rather than unstable implements. In the current study, it seems that instability provided by the sandbags was not enough to produce muscle activation alterations. Asymmetrical movements may produce alterations in loading\textsuperscript{20} that may specially affect OBLIQ activation because of their role as a rotator and trunk stabilizer\textsuperscript{21}. In this study, the water bag could have provided greater asymmetrical disturbances during the exercise due to the fluidity of the water, especially during the final moments of the exercise.

The water bag condition was superior in enhancing LUMB muscle activation. Since this core muscle acts as a spine stabilizer\textsuperscript{11}, it was expected that greater muscle activation levels would appear during conditions requiring higher postural control. However, it seems that when the same absolute load is used across conditions, greater LUMB activation is reached only when higher instability is induced and greater challenge to the postural control systems are provided. For example, similar LUMB muscle activation has been found during a deep squat on a Reebok core board\textsuperscript{22} and a squat, deadlift or vertical shoulder press on a BOSU compared with the stable counterparts\textsuperscript{17}. However, the absence of differences could be explained by the lower instability challenges provided by these devices. In fact, moderately unstable devices like the BOSU failed to enhance muscle activity during squats performed by highly resistance-trained participants\textsuperscript{23}. In accordance with the current results, Anderson & Behm\textsuperscript{24} found that unstable squats performed with the same absolute load provoked higher LUMB muscle activation compared to stable squats performed with the Smith machine and free weights. Indeed, as occurred in the current study, no significant differences were identified during conditions with lower instability difference (i.e., traditional and sandbag conditions). In general, different findings are reported in those studies that used a relative load, where the greater force production that is allowed during the most stable conditions seems to be a key factor for increasing LUMB muscle activity as was demonstrated during a barbell shoulder press at 10RM\textsuperscript{19} and stable deadlifts at 70% of the maximum isometric force\textsuperscript{25}. However, previous literature suggests that all the three options that were used in the current study may provide sufficient levels of muscle activity to improve motor control function\textsuperscript{8}.

Similar muscle activation patterns were repeated for the GM, where only the water bag condition produced higher activity than the other conditions. Similar to the current results, Wahl and Behm\textsuperscript{23} showed that some unstable surfaces did not produce higher muscle activity during squat exercises in highly resistance-trained individuals. More recently, no GM muscle activation differences were observed when participants performed a deep squat task with the same absolute load on a stable and unstable surface.\textsuperscript{22} As in the previously mentioned studies, the addition of an unstable surface did not provoke significantly greater GM activation when compared with stable surfaces during either single limb stance or single limb squat exercises performed with only body weight.\textsuperscript{26} However, positions or exercises that required higher postural control adjustments such as single limb stance or single limb squats demonstrated enhanced GM activity when compared with their double limb counterparts,\textsuperscript{26} which highlights the role of this muscle as a hip and pelvis stabilizer\textsuperscript{27}. These results and the current findings suggest that when an adequate degree of instability is achieved, higher GM activity may be reached when exercises are performed at the same absolute load.

Muscle activity of the AD was not significantly different across the different clean and jerk exercises. Likewise, stable/unstable conditions during the shoulder press exercise with a relative\textsuperscript{19} or the same absolute load\textsuperscript{28} showed an absence of differences. These results may be explained by the glenohumeral stabilizer function provided by this muscle\textsuperscript{29} and the necessity of it being activated to stabilize during either unstable loads (as occurred in the current investigation) or unstable surfaces.\textsuperscript{19} In addition, as was previously reported in other studies where the AD had a primary mover role during the exercise performance, it seems that stable conditions may provide greater or similar muscle activation levels as more unstable conditions.\textsuperscript{30} The use of non-injured participants may be the main limitation in the current study and thus caution should be taken when attempting to extrapolate these results to injured populations. However, the current study provides the first data about the use of
unstable devices during the clean and jerk, indicating that there may be additional benefits to the use of such devices. However, sand and water bags are limited by the amount of weight that can be achieved in each. For example, in the current research the maximal allowed load of both bags was 20 kg. The authors decided that EMG evaluation with the same absolute load would provide valuable and applicable results for when these devices are available at physical therapy or training centers and there is no possibility to measure and calculate a maximal relative load. Future studies should be conducted to investigate the effectiveness of these exercises in relation to various injury conditions.

CONCLUSIONS
The results of the present study support the use of a low-load clean and jerk maneuver as an effective exercise to strengthening the core. These data illustrate that the clean and jerk performed with sandbags does not provide additional benefits to one performed with a bar. However, the clean and jerk performed with the water bag did increase core muscle activation compared to the other conditions. Thus, when barbell, sandbags and water bags with the same low loads are available to perform the clean and jerk exercise, greater core training stimulus would be achieved by using the water bag.

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ABSTRACT

Introduction: Kettlebell (KB) swing exercises have been proposed as a possible method to improve hip and spinal motor control as well as improve power, strength, and endurance.

Purpose: To describe electromyographic (EMG) and sagittal plane kinematics during two KB exercises: the two-handed KB swing (THKS) and the single-handed KB swing (SHKS). In addition, the authors sought to investigate whether or not hip flexor length related to the muscular activity or the kinematics of the exercise.

Methods: Twenty-three healthy college age subjects participated in this study. Demographic information and passive hip flexor length were recorded for each subject. A maximum voluntary isometric contraction (MVIC) of bilateral gluteus maximus (GMAX), gluteus medius (GMED), and biceps femoris (BF) muscles was recorded. EMG activity and sagittal plane video was recorded during both the THKS and SHKS in a randomized order. Normalized muscular activation of the three studied muscles was calculated from EMG data.

Results: During both SHKS and THKS, the average percent of peak MVIC for GMAX was 75.02% ± 55.38, GMED 55.47% ± 26.33, and BF 78.95% ± 53.29. Comparisons of the mean time to peak activation (TTP) for each muscle showed that the biceps femoris was the first muscle to activate during the swings. Statistically significant (p < .05), moderately positive correlations (r = .483 and .417) were found between passive hip flexor length and % MVIC for the GMax during the SHKS and THKS, respectively.

Conclusions: The THKS and SHKS provide sufficient muscular recruitment for strengthening of all of the muscles explored. This is the first study to show significant correlations between passive hip flexor length and muscular activation of hip extensors, particularly the GMax. Finally, the BF consistently reached peak activity before the GMax and GMed during the SHKS.

Key Words: Electromyography, hip flexor, hip extension, kettlebell

Level of Evidence: Level 3
INTRODUCTION
Muscular imbalance and neuromuscular activation order have been implicated in numerous musculoskeletal disorders including low back pain (LBP),
lower extremity injury, and upper extremity injury. Vladimir Janda is a well-known pioneer who studied neuromuscular patterns. Among his contributions to rehabilitation is the concept of the lower crossed syndrome (also known as the crossed pelvis syndrome) described as an imbalance between tight and short hip flexors and lumbar erector spinae (ES) and weak or inhibited gluteal and abdominal muscles. Decreased hip flexor range of motion (ROM) has been described in individuals with a history of LBP, however evidence linking decreased hip flexor ROM with decreased gluteal function is limited. Janda described the “optimal” activation order of muscles contributing to the movement of hip extension, beginning with gluteus maximus activation followed by hamstring activation in coordination with the contralateral ES. However, no consensus exists regarding which side of the ES is activated first. In addition, the long held clinical belief that the gluteals activate prior to the hamstrings in the asymptomatic population has proven false, with consistent evidence showing that the hamstrings activate first during hip extension. Despite this trend, an increased delay between hamstring activation and gluteal activation appears to be present in patients with LBP compared to the healthy population. Preliminary evidence indicates that there may be a relationship between dysfunction of the hip musculature and the low back. However, the exact cause/effect relationship is not yet understood. The role of the strength, power, or endurance of the gluteus maximus (GMAX) in low back pain remains unknown. Cooper et al demonstrated weakness (measured by manual muscle testing) of the gluteus medius (GMED) in subjects with chronic, non-specific LBP when compared to controls. Additionally, decreased hip abduction and external rotation strength has been implicated as predictors of LBP and lower extremity injury. Both Janda and Sahrmann have suggested that attempting to improve gluteal activation through therapeutic exercise may reduce stress on the hip and spine. Numerous methods to improve gluteal activation have been proposed, including the use of cueing and abdominal hollowing, as mechanisms to decrease the delay in gluteal activation. A less common neuromuscular reeducation tool that has become popular in recent years is the use of kettlebell (KB) exercise. Education for the correct performance of kettlebell swinging exercises involves verbal cueing geared toward gluteal activation during hip hinging. In addition, the swinging motion may provide kinesthetic and proprioceptive feedback regarding the desired performance of the technique. Finally, the kettlebell exercise provides training stresses for improving power, strength, and endurance of the hip and lumbo-pelvic musculature.

Deficits of both strength and muscular endurance have been implicated in acute and chronic musculoskeletal dysfunction. Of these, muscular endurance has been suggested as more important than strength in patients with LBP. Jay et al demonstrated that using the kettlebell for targeted training for muscular strength and endurance resulted in decreased neck/shoulder pain and LBP when used in a work hardening program. Despite a lack of evidence in the literature, many clinicians utilize GMAX and GMED strengthening with perceived positive outcomes for patients with LBP. It is generally accepted that muscle activation of a minimum of 50% to 60% of maximum voluntary isometric contraction (MVIC) is necessary as a stimulus to facilitate muscle strengthening. Therefore it would appear that if strengthening the GMAX and medius is the goal, an exercise should provide a stimulus that allows the patient to exceed 50% of MVIC of these muscles during performance of the exercise. A systematic review by Reiman, Bolga, and Loudon identified that the forward step-up yielded the highest electromyographic (EMG) activity of the GMAX (74% ± 43%) MVIC and that the side-bridge into a neutral spine position resulted in the highest EMG activity of the GMED (74% ± 30%) MVIC. McGill and Marshall demonstrated that the two handed kettlebell swing was able to produce an average peak GMAX activation of 76.1% ± 36.6% and an average peak GMED activation of 70.1% ± 23.6% in healthy subjects. This early evidence appears to indicate
that the kettlebell swing may provide a viable alternative for both GMAX and GMED strengthening.

The purpose of this study was to describe EMG and sagittal plane kinematic data during two KB exercises: the two-handed KB swing (THKS) and single-handed KB swing (SHKS). In addition, the authors sought to investigate whether or not hip flexor length related to the muscular activity or the kinematics of the exercise.

METHODS

Participants
A convenience sample of 23 healthy individuals between the ages of 18-30 was recruited for this study. Of this sample, the EMG data of four subjects was found to be unusable due to excessive noise artifact that could not be rectified, leaving a total of 19 subjects for final analysis. This selection was based both upon the availability of age eligible individuals at the institution and the age-relative decreased risk of cardiovascular and musculoskeletal related injury in the group. Exclusion criteria included: preexisting cardiopulmonary conditions which prevented safe exercise participation, musculoskeletal injury or condition that had occurred within eight weeks of study participation, preexisting bleeding or clotting disorder which could increase risk of bleeding during skin preparation, and those who had ample experience using a KB. Ample experience with the KB was defined as any formal instruction on the use of the KB or using the KB on a weekly basis over the period of four weeks or more. Participants were required to have consistently maintained an active lifestyle over the previous month before participating in the physical demands of the current study. An active lifestyle was defined as at least 30 minutes of exercise (i.e. running, walking, resistance training, etc.) performed at least two times per week. The Human Research Review Committee of Grand Valley State University granted IRB approval for this project. All subjects read and signed the informed consent document.

Methods
The participants’ gender, age, height, and weight measurements were recorded. The flexibility of the hip flexor group was measured using a bubble inclinometer (Baseline, Fabrication Enterprises Inc, White Plains, New York 10602 USA) during performance of the modified Thomas test.

Modified Thomas Test
Subjects sat as close to the end of the table as possible to begin the modified Thomas test. They then grasped the front of both knees while the examiner stabilized the patient and assisted them back into a supine position on the table with both hips maximally flexed to the chest to ensure the lumbar spine was flexed and flattened to the table. The subject then slowly lowered the leg to be examined into an extended position with the end of the limb hanging off of the end of the table. The inclinometer was leveled on top of evaluation table in parallel with the floor. The examiner positioned the inclinometer on top of the thigh approximately halfway between the superior patellar border and the anterior superior iliac spine (ASIS) of the pelvis. The angle of hip flexion was recorded as follows: the subject’s thigh lined up with the horizontal level of the table = 0 degrees, test thigh was above the horizontal = negative value (measured in degrees), and test thigh was below the horizontal = positive value (measured in degrees). Horizontal was defined as parallel with the plane of the table. For the purpose of this study, a value of 10 degrees or greater from the horizontal was indicative of 10 degrees of hip flexion, which was considered a “tight” hip flexor (iliopsoas). If the hip flexor was noted to be tight, the examiner passively flexed the knee to examine the contribution of rectus femoris in decreasing hip extension. If the lumbar spine increased in lordosis to the point in which a 1.27 cm piece of PVC tubing could be inserted under the low back, rectus femoris involvement was considered positive. This procedure was repeated on the opposite limb.

Although some questions exist regarding the reliability of the modified Thomas test in determining rectus femoris muscle ROM at the knee joint, it has been shown to have both high intra-rater and inter-rater reliability for hip extension ROM. In addition, a study comparing both goniometric and inclinometer measures of hip extension ROM demonstrated high inter-rater parallel-forms reliability between the two devices, which demonstrates evidence for their interchangeable use. Validity of the modified Thomas test has not been studied.
Two Dimensional (2-D) Kinematic Analysis

Video was captured by two Canon HV20A (Melville, New York, USA) cameras filming at 720p at a rate of 30 frames per second. Dartfish ProSuite version 6.0 (Alpharetta, Georgia, USA) was utilized for frame-by-frame analysis (30 frames per second) and measurement of relative hip and knee angles of movement during the KB swing. The purpose of the kinematic analysis was to determine kinematic variations, which can be identified in a clinical setting from a sagittal view. The use of sagittal plane video analysis has been shown to be a valid and reliable measure of hip and knee joint motion when compared to goniometric measures. In the analysis, the authors provided a novel attempt to produce a standardized nomenclature for key points of movement during the KB swing, and chose not to utilize frontal plane video data. Sagittal plane kinematic analysis of the ankle, knee, and hip were emphasized.

The camera was placed 4.3 meters away from the position of the subject. Markers were placed at anatomical landmarks in order to provide reference points for consistency in measurements of trunk and lower extremity joint angles. To accomplish this, a 1" strip of colored Kinesio® Tex Tape™ (Kinesio USA, LLC. Albuquerque, NM) was placed along the mid-axillary line on both sides of the subject at the level of rib 10, and smaller pieces (2.5 cm square pieces) placed over the greater trochanters of both femurs, lateral femoral epicondyles, and the lateral malleoli of the tibia at the ankle. Upon completion of the study, videos were removed from the recording cameras and laptop and archived to DVD and/or external storage device for analysis. A single investigator interpreted the results of hip flexion angles obtained during sagittal plane kinematic analysis in attempt to maximize intra-rater reliability.

Electromyography

The Biopac Tel-100 EMG System (Biopac Systems, Goleta, CA) was used to measure electromyographic activity during the KB swings. Acqknowledge software version 3.9.1 was used to analyze electromyography (EMG) data. Bipolar adhesive surface electrodes (Noraxon Dual Electrodes, Ag-AgCl, spacing 2.0 cm, Noraxon USA, Inc, Scottsdale, AZ) were placed over relevant muscle bellies.

Data were collected by placing electrodes as described by Dondelinger over the following muscles: right and left GMAX muscle bellies between the 1st-3rd sacral the level of the greater trochanter; the GMED electrode was placed parallel to the muscle fibers over the proximal third of the distance between the iliac crest and greater trochanter; the biceps femoris placement had an electrode over the muscle belly midway between the knee and hip.

Each subject (when appropriate) had the area shaved of hair with a disposable razor and skin was cleansed, abraded, and dried prior to electrode placement by an investigator of the same gender to maintain modesty. To elicit the maximum isometric contraction for each muscle, the participants were placed into the positions described by Kendall and Dondelinger, and their maximum contraction during tester-induced resistance was recorded. The MVIC for each subject was established by measuring the average peak EMG activity over two trials of a resisted isometric contraction, as a measure of each muscle’s maximal strength. The percent of MVIC for each muscle was calculated by averaging the peak EMG activity of each muscle, collected during three repetitions of the right and left SHKS and the THKS. The highest percent of MVIC of each muscle group was used to establish average values for statistical analysis. Time to peak (TTP) was measured from the bottom swing, or ending of the loading phase, to peak contraction during the same three reps used to establish percent of MVIC during each set of swings. The lowest average value for TTP, which is the fastest value, between right and left muscle groups was used during statistical analyses. The fastest value was utilized because the authors believed that it represented the best performance during the testing session. Raw EMG data were filtered using a band-pass determination with a low frequency of 20 Hz and a high pass frequency of 500 Hz. This was done in order to eliminate as much noise artifact as possible without compromising the relevant electrical signals given off by the muscles.

KB Swing Standardization Device

This device, henceforth referred to as the “manipulan-dum,” was used as a method to standardize performance of the KB swing and to electronically mark the bottom and top phases of the KB swinging motion. Pressure sensitive electrical switches were attached to foam boards, which served as contact points for the KB. (Figure 1)
followed by two minutes of rest. Subjects then performed 10 repetitions of THKS, left SHKS, and right SHKS, in randomly assigned order determined by a coin flip. Both the THKS and each of the SHKS were performed with the same subject self-selected weight. These swings were performed at a rate of 45 beats per minute (BPM) by following a computerized metronome. Each subject performed all three KB swing variations, with 60-second rest intervals between conditions. EMG data were recorded and subjects were video recorded in the sagittal plane while performing the swings. (Figure 2)

**Statistical Analysis**

Statistical analyses were performed using IBM SPSS Version 20. The independent variables were the sagittal plane hip extension findings (active hip extension) from video analysis, Thomas test measurements (passive hip extension or ROM), and gender. The dependent variables were TTP and percent of MVIC. Independent sample t-tests were used to establish gender differences in percent of MVIC during SHKS and THKS as well as TTP, and therefore activation order. Paired t-tests were utilized to establish differences in TTP between LSHKS, RSHKS, and THKS. Finally, multi-linear regression analyses were performed to determine existence of relationships between hip flexor tightness (Thomas Test), hip extension ROM values (kinematic analysis), and gender and percent of MVIC and TTP. Significant differences were recorded at a value of p < .05. Strength of correlations was described using the following scale.
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outlined by Portney and Watkins: 0.0-.29 = weak correlation, .30-.59 = a moderate correlation, and .60 and above was considered a strong correlation.45

RESULTS

Descriptive Data

Subject Demographics
The mean subject age was 24 years (SD +/-1.97), average weight in kilograms was 70.7 kg, (SD +/- 13.3), and average height was 178 cm, (SD +/-8.25). Average Thomas test measurements were 15.5 (left) to 16.8 (right) degrees of extension across the sample (SD of 6.27-7.58 left to right, respectively). Therefore, the subjects were able to, on average, extend 15.5° on the left and 16.8° on the right below the horizontal during the Thomas test and demonstrated no limitations in hip flexor flexibility.

Descriptive Data for Percent of MVIC
For both males and females, SHKS yielded 74.2-81.4% of MVIC for the GMAX, SD of 49.0-61.3% and 56.0-57.4% of MVIC for GMED, with an SD of 25.9-27.7% for the entire sample. Two-handed kettlebell swings yielded an average of 69.4% of MVIC for the GMAX and 53.04% of MVIC for the GMED. For these means, the highest percent of MVIC between the left and right sides for each of the 19 subjects was utilized. For further demographic information and gender specific means across the sample, please refer to Table 1.

Descriptive Analysis of Hip Flexion and Extension ROM
Kinematic analysis of average terminal hip extension during SHKS (left and right averages combined) revealed an average of -8.5° (± 5.3°) for both genders (males = -8.8° ± 5.58° / females = -8.1° ± 5.32°) and an average of -9.7° (± 7.8°) for both genders (males = -8.4° ± 7.72° / females = -10.9° ± 8.08°) for THKS. To clarify, the negative value during the kinematic analysis represents a position of hip extension and a positive value is indicative of a position of hip flexion. Kinematic analysis of average terminal hip flexion during SHKS (left and right averages combined) revealed an average of 84.8° (± 10.7°) for both genders (males = 84.7 ± 12.5 / females = 84.8 ± 9.3) and an average of 85.4° (± 9.0°) for both genders (males = 84.8 ± 9.42 / females = 85.9 ± 9.03 ) for THKS.

Table 1. Subject demographics, including means and standard deviations of all subjects and separated by gender.

<table>
<thead>
<tr>
<th></th>
<th>Age (Mean Years/Std. Deviation)</th>
<th>Weight (kg)</th>
<th>Height (cm)</th>
<th>SHKS % MVIC GMAX</th>
<th>THKS % MVIC GMAX</th>
<th>SHKS % MVIC GMED</th>
<th>THKS % MVIC GMED</th>
<th>Thomas Test Left (degrees)</th>
<th>Thomas Test Right (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample</td>
<td>24/1.97</td>
<td>70.7/13.3</td>
<td>178/8.25</td>
<td>74.2/49.0</td>
<td>69.4/55.9</td>
<td>57.4/25.9</td>
<td>53.0/25.4</td>
<td>15.5/6.27</td>
<td>16.8/7.58</td>
</tr>
<tr>
<td>(N=19)</td>
<td></td>
<td></td>
<td></td>
<td>Left/Right</td>
<td>Left/Right</td>
<td>Left/Right</td>
<td>Left/Right</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>24.1/2.57</td>
<td>80.5/10.0</td>
<td>181/6.78</td>
<td>64.5/30.7</td>
<td>54.6/28.6</td>
<td>60.8/28.6</td>
<td>43.0/12.9</td>
<td>14.1/5.62</td>
<td>12.6/6.91</td>
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<tr>
<td>(N=9)</td>
<td></td>
<td></td>
<td></td>
<td>Left/Right</td>
<td>Left/Right</td>
<td>Left/Right</td>
<td>Left/Right</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Women</td>
<td>23.9/1.37</td>
<td>61.8/8.79</td>
<td>171/6.47</td>
<td>83.0/77.7</td>
<td>82.8/24.4</td>
<td>54.3/29.9</td>
<td>62.0/30.8</td>
<td>16.7/6.86</td>
<td>20.8/6.05</td>
</tr>
<tr>
<td>(N=10)</td>
<td></td>
<td></td>
<td></td>
<td>Left/Right</td>
<td>Left/Right</td>
<td>Left/Right</td>
<td>Left/Right</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

SHKS = single-handed kettlebell swing; THKS = two-handed kettlebell swing; percent of MVIC = Percent of maximal voluntary isometric contraction; Gluteus Maximus = GMAX; and Gluteus Medius = GMED.
Descriptive Analysis of 1D Sagittal Kinematics

Although not objectively measured, a number of subjectively descriptive phases of movement during all KB swings were noted using videographic recordings of sagittal plane kinematics. These phases are clearly visible both with the naked eye and with the use of simple video recording software. Furthermore, although not objectively measured, a consistent curvilinear path of movement of the KB was subjectively observed on video analysis of the subjects performing the swinging tasks. A notable limitation to the analysis of phases is the authors' inability to objectively synchronize kinematic and EMG data, and this will be further discussed in the limitations section. Based on the kinematic data, the authors propose a standardized nomenclature for defining KB swings. Consisting of five phases, the authors define terminal hip flexion of the KB swing as the “pre-swing phase”, the transition from terminal hip flexion toward hip extension as “acceleration”, the phase between maximal hip flexion and hip extension as the “swing phase”, terminal hip extension as the “terminal swing phase”, and the return from terminal hip extension phase to hip flexion as the “return phase”. (Figure 3)

Statistical Results

Mean Differences in Time to Peak between Muscle Groups During All Swings

Significant differences were observed between the mean TTP of the GMAX and BF with the left SHKS (p = .006), the GMAX and BF with the right SHKS (p = .010), between the TTP of the BF of the THKS and both left and right SHKS (p = .016 and .028, respectively), and TTP of the GMED during left SHKS in comparison to the THKS (p = .043). These statistically significant findings demonstrate that the first muscle to be activated of those investigated was the BF, across single-handed swings and that the BF had a faster time to peak in SHKS than THKS. The mean differences between the GMAX and BF during the THKS were not statistically significant, but did show that the GMAX had a longer TTP than the BF did, as evidenced by the positive mean value in column 2 (.051 seconds). The full results can be seen in Table 3.

Sagittal Hip Extension, and Percent of MVIC

A statistically significant strong and negative correlation existed between hip flexor length (as measured...
by the Thomas test) and GMAX muscular activation ($r = -0.651$) for female subjects but not for males. The types of swings are indicated in the descriptions below each table. During the THKS, moderately positive correlations were found between GMAX percent of MVIC and Thomas test measurements, with a correlation coefficient of 0.417. Weak and positive correlations were found between active sagittal plane hip extension ($r = 0.190$), while weak, negative correlations were found between percent of MVIC and gender ($r = -0.259$). Correlations are presented in Table 4.

### DISCUSSION AND CONCLUSION

The purpose of this study was to describe EMG and sagittal plane kinematic data during two KB exercises: the THKS and the SHKS and to investigate whether or not hip flexor length related to the muscular activity or the kinematics of the exercise. KB swings have been suggested as a beneficial technique for neuromuscular education. It is widely believed that KB swings emphasize gluteal activation. Education for performance of KB exercises involves verbal cueing directed specifically toward gluteal activation, and, subsequently, the swinging motion provides kinesthetic and proprioceptive feedback regarding appropriate performance of the technique. Recent evidence from McGill and Marshall demonstrated that the two handed KB swing was able to produce an average peak GMAX activation of 76.1% ± 36.6% MVIC and an average peak GMED activation of 70.1% ± 23.6% MVIC in healthy subjects. This is well within the 50% to 60% of MVIC suggested to be a sufficient stimulus to facilitate muscle strengthening. This early evidence appears to indicate that the KB swing may provide a viable alternative for both GMAX and GMED strengthening. Beyond McGill and Marshall's recent examination of the EMG, ground reaction forces (GRFs), and 3D kinematic data of the THKS on male subjects, limited descriptive studies have examined EMG and kinematics of the THKS and SHKS across both genders.

### Table 2. Descriptive Phases of the Kettlebell swing

<table>
<thead>
<tr>
<th>Phase Title</th>
<th>Phase Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Swing Phase (Figure 3a)</td>
<td>Terminal hip flexion with the KB between and behind the legs with its momentum halted. The lowest amount of muscle activity occurs during this phase.</td>
</tr>
<tr>
<td>Acceleration Phase (Figure 3b)</td>
<td>Transition from terminal hip flexion toward hip extension with the KB forcibly accelerated in a pendular anterior/superior trajectory. The highest GMAX, GMED, and BF muscle activity occurs during this phase.</td>
</tr>
<tr>
<td>Swing Phase (Figure 3c)</td>
<td>Transition from acceleration through hip extension with the KB travelling in an anterior/superior curvilinear path. Variable pulsatile muscle activity occurs during this phase.</td>
</tr>
<tr>
<td>Terminal Swing Phase (Figure 3d)</td>
<td>Terminal hip extension with the KB suspended at the top of its peak trajectory in line with the eyes of performer. Low level GMAX, GMED, and BF activity occurs during this phase.</td>
</tr>
<tr>
<td>Return Phase (Figure 3e)</td>
<td>Return from terminal hip extension towards hip flexion with the KB reversing its curvilinear trajectory either by the effect of gravity or through forcible concentric contraction (an advanced technique not performed by our subjects). Low level GMAX, GMED, and BF activity occurs during the non-advanced form of this exercise performed in this study during this phase.</td>
</tr>
</tbody>
</table>
that gluteal activation may be modified by alterations in hip flexor flexibility.

**Kinematics**

Measurement of passive ROM via the modified Thomas test demonstrated an average of 14° (± 9.8°) of hip extension for both genders, indicating extension of the hip beyond neutral in the test position. Despite the notable availability of passive hip extension ROM, kinematic analysis of video taken during the data collection revealed that none of the subjects obtained neutral hip position while per-

<table>
<thead>
<tr>
<th>Muscle Pair</th>
<th>Mean Difference (seconds)</th>
<th>Std. Deviation</th>
<th>2 Tailed Sig. (p &lt; .05)</th>
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<tr>
<td>GMAX -L - BF -L</td>
<td>.0992105</td>
<td>.1381029</td>
<td>.006*</td>
</tr>
<tr>
<td>GMAX -L - GMED -L</td>
<td>.0238947</td>
<td>.0853990</td>
<td>.238</td>
</tr>
<tr>
<td>GMAX-R - BF -R</td>
<td>.0884211</td>
<td>.1346759</td>
<td>.010*</td>
</tr>
<tr>
<td>GMAX-R - GMED -R</td>
<td>-.0210000</td>
<td>.0852767</td>
<td>.297</td>
</tr>
<tr>
<td>GMAX-T - BF -T</td>
<td>.0514737</td>
<td>.1427384</td>
<td>.133</td>
</tr>
<tr>
<td>GMAX-T - GMED -T</td>
<td>-.0268947</td>
<td>.0830608</td>
<td>.175</td>
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<tr>
<td>BF -L - BF -T</td>
<td>-.0716316</td>
<td>.1169208</td>
<td>.016*</td>
</tr>
<tr>
<td>BF-R - BF -T</td>
<td>-.0554737</td>
<td>.1010354</td>
<td>.028*</td>
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<tr>
<td>GMAX -L - GMAX -T</td>
<td>-.0238947</td>
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<td>.487</td>
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<tr>
<td>GMAX-R - GMAX -T</td>
<td>-.0185263</td>
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<td>.391</td>
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<td>GMED -L - GMED -T</td>
<td>-.0746842</td>
<td>.1491647</td>
<td>.043*</td>
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<tr>
<td>GMED-R - GMED -T</td>
<td>-.0244211</td>
<td>.0682889</td>
<td>.136</td>
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</tbody>
</table>

EMG=electromyographic; SHKS= single handed kettlebell swing; THKS= two handed kettlebell swing; GMAX-L= left gluteus maximus during SHKS; BF-L= left biceps femoris during SHKS; GMED-L= left gluteus medius during SHKS; GMAX-R= right gluteus maximus during SHKS; BF-R= right biceps femoris during SHKS; GMED-R= right gluteus medius during SHKS; BF-T= mean activation of both biceps femoris muscles during the THKS; GMED-T= mean activation of both gluteus medius muscles during the THKS; GMAX-T= mean activation of both gluteus maximus muscles during the THKS.

Vladimir Janda previously discussed an association between hip flexors ROM and gluteal activation. Evidence for decreased hip flexor ROM exists in individuals with a history of LBP; however, to the best of the authors’ knowledge, no literature has previously demonstrated associations between hip flexor tightness and gluteal activation. Although flexibility and ROM of the hip flexor was not evaluated, previous research has demonstrated that greater MVIC activation of the GMAX occurs at 0° of hip extension compared to 30°, 60°, or 90° of hip flexion. Theoretical implications of the existence of this imbalance are that gluteal activation may be modified by alterations in hip flexor flexibility.
within the current study, with an average of 1° of hip extension while performing a KB swing. The 8.5-9.8° difference in both hip flexion and hip extension between subjects may in part be due to differences in verbal cues given in the instructional sessions, McGill and Marshall emphasized a “squat” based KB swing and gave a target of chest height, while the instructions emphasized in this study emphasized a “pendular motion” through hip hinging with a target of eye height and controlled hip ROM for both the bottom and the top of the swing through the targets of the manipulandum. Furthermore, the authors of the current study attempted to control the velocity of the technique through the use of a metronome, which may have influenced the motor program utilized to reach terminal ranges based on higher or lower velocities, which were not discussed in the McGill and Marshall study. In addition, some of the variance may have been related to differences in accuracy of measurements obtained during 3-D versus one-dimensional kinematics.

Table 4. Gluteus Maximus Correlations -Correlation between GMAX % of MVIC and Thomas test findings, gender, and sagittal plane hip extension. P-values for the correlations between each of the two variables being compared are also presented.

<table>
<thead>
<tr>
<th></th>
<th>GMAX % MVIC</th>
<th>Thomas Test</th>
<th>Gender</th>
<th>THKS - Hip Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson Correlation</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GMAX % MVIC</td>
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<td>.417</td>
<td>-.259</td>
<td>.190</td>
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<td>Thomas Test</td>
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<td>1.000</td>
<td>-.651</td>
<td>-.331</td>
</tr>
<tr>
<td>Gender</td>
<td>-.259</td>
<td>-.651</td>
<td>1.000</td>
<td>.294</td>
</tr>
<tr>
<td>THKS - Hip Extension</td>
<td>.190</td>
<td>-.331</td>
<td>.294</td>
<td>1.000</td>
</tr>
<tr>
<td>Sig. (1-tailed)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GMAX % MVIC</td>
<td>.</td>
<td>.038</td>
<td>.142</td>
<td>.218</td>
</tr>
<tr>
<td>Thomas Test</td>
<td>.038</td>
<td>.</td>
<td>.001*</td>
<td>.083</td>
</tr>
<tr>
<td>Gender</td>
<td>.142</td>
<td>.001</td>
<td>.</td>
<td>.111</td>
</tr>
<tr>
<td>THKS - Hip Extension</td>
<td>218</td>
<td>.083</td>
<td>.111</td>
<td>.</td>
</tr>
</tbody>
</table>

GMAX % MVIC= gluteus maximus percent maximum voluntary isometric contraction; THKS- Hip Extension= two handed kettlebell swing measurement of hip extension in the sagittal plane. *denotes statistically significant correlation at p<0.05.

forming any of the KB swings. Average terminal hip extension during the SHKS (left and right averages combined) lacked a mean of 8.5° (± 5.3°) from neutral hip extension for both genders (males = -8.8° ± 5.58° / females = -8.1° ± 5.32°) and lacked a mean of 9.7° (± 7.8°) from neutral hip extension for both genders (males = -8.4° ± 7.72° / females = -10.9° ± 8.08°) during the THKS. This indicates that for both the SHKS and the THKS neither gender performed throughout their full available hip extension, despite cueing during the instructional sessions. Kinematic analysis of average terminal hip flexion during the SHKS (left and right averages combined) revealed a mean of 84.8° (± 10.7°) for both genders (males = 84.7° ± 12.5° / females = 84.8° ± 9.3°) and a mean of 85.4° (± 9.0°) for both genders (males = 84.8° ± 9.42° / females = 85.9° ± 9.03°) during the THKS. This indicates that during performance of both the SHKS and THKS, hip flexion near 90° was obtained at active terminal flexion. These hip flexion ROM values are greater than those observed by McGill and Marshall whose subjects performed an average of 75° of hip flexion at the bottom of the swing, however, they only used male subjects. Furthermore, McGill and Marshall found their subjects performed greater hip extension than the subjects within the current study, with an average of 1° of hip extension while performing a KB swing. The 8.5-9.8° difference in both hip flexion and hip extension between subjects may in part be due to differences in verbal cues given in the instructional sessions, McGill and Marshall emphasized a “squat” based KB swing and gave a target of chest height, while the instructions emphasized in this study emphasized a “pendular motion” through hip hinging with a target of eye height and controlled hip ROM for both the bottom and the top of the swing through the targets of the manipulandum. Furthermore, the authors of the current study attempted to control the velocity of the technique through the use of a metronome, which may have influenced the motor program utilized to reach terminal ranges based on higher or lower velocities, which were not discussed in the McGill and Marshall study. In addition, some of the variance may have been related to differences in accuracy of measurements obtained during 3-D versus one-dimensional kinematics.

Peak Muscle Activation

On an average, peak muscle activation for GMAX was 75.02% ± 55.38% (THKS = 69.44% ± 55.90 / LSHKS = 74.24% ± 48.98% / RSHKS = 81.39% ±
61.27%) in all KB swing techniques. It has been previously suggested that between 50% to 60% of MVIC is necessary to facilitate muscle strengthening.22-24 This indicates that both forms of KB swings may induce sufficient muscular activation to potentially promote muscle strengthening of the GMAX. Although the GMAX activation results of this present study were slightly lower on average, McGill and Marshall similarly demonstrated peak GMAX activation over 60% of MVIC (76.1% ± 36.6%).18 The current results for GMAX MVIC are higher than a single leg squatting activity (57% ± 44%) 23 and similar to the highest level of GMAX activation previously identified in a systematic review by Reiman et al during performance of the step-up activity (74% ± 43% MVIC).25 Curiously, although the back squat is popularly thought of as an exercise to strengthen the GMAX, it fails to exceed peak muscle activation of 35%, regardless of depth, stance, or weight utilized.47,49

Average peak muscle activation for GMED also met the minimum of 50% of MVIC, which meets the current suggested standard for muscle strengthening. Average peak percent of MVIC for GMED was 55.47% ± 26.33% (THKS = 53.0% ± 25.4% / LSHKS = 57.4% ± 25.9%, / RSHKS = 56.0% ± 27.7%), This average is less than the results of McGill and Marshall who demonstrated average peak GMED activation of 70.1% ± 23.6% in males.18 It is possible that an additional training effect was present in McGill and Marshall's work, as most of their subjects had experience with the KB, whereas none of subjects in this study were formally trained in the KB, nor did they frequently utilize a KB in their training.18 Despite having lower values than those described in the work of McGill and Marshall, values were greater than many clinically utilized GMED activities, including the clam shell exercise (38% ± 29% for a 60° clamshell to 40% ± 38% in a 30° clamshell), the side lunge (39% ± 19%), and the forward lunge (42% ± 21%) exercises as evaluated by Distefano et al.22 The GMED activation in both the SHKS and THKS were close to both the lateral band walk (61% ± 34%) and single limb squat (64% ± 24%), but not as high as the sidelying hip abduction exercise (81% ± 42%).21 Regardless, it is clear that the THKS and SHKS can be utilized for a sufficient stimulus for GMED strengthening.

Perhaps the most interesting comparison that can be made between the current work and the work of McGill and Marshall18 was the difference in average

<table>
<thead>
<tr>
<th>Correlations</th>
<th>Glute med % MVIC</th>
<th>Thomas Test</th>
<th>Gender</th>
<th>THKS - Hip Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson Correlation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Glute med % MVIC</td>
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<td>Thomas Test</td>
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<td>1.000</td>
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<tr>
<td>Gender</td>
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<td>.294</td>
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<td>THKS - Hip Extension</td>
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<td>-.331</td>
<td>.294</td>
<td>1.000</td>
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<tr>
<td>Sig. (1-tailed)</td>
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<tr>
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<td>Thomas Test</td>
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<tr>
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<tr>
<td>THKS - Hip Extension</td>
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<td>.111</td>
<td>.</td>
</tr>
</tbody>
</table>

GMED % MVIC= gluteus medius percent maximum voluntary isometric contraction; THKS- Hip Extension= two handed kettlebell swing measurement of hip extension in the sagittal plane. *denotes statistically significant correlation at p<0.05.

Table 5. Gluteus Medius Correlations –Correlation between GMED % MVIC and Thomas test findings, gender, and sagittal plane hip extension. P-values for the correlations between each of the two variables being compared are also presented.
The association between hip extension ROM may indirectly have been demonstrated in the work of Worrell et al, who demonstrated that peak MVIC was weakest at 90° of hip flexion but progressively increased until the highest peak activation was obtained at zero degrees of hip extension. To the best of the authors' knowledge, this is the first study to demonstrate an association between hip ROM/flexibility and gluteal activation with a closed chain activity. Mauntel et al examined numerous lower extremity PROM measures and their influence on lower extremity muscle activation during a single leg squat but found no relationship between passive hip extension and muscle activation. Although speculative and requiring further research, the current results may provide some clinical value regarding the relationship between hip extension ROM and muscle performance, and support the premise which Janda laid in his description of an association between tight hip flexors and a under recruited GMAX.

Correlations
During the THKS, a moderate positive correlation was found between average peak GMAX percent of MVIC and Thomas test measurements, with a correlation coefficient of 0.417. Weak and positive correlations were found between active hip extension (sagittal kinematic hip extension) and GMAX activation ($r = 0.246$), while weak and negative correlations ($r = -0.318$) were found between percent of MVIC and gender (females had greater GMAX activation). Based on these results, it appears that the greater the available passive or active hip extension ROM (the less “tight” or “short” the hip flexor), the greater the GMAX percent of MVIC. Although not strong, evidence of moderate positive correlation between GMAX activation and passive hip extension (the Thomas test) as well as weak positive correlation to dynamic/active hip extension (kinematic sagittal hip extension) is an interesting finding, as the original hypothesis was that no correlation would be seen due to a lack of existing evidence associated with static hip flexor length/static hip extension ROM. However, the association between hip extension ROM may indirectly have been demonstrated in the work of Worrell et al, who demonstrated that peak MVIC was weakest at 90° of hip flexion but progressively increased until the highest peak activation was obtained at zero degrees of hip extension. To the best of the authors' knowledge, this is the first study to demonstrate an association between hip ROM/flexibility and gluteal activation with a closed chain activity. Mauntel et al examined numerous lower extremity PROM measures and their influence on lower extremity muscle activation during a single leg squat but found no relationship between passive hip extension and muscle activation. Although speculative and requiring further research, the current results may provide some clinical value regarding the relationship between hip extension ROM and muscle performance, and support the premise which Janda laid in his description of an association between tight hip flexors and a under recruited GMAX.

Moderate and negative correlations were found between average peak GMED percent of MVIC and hip extension ($r = -0.348$) and gender ($r = -0.384$), indicating a higher percent of GMED MVIC activation among women during the THKS. Although not an objective of this study, it could be postulated that this increased activation may be the result of increased effort relative to the proportion of lean body mass to the mass of the kettlebell, which may be gender specific. Thomas test measurements had a moderately positive relationship ($r = 0.396$) with percent of GMED MVIC during the THKS. This finding is truly novel, as no proposed associations between passive hip ROM/flexibility and GMED activity has previously been made. Similar to the GMAX, the less hip extension ROM available, the weaker the GMED activation.

Correlations
During the THKS, a moderate positive correlation was found between average peak GMAX percent of MVIC and Thomas test measurements, with a correlation coefficient of 0.417. Weak and positive correlations were found between active hip extension (sagittal kinematic hip extension) and GMAX activation ($r = 0.246$), while weak and negative correlations ($r = -0.318$) were found between percent of MVIC and gender (females had greater GMAX activation). Based on these results, it appears that the greater the available passive or active hip extension ROM (the less “tight” or “short” the hip flexor), the greater the GMAX percent of MVIC. Although not strong, evidence of moderate positive correlation between GMAX activation and passive hip extension (the Thomas test) as well as weak positive correlation to dynamic/active hip extension (kinematic sagittal hip extension) is an interesting finding, as the original hypothesis was that no correlation would be seen due to a lack of existing evidence associated with static hip flexor length/static hip extension ROM. However, the association between hip extension ROM may indirectly have been demonstrated in the work of Worrell et al, who demonstrated that peak MVIC was weakest at 90° of hip flexion but progressively increased until the highest peak activation was obtained at zero degrees of hip extension. To the best of the authors' knowledge, this is the first study to demonstrate an association between hip ROM/flexibility and gluteal activation with a closed chain activity. Mauntel et al examined numerous lower extremity PROM measures and their influence on lower extremity muscle activation during a single leg squat but found no relationship between passive hip extension and muscle activation. Although speculative and requiring further research, the current results may provide some clinical value regarding the relationship between hip extension ROM and muscle performance, and support the premise which Janda laid in his description of an association between tight hip flexors and a under recruited GMAX.

Moderate and negative correlations were found between average peak GMED percent of MVIC and hip extension ($r = -0.348$) and gender ($r = -0.384$), indicating a higher percent of GMED MVIC activation among women during the THKS. Although not an objective of this study, it could be postulated that this increased activation may be the result of increased effort relative to the proportion of lean body mass to the mass of the kettlebell, which may be gender specific. Thomas test measurements had a moderately positive relationship ($r = 0.396$) with percent of GMED MVIC during the THKS. This finding is truly novel, as no proposed associations between passive hip ROM/flexibility and GMED activity has previously been made. Similar to the GMAX, the less hip extension ROM available, the weaker the GMED activation.

Although no statistically significant differences were noted, females consistently had higher average peak percent of MVIC of GMAX in all swings, and a higher means of percent of MVIC of GMED during the THKS. Curiously, the only significant statistical finding ($p = 0.001$) in correlational analysis was the strong negative correlation ($r = -0.651$) between gender and Thomas test results (females had greater ROM in the Thomas test), and based on other moderate and weak GMAX correlations and previous evidence regarding maximal GMAX MVIC occurring with
is limited to like populations. Next, the fashion in which hip extension (as a measure of hip flexor length) was measured could lend itself to slightly increased variance as two separate investigators took these measurements based on the subject's gender in order to maintain modesty. However, to decrease possible variance in inter-rater measurements, a PVC pipe was used under the subject's lumbar spine to determine when movement occurred. Due to all of the subjects falling within the definition of “normal” hip flexor length, the authors developed a numerical scale to categorically rank levels of increasing hip flexor length. If the scale was too narrow, it may have masked any underlying correlations between hip flexor length and gluteal activation that may have been present otherwise.

As previously noted, and in contrast to the study by McGill et al,18 the subjects in this study were inexperienced KB users and therefore were allowed to self-select the KB weight for safety and comfort purposes. Varying the KB weight based on bodyweight and subject preference may have increased variability in percent MVIC values. Furthermore, although not examined, some of the outliers may have utilized greater ES activation or upper back and arm musculature than hip musculature in order to perform the KB swings, and this could account for some of the lower activation of recorded muscles for some subjects.

Finally, the inability to synchronize the outputs from the Dartfish and EMG software into one cohesive data set limited the authors’ ability to directly associate kinematics with EMG activity. During each swing cycle (defined as beginning with pre-swing and ending with the return phase) a significant delay between the frequency of video collection (29.97 frames per second) and the frequency of EMG recording (1,000 data points per second) limits the authors’ ability to associate the exact timing of kinematic and muscle activity.

**Conclusions**

The THKS and SHKS are versatile exercises that demonstrate the ability to provide a stimulus sufficient to strengthen the GMAX, GMED and BF during a closed kinetic chain task. The terminal flexion and extension movements of the hip are fairly consistent

**Muscle Activation Order**

In agreement with previous research regarding the activation order of hamstrings compared to gluteals throughout the movement of hip extension,9-11 the hamstrings activated first in all forms of KB swings across gender, hip flexor ROM, and kinematic hip flexion or extension. Significant differences (p < 0.05) were calculated between the mean TTP of the GMAX and BF between left (p = 0.006) and right (p = 0.010) sided SHKS (BF activated first in both swings), between the TTP of the BF of the THKS and both SHKS (BF activated earlier in both the left SHKS p = 0.016 and right SHKS p = 0.028 and THKS). This is despite emphasis during the education of the swings on conscious activation of the gluteals. These results are in agreement with McGill and Marshall, where the BF was also activated prior to the GMAX (at 52% of the swing cycle versus 57% respectively).18

Regarding comparing GMED activation between THKS and SHKS, the TTP of the GMED was earlier in the left SHKS (p = 0.043) than GMED of THKS. Although not officially recorded, it was noted during the instructional sessions that the majority of the subjects were right handed, which may partially explain for the differences in earlier activation with the left SHKS than the right due to the time of pelvic control necessary to control the KB in the non-dominant hand.

**Limitations**

The sample population included only young healthy subjects; therefore, the generalizability of the results is limited to like populations. Next, the fashion in which hip extension (as a measure of hip flexor length) was measured could lend itself to slightly increased variance as two separate investigators took these measurements based on the subject's gender in order to maintain modesty. However, to decrease possible variance in inter-rater measurements, a PVC pipe was used under the subject's lumbar spine to determine when movement occurred. Due to all of the subjects falling within the definition of “normal” hip flexor length, the authors developed a numerical scale to categorically rank levels of increasing hip flexor length. If the scale was too narrow, it may have masked any underlying correlations between hip flexor length and gluteal activation that may have been present otherwise.

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and are easily observed or recorded from a sagittal plane view, using a video camera in a clinical or gym environment, and can be divided into five phases for education and training purposes. It appears that both passive and active hip extension ROM are associated with muscle activation of the GMAX, GMED, and BF. In addition, females appear to have greater GMAX activation in all KB swinging activities than their male counterparts. The descriptive data provided in this study supports the use of and clinical value of the KB swinging exercises in order to address a number of clinical strength and endurance impairments specific to the GMAX, GMED, and BF.

REFERENCES
23. Ayotte NW, Stetts DM, Keenan G, Greenway EH. Electromyographical analysis of selected lower


ABSTRACT

Background: Self-myofascial release (SMR) is a popular intervention used to enhance a client’s myofascial mobility. Common tools include the foam roll and roller massager. Often these tools are used as part of a comprehensive program and are often recommended to the client to purchase and use at home. Currently, there are no systematic reviews that have appraised the effects of these tools on joint range of motion, muscle recovery, and performance.

Purpose: The purpose of this review was to critically appraise the current evidence and answer the following questions: (1) Does self-myofascial release with a foam roll or roller-massager improve joint range of motion (ROM) without effecting muscle performance? (2) After an intense bout of exercise, does self-myofascial release with a foam roller or roller-massager enhance post exercise muscle recovery and reduce delayed onset of muscle soreness (DOMS)? (3) Does self-myofascial release with a foam roll or roller-massager prior to activity affect muscle performance?

Methods: A search strategy was conducted, prior to April 2015, which included electronic databases and known journals. Included studies met the following criteria: 1) Peer reviewed, English language publications 2) Investigations that measured the effects of SMR using a foam roll or roller massager on joint ROM, acute muscle soreness, DOMS, and muscle performance 3) Investigations that compared an intervention program using a foam roll or roller massager to a control group 4) Investigations that compared two intervention programs using a foam roll or roller massager. The quality of manuscripts was assessed using the PEDro scale.

Results: A total of 14 articles met the inclusion criteria. SMR with a foam roll or roller massager appears to have short-term effects on increasing joint ROM without negatively affecting muscle performance and may help attenuate decrements in muscle performance and DOMS after intense exercise. Short bouts of SMR prior to exercise do not appear to effect muscle performance.

Conclusion: The current literature measuring the effects of SMR is still emerging. The results of this analysis suggests that foam rolling and roller massage may be effective interventions for enhancing joint ROM and pre and post exercise muscle performance. However, due to the heterogeneity of methods among studies, there currently is no consensus on the optimal SMR program.

Keywords: Massage, muscle, treatment

Level of Evidence: 2c

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INTRODUCTION

Self-myofascial release (SMR) is a popular intervention used by both rehabilitation and fitness professionals to enhance myofascial mobility. Common SMR tools include the foam roll and various types of roller massagers. Evidence exists that suggests these tools can enhance joint range of motion (ROM)\(^1\) and the recovery process by decreasing the effects of acute muscle soreness\(^2\), delayed onset muscle soreness (DOMS)\(^3\), and post exercise muscle performance\(^4\). Foam rollers and roller massage bars come in several sizes and foam densities (Figure 1). Commercial foam rolls are typically available in two sizes: standard (6 inch x 36 inch)\(^5\) and half size (6 inch x 18 inches)\(^6\). With foam rolling, the client uses their bodyweight to apply pressure to the soft tissues during the rolling motion. Roller massage bars also come in many shapes, materials, and sizes. One of the most common is a roller massage bar constructed of a solid plastic cylinder with a dense foam outer covering\(^7,8\). The bar is often applied with the upper extremities to the target muscle. Pressure during the rolling action is determined by the force induced by the upper extremities. The tennis ball has also been considered a form of roller massage and has been studied in prior research\(^9\).

For both athletes and active individuals, SMR is often used to enhance recovery and performance. Despite the popularity of SMR, the physiological effects are still being studied and no consensus exists regarding the optimal program for range of motion, recovery, and performance\(^10\). Only two prior reviews have been published relating to myofascial therapies. Mauntel et al\(^11\) conducted a systematic review assessing the effectiveness of the various myofascial therapies such as trigger point therapy, positional release therapy, active release technique, and self-myofascial release on joint range of motion, muscle force, and muscle activation. The authors appraised 10 studies and found that myofascial therapies, as a group, significantly improved ROM but produced no significant changes in muscle function following treatment\(^12\). Schroder et al\(^13\) conducted a literature review assessing the effectiveness self-myofascial release using a foam roll and roller massager for pre-exercise and recovery. Inclusion criteria was randomized controlled trials. Nine studies were included and the authors found that SMR appears to have positive effects on ROM and soreness/fatigue following exercise\(^14\). Despite these reported outcomes, it must be noted that the authors did not use an objective search strategy or grading of the quality of literature.

Currently, there are no systematic reviews that have specifically appraised the literature and reported the effects of SMR using a foam roll or roller massager on these parameters. This creates a gap in the translation from research to practice for clinicians and fitness professionals who use these tool and recommend these products to their clients. The purpose of this systematic review was to critically appraise the current evidence and answer the following questions: (1) Does self-myofascial release with a foam roll or roller-massager improve joint range of motion without effecting muscle performance? (2) After an intense bout of exercise, does self-myofascial release with a foam roller or roller-massager enhance post exercise muscle recovery and reduce DOMS? (3) Does self-myofascial release with a foam roll or roller-massager prior to activity affect muscle performance?

Methods

Search Strategy

A systematic search strategy was conducted according the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for reporting systematic reviews (Figure 2).\(^15,16\) The following databases were searched prior to April 2015: PubMed, PEDro, Science Direct, and EBSCOhost. A direct search of known journals was also conducted to identify potential publications. The search terms included individual or a combination of the following: self; myofascial; release; foam roll; massage; roller; athletic; performance; muscle; strength; force production; range of motion; fatigue; delayed onset of muscle soreness. Self-myofascial release was operationally defined as a self-massage technique using a device such as a foam roll or roller massager.

Study Selection

Two reviewers (MC and ML) independently searched the databases and selected studies. A third independent reviewer (SC) was available to resolve any disagreements. Studies considered for inclusion met...
the following criteria: 1) Peer reviewed, English language publications 2) Investigations that measured the effects of SMR using a foam roll or roller massager on joint ROM, acute muscle soreness, DOMS, and muscle performance 3) Investigations that compared an intervention program using a foam roll or roller massager to a control group 4) Investigations that compared two intervention programs using a foam roll or roller massager. Studies were excluded if they were non-English publications, clinical trials that included SMR as an intervention but did not directly measure its efficacy in relation to the specific questions, case reports, clinical commentary, dissertations, and conference posters or abstracts.

**Data Extraction and Synthesis**

The following data were extracted from each article: subject demographics, intervention type, intervention parameters, and outcomes. The research design of each study was also identified by the reviewers. Qualifying manuscripts were assessed using the PEDro (Physiotherapy Evidence Database) scale for appraising the quality of literature. Intra-observer agreement was calculated using the Kappa statistic. For each qualifying studies, the levels of significance (p-value) is provided in the results section for comparison and the effect size (r) is also provided or calculated from the mean, standard deviation, and sample sizes, when possible. Effect size of >0.70 was considered strong, 0.41 to 0.70 was moderate, and < 0.40 was weak.

**Results**

A total of 133 articles were initially identified from the search and 121 articles were excluded due to not meeting the inclusion criteria. A total of 14 articles met the inclusion criteria. Reasons for exclusion of manuscripts are outlined in Figure 2. The reviewers Kappa value for the 14 articles was 1.0 (perfect agreement). Table 1 provides the PEDro score for each of the qualifying studies and Appendix 1 provide a more thorough description of each qualifying study.

**Study Characteristics**

All qualifying manuscripts yielded a total of 260 healthy subjects (Male-179, Female-81) (mean 19.6 years ± 3.10, range 15-34 years) with no major comorbidities that would have excluded them from testing. Eleven studies reported including recreationally active individuals (e.g. exercising at least 2-3 days per week), one study included a range of subjects from recreational to highly active, one study included collegiate athletes, and one study included physically untrained individuals. Due to the methodological diversity among qualifying studies, a more descriptive results section is provided so the reader can understand the various interventions and measures that were used for each study. The qualifying studies will be group and analyzed according to the proposed questions.

**JOINT RANGE OF MOTION**

**Foam Roller**

Five studies used a foam roller as the main tool and measured its effects on ROM. Of the aforementioned five studies, three reported using a 6 inch x 36 inch polyethylene foam roller and two studies.
reported using a 6 inch x 36 inch high density foam roll constructed out of a hollow PVC pipe and outer ethylene acetate foam. Two studies7,8 used a standard cadence for the foam roll interventions and all studies5,7-9,18 used the subject’s bodyweight. All studies5,7-9,18 measured the immediate effects (within 10 minutes after the intervention) and several other post-test time points. The SMR intervention period for all studies ranged from two to five sessions for 30 seconds to one minute.5,7,8,18

### Foam Rolling: Hip ROM

Two studies5,8 measured hip ROM after a prescribed intervention of foam rolling. Bushell et al5 foam rolled the anterior thigh in the sagittal plane (length of the muscle) and measured hip extension ROM of subjects in the lunge position with video analysis and used the Global Perceived Effect Scale (GPES) as a secondary measure. Thirty one subjects were assigned to an experimental (N=16) or control (N=15) group and participated in three testing sessions that were held one week apart with pre-test and immediate post-test measures. The experimental group foam rolled for three, one-minute bouts, with 30 second rests in between. There were no reported cadence guidelines for the intervention. The control group did not foam roll. The authors found a significant (p≤0.05, r=-0.11) increase in hip extension

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**Table 1. PEDro scores for qualified studies**

<table>
<thead>
<tr>
<th>Study</th>
<th>Item 1</th>
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<th>Item 3</th>
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**PEDro Criteria:** Item 1 (Eligibility criteria), Item 2 (Subjects randomly allocated), Item 3 (Allocation concealed), Item 4 (Intervention groups similar), Item 5 (Subjects were blinded), Item 6 (Therapists administering therapy blinded), Item 7 (All assessors blinded), Item 8 (At least 1 key outcome obtained from more than 85% of subjects initially allocated), Item 9 (All subjects received treatment or control intervention or an Intention-to-treat analysis performed), Item 10 (Between group comparison reported for at least one key outcome), Item 11 (study provides both point measures and measures of variability for at least one key outcome)
ROM during the second session in the experimental group. However, hip extension measures returned to baseline values after one week. The authors also found higher GPE score in the intervention group.

Mohr et al. measured the effects of foam rolling combined with static stretching on hip flexion ROM. The authors randomized subjects (N = 40) into three groups: (1) foam rolling and static stretching, (2) foam rolling, (3) static stretching. The foam rolling intervention consisted of rolling the hamstrings in the sagittal plane using the subjects bodyweight (three session of 1 minute) with a cadence of one second superior (towards ischial tuberosity) and one second inferior (towards popliteal fossa) using the subjects bodyweight. Static stretching of the hamstrings consisted of three sessions, held for one minute. Hip flexion ROM was measured immediately after each intervention in supine with an inclinometer. Upon completion of the study, the authors found that foam rolling combined with static stretching produced statistically significant increases (p = 0.001, r = 7.06) in hip flexion ROM. Also greater change in ROM was demonstrated when compared to static stretching (p = 0.04, r = 2.63) and foam rolling (p = 0.006, r = 1.81) alone.

**Foam Rolling: Sit and Reach**

Peacock et al. examined the effects of foam rolling along two different axes of the body combined with a dynamic warm-up in male subjects (N = 16). The authors examined two conditions: medio-lateral foam rolling followed by a dynamic warm-up and anteroposterior foam rolling followed by a dynamic warm-up. All subjects served as their own controls and underwent the two conditions within 7-days of each other. The foam rolling intervention consisted of rolling the posterior lumbopelvis (erector spinae,
multifidus), gluteal muscles, hamstrings, calf region, quadriceps, and pectoral region along the two axes (1 session for 30 seconds per region) using the subjects bodyweight. There was no reported cadence guidelines for the foam roll intervention. The dynamic warm-up consisted of a series of active body-weight movements that focused on the major joints of the body (20 repetitions for each movement).18 Outcome measures included the sit and reach test and several other performance tests including the vertical jump, broad jump, shuttle run, and bench press immediately after the intervention. Foam rolling in the mediolateral axis had a significantly greater effect (p≤0.05, r=0.16) on increasing sit and reach scores than rolling in the anteroposterior axis with no other differences among the other tests.18

**Foam Rolling: Knee ROM**

MacDonald et al7 examined the effects of foam rolling on knee flexion ROM and neuromuscular activity of the quadriceps in male subjects (N=11). Subjects served as their own controls and were tested twice: once after two sessions of 1 minute foam rolling in the sagittal plane on the quadriceps from the anterior hip to patella (cadence of 3 to 4 times per minute), and additionally after no foam rolling (control). The outcome measures included knee flexion ROM, maximal voluntary contraction (MVC) of the quadriceps, and neuromuscular activity via electromyography (EMG). Subjects were measured for all the above parameters pre-test, 2 minutes after the two conditions, and 10 minutes after. The authors found a significant increase (p<0.001, r=1.13) of 10° at 2 minutes post-test and a significant increase (p<0.001, r=0.92) of 8° at 10 minutes post-test of knee flexion ROM following foam rolling when compared to the control group. There were no significant differences in knee extensor force and neuromuscular activity among all conditions.7

**Foam Rolling: Ankle ROM**

Skarabot et al9 measured the effects of foam rolling and static stretching on ankle ROM in adolescent athletes (N = 5 female, 6 male). The authors randomized subjects into three groups (conditions): (1) foam rolling, (2) static stretching, and (3) foam roll and static stretching. The foam rolling intervention consisted of three sessions of 30 seconds rolling on the calf region while the static stretching intervention consisted of a single plantarflexor static stretch performed for three sets of 30 seconds. There were no reported cadence guidelines for the foam rolling intervention. The outcome measure was dorsiflexion ROM measured in the lunge position pre-test, immediately post-test, 10, 15, and 20 minutes post-test. From pre-test to immediately post-test, static stretching increased ROM by 6.2% (p <0.05, r=-0.13) and foam rolling with static stretching increased ROM by 9.1% (p<0.05, r=-0.27) but no increases were demonstrated for foam rolling alone. Post hoc testing revealed that foam rolling with static stretching was superior to foam rolling. All changes from the interventions lasted less than 10 minutes.9

**Roller Massage**

Five studies1,10-12,19 qualified for this analysis that used some type of a roller massager as the main tool. Two studies1,10 reported using a mechanical device connected to a roller bar that created a standard force and cadence. Two studies11,19 reported using a commercial roller bar that was self-administered by the subjects using an established pressure but no standard cadence. One study12 reported using a tennis ball as a self-administered roller massager with no standard pressure or cadence. All studies measured the acute effects in which measurements were taken within 10 minutes after the intervention period along with other post-test time points. The intervention period for all studies ranged from two to five sessions for five seconds to two minutes.1,10-12,19

**Roller Massage: Ankle ROM**

Halperin et al11 compared the effects of a roller massage bar versus static stretching on ankle dorsiflexion ROM and neuromuscular activity of the plantar flexors. The authors randomized subjects (N=14) into 3 groups: (1) foam rolling and static stretching, (2) foam rolling, (3) static stretching. The roller massage intervention consisted of the subjects using the roller bar to massage the plantar flexors for three sets of 30 seconds at a cadence of one second per roll (travel the length of the muscle in one second). The pressure applied was equivalent to 7/10 pain on a numeric pain rating scale. Subjects established this level prior to testing. The static stretching intervention consisted of a standing calf stretch for three sets
of 30 seconds using the same discomfort level of 7/10 to gauge the stretch. The outcome measures included ankle dorsiflexion ROM, static single leg balance for 30 seconds, MVC of the plantar flexors, and neuromuscular activity via EMG. Measurements were taken pre-test, immediate post-test, and 10 minutes post-test. Both the roller massage \((p<0.05, r=0.26, 4\%)\) and static stretching \((p<0.05, r=0.27, 5.2\%)\) increased ROM immediately and 10 minutes post-test. The roller massage did show small improvements in muscle force relative to static stretching at 10 minutes post-test. Significant effects were not found for balance, MVC, or EMG.

**Roller Massage: Knee ROM**

Bradbury-Squires et al\(^{10}\) measured the effects of a roller massager intervention on knee joint ROM and neuromuscular activity of the quadriceps and hamstrings. Ten subjects experienced three randomized experimental conditions: (1) 5 repetitions of 20 seconds (2) 5 repetitions of 60 seconds, (3) no activity (control).\(^{10}\) The roller massage intervention was conducted by a constant pressure apparatus that applied a standard pressure (25\% of body weight) through the roller bar to the quadriceps. Subjects sat upright in the apparatus and activity moved their body to allow the roller to travel up and down the quadriceps. The subjects rolled back and forth at a cadence of 30 beats per minute (BPM) on a metronome, which allowed a full cycle to be completed in four seconds (two seconds towards hip, two seconds towards patella). The main pre-test, post-test outcome measures included the visual analog scale (VAS) for pain, knee joint flexion ROM, MVC for knee extension, and EMG activity of the quadriceps and hamstrings during a lunge. The authors found a 10\% increase in post-intervention knee ROM at 20 seconds and a 16\% increase at 60 seconds post-intervention when compared to the control \((p<0.05)\). There was a significant increase in knee ROM and neuromuscular efficiency (e.g. reduced EMG activity in quadriceps) during the lunge. There was no difference in VAS scores between the 20 and 60 second interventions.\(^{10}\)

**Roller Massage: Hip ROM**

Mikesky et al\(^{19}\) measured the effects of a roller massager intervention on hip ROM and muscle performance measures. The authors recruited 30 subjects and measured the effects of three randomized interventions: (1) control, (2) placebo (mock non-perceivable electrical stimulation), (3) SMR with roller massager. Testing was performed over three days in which one of the randomized interventions were introduced and lasted for two minutes. The roller massage intervention consisted of the subject rolling the hamstrings for two minutes with no set pressure or cadence. The outcome measures consisted of hip flexion AROM, vertical jump height, 20-yard dash, and isokinetic knee extension strength.\(^{19}\) All outcomes were measured pre and immediately post the intervention. No acute improvements were seen in any of the outcome measures following the roller massager intervention.\(^{19}\)

**Roller Massage: Sit and Reach**

Sullivan et al\(^{1}\) measured the effects of a roller massager intervention on lower extremity ROM and neuromuscular activity. The authors used a pre-test, immediate post-test comparison of 17 subjects (8 experimental, 9 control) using the sit and reach test to measure flexibility, MVC, and neuromuscular activity via EMG measures of the hamstrings.\(^{1}\) The roller massager intervention consisted of four trials (one set of 5 seconds, one set of 10 seconds, two sets of 5 seconds, 2 sets of 10 seconds) to the hamstrings using a constant pressure apparatus connected to the roller massage bar which is similar to the apparatus and procedure described in Bradbury-Squires et al\(^{10}\) study. The apparatus was set at a constant pressure of (13 kg) and cadence (120 BPM). Testing was conducted over two days with two intervention sessions per day on opposing legs separated by a 30 minute rest period. The control group attended a third session that included the pre-test and post-test measures but no intervention. The use of a roller massager produced a 4.3\% \((p<0.0001)\) increase in sit and reach scores after the intervention periods of one and two sets of 5 seconds. There was a trend \((p=0.069, r=0.21)\) for 10 seconds of rolling to increase ROM more than five seconds of rolling. There were no significant changes in MVC or EMG activity after the rolling intervention.\(^{1}\)

Grieve et al\(^{12}\) conducted a study measuring the effects of roller massage to the plantar aspect of the foot using a tennis ball. The authors randomized 24 subjects to an experimental or control group. The
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Roller massage (tennis ball) intervention consisted of one session of SMR to each foot for two minutes. There was no established pressure or cadence. The author measured pre-test and immediate post-test flexibility using the sit and reach test as the main outcome measure. Upon completion of the study, the authors found a significant increase ($p=0.03$, $r=0.21$) in post-test sit and reach scores when compared to the control scores.

**POST-EXERCISE MUSCLE RECOVERY AND REDUCTION OF DOMS**

Three studies used an exercised induced muscle damage program followed by an SMR intervention and measured the effects of SMR on DOMS and muscle performance. Two studies used a custom foam roller made out of a polyvinyl chloride pipe (10.16 cm length, 0.5 cm width) surrounded by neoprene foam (1 cm thick) and utilized the subject’s own body weight using a standard cadence. One study used a commercial roller massage bar which was administered by the researchers using an established pressure and standard cadence. The intervention period for all studies ranged from 10 to 20 minutes.

**Foam Roller**

Macdonald et al measured the effects of foam rolling as a recovery tool after exercise induced muscle damage. The authors randomized 20 male subjects to an experimental (foam roll) or control group. All subjects went through the same protocol which included an exercise induced muscle damage program consisting of 10 sets of 10 repetitions of the back squats (two minutes of rest between sets) at 60% of the subjects one repetition maximum (RM) and four post-test data collection periods (post 0, post 24, post 48, post 72 hours). At each post-test period, the experimental group used the foam roll for a 20 minute session. The subject’s pain level was measured every 30 seconds and the amount of force placed on the foam roll was measured via a force plate under the foam roll. The foam roll intervention consisted of two 60 second bouts on the anterior, posterior, lateral, and medial thigh. The subjects used their own body weight with no standard cadence. The main outcome measures included the VAS for pain, pressure pain threshold of the quadriceps using an algometer, 30m sprint speed, standing broad jump, and the T-test. Foam rolling reduced subjects pain levels at all post treatment points (Cohen d range 0.59-0.84) and improvements were noted in performance measures including sprint speed (Cohen d range 0.68-0.77), broad jump (Cohen d range 0.48-0.87), and T-test scores (Cohen d range 0.54) in comparison with the control condition.

**Roller Massage**

Jay et al measure the effects of roller massage as a recovery tool after exercise induced muscle damage to the hamstrings. The authors randomized 22 healthy untrained males into an experimental and control group. All subjects went through the same DOMS protocol, which included 10 sets or 10 repetitions of stiff-legged deadlifts using a kettlebell, with a 30 second rest between sets. The roller massage intervention included one session of 10 minutes of massage in the sagittal plane to the hamstrings using “mild pressure” at a cadence of 1-2 seconds per stroke by the examiner. The main outcome measures included the VAS for pain and pressure...
pain threshold measured by algometry. The sit and reach test was used as a secondary outcome measure. The outcomes were measured immediately post-test, and 10, 30, and 60 minutes thereafter. The roller massage group demonstrated significantly (p<0.0001) decreased pain 10 minutes and increased (p=0.0007) pressure pain thresholds up to 30 minutes post intervention. However, there were no statistically significant differences when compared to the control group at 60 minutes post-test. There was no significant difference (p=0.18) in ROM between groups.20

MUSCLE PERFORMANCE
Three studies4,18,19 qualified for this part of the analysis that measured the effects of self-myofascial release prior to muscular performance testing using a standard size high density commercial foam roll19, standard commercial foam roll18, and a commercial roller massager.19 The intervention for two studies4,18 began with a dynamic warm-up consisting of a series of lower body movements prior to the foam rolling intervention that lasted for one session of 30 seconds on the each of the following regions: lumbopelvis and all hip regions (anterior, posterior, lateral, and medial). The subjects used their own body weight with no standard cadence.4,18 One study19 used a combined five minute warm-up on a bike with the roller massager intervention which lasted for a period of one session for two minutes on the hamstrings.

Healey et al4 measured the effects of foam rolling on muscle performance when performed prior to activity. The authors randomized 26 subjects who underwent two test conditions. The first condition included a standard dynamic warm-up followed by one session of SMR with the foam roll for 30 seconds on the following muscles: quadriceps, hamstrings, calves, latissimus dorsi, and the rhomboids. Subjects used their own weight and no standard cadence was used. The second condition included a dynamic warm-up followed by a front planking exercise for three minutes. Subjects were used as their own controls and the two test sessions were completed on two days. The main outcome measures included pre-test, post-test muscle soreness, fatigue, and perceived exertion (Soreness on Palpation Rating Scale, Overall Fatigue Scale, Overall Soreness Scale, and Borg CR-10) and performance of four athletic tests: isometric strength, vertical jump height, vertical jump for power, and the 5-10-5 shuttle run.4 No significant difference was seen between the foam rolling and planking conditions for all four athletic tests. There was significantly less (p<0.05, r=0.32) post treatment fatigue reported after foam rolling than the plank exercise.4

Peacock et al18 also examined the effects of foam rolling on muscle performance in addition to the sit and reach distance described in the prior section on joint ROM. The authors measured performance immediately after the intervention using several tests which included the vertical jump, broad jump, shuttle run, and bench press. There was no significant difference found between the mediolateral and anteroposterior axis foam rolling for all performance tests.18

Mikesky et al19 also measured the effects of a roller massager on muscle performance along with hip joint ROM which was described in the prior section. The authors measured vertical jump height, 20 yard dash, and isokinetic knee extension strength pretest and immediately post-test the intervention.19 The use of the roller massager showed no acute improvements in all performance outcome measures.19

DISCUSSION
The purpose of this systematic review was to appraise the current literature on the effects of SMR using a foam roll or roller massager. The authors sought to answer the following three questions regarding the effects of SMR on joint ROM, post-exercise muscle recovery and reduction of DOMS, and muscle performance.

Does self-myofascial release with a foam roll or roller-massager improve joint range of motion without effecting muscle performance?

The research suggests that both foam rolling and the roller massage may offer short-term benefits for increasing sit and reach scores and joint ROM at the hip, knee, and ankle without affecting muscle performance.5,7-9,18 These finding suggest that SMR using a foam roll for thirty seconds to one minute (2 to 5 sessions) or roller massager for five seconds to two minutes (2 to 5 sessions) may be beneficial for enhancing joint flexibility as a pre-exercise warmup and cool down due to its short-term ben-
benefits. Also, that SMR may have better effects when combined with static stretching after exercise. It has been postulated that ROM changes may be due to the altered viscoelastic and thixotropic property (gel-like) of the fascia, increases in intramuscular temperature and blood flow due to friction of the foam roll, alterations in muscle-spindle length or stretch perception, and the foam roller mechanically breaking down scar tissue and remobilizing fascia back to a gel-like state.

After an intense bout of exercise, does self-myofascial release with a foam roller or roller-massager enhance post exercise muscle recovery and reduce DOMS?

The research suggests that foam rolling and roller massage after high intensity exercise does attenuate decrements in lower extremity muscle performance and reduces perceived pain in subjects with a post exercise intervention period ranging from 10 to 20 minutes. Continued foam rolling (20 minutes per day) over 3 days may further decrease a patient's pain level and using a roller massager for 10 minutes may reduce pain up to 30 minutes. Clinicians may want to consider prescribing a post-exercise SMR program for athletes who participate in high intensity exercise. It has been postulated that DOMS is primarily caused by changes in connective tissue properties and foam rolling or roller massage may have an influence on the damaged connective tissue rather than muscle tissue. This may explain the reduction in perceived pain with no apparent loss of muscle performance. Another postulated cause of enhanced recovery is that SMR increases blood flow thus enhances blood lactate removal, edema reduction, and oxygen delivery to the muscle.

Does self-myofascial release with a foam roll or roller-massager prior to activity affect muscle performance?

The research suggests that short bouts of foam rolling (1 session for 30 seconds) or roller massage (1 session for 2 minutes) to the lower extremity prior to activity does not enhance or negatively affect muscle performance but may change the perception of fatigue. It's important to note that all SMR interventions were preceded with a dynamic-warm-up focusing on the lower body. Perhaps the foam roller or roller massagers' influence on connective tissue rather than muscle tissue may explain the altered perception of pain without change in performance. The effects of foam rolling or roller massage for longer time periods has not been studied which needs to be considered for clinical practice.

Clinical Application

When considering the results of these studies for clinical practice four key points must be noted. First, the research measuring the effects of SMR on joint ROM, post-exercise muscle recovery and reduction of DOMS, and muscle performance is still emerging. There is diversity among study protocols with different outcome measures and intervention parameters (e.g. treatment time, cadence, and pressure). Second, the types of foam and massage rollers used in the studies varied from commercial to custom made to mechanical devices attached to the rollers. It appears that higher density tools may have a stronger effect than softer density. Curran et al found that the higher density foam rolls produced more pressure to the target tissues during rolling than the typical commercial foam roll suggesting a potential benefit. Third, all studies found only short-term benefits with changes dissipating as post-test time went on. The long-term efficacy of these interventions is still unknown. Fourth, the physiological mechanisms responsible for the reported findings in these studies are still unknown.

Limitations

It should be acknowledged that SMR using a foam roll or roller massager is an area of emerging research that has not reached its peak and this analysis is limited by the chosen specific questions and search criteria. The main limitations among qualifying studies were the small sample sizes, varied methods, and outcome measures which makes it difficult for a direct comparison and developing a consensus of the optimal program.

Conclusion

The results of this systematic review indicate that SMR using either foam rolling or roller massage may have short-term effects of increasing joint ROM without decreasing muscle performance. Foam rolling and roller massage may also attenuate decrements in
muscle performance and reduce perceived pain after an intense bout of exercise. Short bouts of foam rolling or roller massage prior to physical activity have no negative affect on muscle performance. However, due to the heterogeneity of methods among studies, there currently is no consensus on the optimal SMR intervention (treatment time, pressure, and cadence) using these tools. The current literature consists of randomized controlled trials (PEDRO score of 6 or greater), which provide good evidence, but there is currently not enough high quality evidence to draw any firm conclusions. Future research should focus on replication of methods and the utilization of larger sample sizes. The existing literature does provide some evidence for utility of methods in clinical practice but the limitations should be considered prior to integrating such methods.

REFERENCES


### Appendix 1. Description of qualified studies

<table>
<thead>
<tr>
<th>Author</th>
<th>Type of Study</th>
<th>Subjects</th>
<th>Device</th>
<th>Target Region</th>
<th>Outcome Measures</th>
<th>SMR Intervention</th>
</tr>
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<tbody>
<tr>
<td>Bashill et al</td>
<td>RCT</td>
<td>N=31 (12M,19F)</td>
<td>Foam roll</td>
<td>Anterior Thigh</td>
<td>Hip Extension ROM in Lunge</td>
<td>Type: Foam roll</td>
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<td>Control (N=15)</td>
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<td>RCT</td>
<td>N = 40 M Stretching (N=10)</td>
<td>Foam Roll</td>
<td>Posterior Thigh</td>
<td>Hip Flexion ROM</td>
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<td>Stretch and FR. (N=10)</td>
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<td></td>
<td>Session: 3 sessions</td>
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<td>Peacock et al</td>
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<td>N = 16 M Within subject design</td>
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<td>Lumbo-pelvis gluteal muscles, hamstrings, calf region, quadriceps and pectoral</td>
<td>Sit-and-Reach (ROM)</td>
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<td></td>
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<td></td>
<td>Vertical Jump Broad Jump Shuttle Run Bench Press</td>
<td>Session: 1 (per muscle group)</td>
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<td>RCT</td>
<td>N = 11 M</td>
<td>Foam roll</td>
<td>Quadriceps</td>
<td>Knee flexion ROM MVC EMG</td>
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<td>Session: 2 sessions</td>
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<tr>
<td>Skarbot et al</td>
<td>RCT</td>
<td>N=11 (6M, 5F)</td>
<td>Foam roll</td>
<td>Ankle</td>
<td>Ankle ROM</td>
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<td>Session: 5 session</td>
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<tr>
<td>Holopainen et al</td>
<td>RCT</td>
<td>N=14 (12M, 2F)</td>
<td>Roller massage</td>
<td>Ankle</td>
<td>Dorsiflexion ROM MVC EMG Balance</td>
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<td>Session: 3 sessions</td>
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<td>Bradbury et al</td>
<td>RCT</td>
<td>N = 10M</td>
<td>Roller massage machine</td>
<td>Knee</td>
<td>Knee flexion ROM VAS MVC EMG</td>
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<td></td>
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<td></td>
<td>Session: 5 sets of each</td>
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<td>Miloszky et al</td>
<td>RCT</td>
<td>N=30 (7M, 23F)</td>
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<td>Session: 1 session</td>
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<td>Sullivan et al</td>
<td>RCT</td>
<td>N = 17 (7 M, 10 F)</td>
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<td>Hamstrings</td>
<td>Sit and reach EMG MVC (Isometric Force)</td>
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<td>Session: 2 (5 seconds), 2 (10 seconds)</td>
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<tr>
<td>Grieve et al</td>
<td>RCT</td>
<td>N = 24 (8 M, 16 F)</td>
<td>Tennis Ball</td>
<td>Plantar foot</td>
<td>Sit and reach</td>
<td>Type: Tennis ball</td>
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<td>Session: 1</td>
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<td>MacDonald et al (2013)</td>
<td>RCT</td>
<td>N = 20M (Control= 10 Experimental=10)</td>
<td>Foam roll</td>
<td>anterior, posterior, lateral, and medial thigh</td>
<td>Knee ROM NPRS MVC EMG</td>
<td>Type: Foam roll</td>
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<td>Session: 1 (post DOMS protocol)</td>
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<tr>
<td>Peerecy et al</td>
<td>RCT</td>
<td>N = 8 M</td>
<td>Foam roll</td>
<td>anterior, posterior, lateral, and medial thigh</td>
<td>Pressure pain threshold 30-m sprint Standing broad-jump T-test</td>
<td>Type: Foam roll</td>
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<td>Jay et al</td>
<td>RCT</td>
<td>N = 22 M</td>
<td>Roller massage</td>
<td>Hamstrings</td>
<td>VAS Pressure pain threshold Sit and reach</td>
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<td>Healey et al</td>
<td>RCT</td>
<td>N = 26 (13 M, 13 F)</td>
<td>Foam roll</td>
<td>Quadriceps, hamstrings, calves, latissimus dorsi, rhomboids</td>
<td>Patellar Rating Scale Overall Soreness Scale Borg CR-10 Isokinetic strength Vertical jump height 2-10x1 shuttle run</td>
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<td>Session: 1 session</td>
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ROM: Range of motion
MVC: Maximum voluntary contraction
NPRS: Numeric Pain Rating Scale
EMG: Electromyography
VAS: Visual analog scale
ABSTRACT

Introduction: The initial rapid eccentric contraction of a stretch-shortening cycle (SSC) activity is typically reported to accentuate the subsequent concentric jump performance. Some researchers have rationalized that adding elastic resistance (ER) to explosive type activities (e.g. countermovement jumps and drop jumps) would increase excitatory stretch reflex activity and mechanical recoil characteristics of the musculotendinous tissues. The purpose of this meta-analysis was to examine the available literature on jumping movements augmented with ER and to provide a quantitative summary on the effectiveness of this technique for enhancing acute eccentric and concentric jumping performance.

Methods: In a random-effects model, the Hedges’s g effect size (ES) was used to calculate the biased corrected standardized mean difference between the augmented and similar non-augmented jumps.

Results: The results demonstrated that augmented jumps provided a greater eccentric loading compared to free jumps (Hedges’s g ES = 0.237, p = 0.028). However the concentric performance was significantly impaired, particularly if the downward elastic force was used during concentric phase as well (ES = -2.440, p < 0.001). Interestingly, no performance decrement was observed in those studies, which released the bands at the beginning of the concentric phase (ES = 0.397, p = 0.429).

Discussion: The authors postulated that the excessive eccentric loading might trigger reflex inhibition, alter the muscle stiffness, increase downward hip displacement and dissipate mechanical recoil properties. These results suggest that the release of elastic force at the beginning of the concentric phase seems to be a critical point to avoid impairment of acute concentric performance in augmented jumps.

Level of Evidence: 2a

Keywords: Elastic tubing, exercise bands, surgical tubing, stretch-shortening cycle, strength, power
INTRODUCTION
Elastic resistance (ER) devices including elastic bands, rubber bands, and tubing (surgical tubing, sport cords and bungy cords) are portable, low cost, and easy maintenance training devices, which have been utilized alone or in conjunction with other training devices to provide resistance in strength and power training programs.1-6 The ER provides both mechanical advantages and disadvantages when compared to traditional free weight and machine resistance devices.7-12 Some investigators postulated that due to inadequate external force, ER may not elicit maximal muscle tension in the active muscles.13 However, the proponents of ER recommended that by employing a simple adjustment in the initial length of the elastic material14,15 and using additional units of elastic bands in parallel17,16 an adequate increase in elastic force will be provided, which can lead the active muscles to develop tension across the entire concentric phase.17,18

In order to optimize the magnitude of external load provided by ER, some investigators have examined the combination of resistance generated by fixed loads (e.g. barbell) and the ER.19,20 Using this technique has also been postulated to overcome the mechanical disadvantage of free weights exercises (i.e. decreased resistive force once inertia is overcome and momentum increases).20-24 In a comprehensive meta-analysis, Soria-Gila and colleagues25 have examined the research-based effect of ER plus free-weight loaded training on muscular strength gains during bench press and squat exercises and suggested that this could be an effective technique to improve maximal strength (i.e. 1 repetition maximum) both in athletes and untrained subjects.

The present meta-analysis is focused on the application of ER during explosive exercises such as counter-movement jump (CMJ) and drop jump (DJ)26-28. The augmented body mass and gravitational acceleration induced by ER during the eccentric phase of jumping movements is thought to amplify the stretch-shortening cycle (SSC) mechanism (a detailed discussion of the SSC is beyond the focus of the present paper, for more information the reader is directed to references29,30). Investigators have speculated that during augmented jumps, the active muscles experience a greater pre-stretch state during the eccentric phase, which can generate and store elastic energy in the contractile components of musculotendinous structures and enhance the myoelectric potentiation and the stretch reflex mechanisms.29,31-33. The release of this stored elastic energy during the concentric phase may result in improvement of subsequent force and power generating capability during jumping, running and other SSC type activities.26,31,34-35 Although there have been a number of studies investigating primarily the acute kinetic and kinematic variables during augmented jumps with ER,26-28,35,36 there has not been a systematic review of the literature conducted which synthesizes previous data and provides summative information about the effectiveness of augmented jumps with ER on acute eccentric and concentric jumping performance. Therefore, the purpose of this meta-analysis was to examine the available literature on jumping movements augmented with ER and to provide a quantitative summary on the effectiveness of this technique for enhancing acute eccentric and concentric jumping performance.

METHODS
Search strategy and inclusion/exclusion criteria
This review of the literature included studies that examined the effect of using additional ER during CMJ or DJ movements on acute eccentric and concentric jumping performance. A literature search was performed by the three authors separately and independently using MEDLINE, SPORT Discus, ScienceDirect, Web of Science and Google Scholar databases. The topic was searched using a combination of keywords including: elastic tubing, elastic bands, exercise cord, Thera-Band, elastic resistance training, elastic band exercises, bungy exercise, augmented resistance training, accentuated jump, counter-movement jump, drop jump, augmented elastic training, elastic band exercises, bungy exercise, augmented resistance training, accentuated jump, counter-movement jump, drop jump, augmented elastic training, loaded resistance training, and loaded elastic exercise. All references from the selected articles were also manually crosschecked by the authors to identify relevant studies that might have been missed in the search and to eliminate duplicates.

Inclusion Criteria (study selection)
Studies examining the acute effects of jumping movements augmented with ER on concentric and eccentric jumping performance were included in the review...
if they fulfilled the following selection criteria: 1) the study investigated the effect of using ER during augmented CMJ or DJ on eccentric or concentric jumping performance, 2) the study quantified and compared at least one of the following measurements between an augmented jump with ER and a free (non-augmented) jump: eccentric and/or concentric peak ground reaction force (GRF), mean GRF, peak impulse, mean impulse, peak power, or mean power. Since a faster peak eccentric loading (lengthening) may amplify the SCC mechanism and enhance take off velocity and performance, studies which reported peak velocity were also included to the meta-analysis, 3) the study used healthy, active human subjects, 4) the study was written in English and published between 1987 – 2015 and 5) the study was published in a peer-reviewed journal (abstracts and unpublished studies were excluded). Studies were excluded if 1) elastic resistance was a part of a mechanical training device (e.g. Vertimax) and 2) other movements except CMJ and DJ were studied.

Meta-analytic statistical comparisons were made with the Comprehensive Meta-analysis software (BioStat Inc. Englewood, New Jersey, USA). A random-effects model was used to examine the grouped data extracted from the different studies. The Hedges’s g effect size (ES) was used to calculate the biased corrected standardized mean difference between the ER augmented and similar non-augmented jumps. ES calculations were conducted to evaluate the magnitude of the difference according to the criterion of 0.80 large; 0.50 medium and 0.20 small. The Hedges’s g ES was calculated based on the mean and standard deviation of the two modes of jumps using one of the following variables: peak GRF, mean GRF, peak velocity, peak impulse, mean impulse, peak power, mean power. In order to address the influence of using ER on eccentric and concentric phases of jumping performance, separate analyses were performed the two phases. The Hedges’s g ES and 95% CIs for the outcomes of each study were illustrated in a forest plots.

The examination of inter-study heterogeneity was based on computing the weighted sum of squares [Q value] of the effect sizes included with the meta-analysis. The difference of every effect size from the mean effect size was calculated and squared. Then, the sum the weighted squares was computed. The I-squared (I²) and the p-values (p < 0.05) were also considered to determine if the dispersion observed in the forest plot reflects difference in the true effect sizes or random sampling error.

RESULTS

From 41 full text articles assessed for eligibility, five articles met the inclusion criteria for the meta-analysis. Four studies employed the recoil force of ER during entire eccentric phase of jumps (Figure 1).

For CMJ, the eccentric phase included from the initiation of lowering the center of mass to the lowest displacement of the hip while for DJs, the eccentric
phase encompassed the entire landing phase to the lowest displacement of the hip. Therefore one meta-analysis was performed to measure the effect of ER on the eccentric jumping performance. However, in two of the five included studies that quantified concentric performance, the elastic bands were released during the concentric phase of the movement, once the subject reached full flexion of hip and knee during both types of jumps. Since it had been hypothesised that using this technique could eliminate the restriction of the ER external load and facilitate the concentric power production, separate analyses were conducted to quantify and compare the concentric performance between the studies whose methods involved release of the bands and those whose methods did not. In addition, since various resistance of ER might provide different acute effects on eccentric and concentric performance, separate data points from Aboodarda et al (who used ER equivalent to 20% and 30% of bodyweight) and Markovic and Jaric’ (who used ER equivalent to 15% and 30% of bodyweight) are presented in the analysis (Table 1).

### Eccentric jumping performance

Table 2 displays data from the four studies that met the inclusion criteria for the meta-analysis. Six effect sizes (from the four studies) were included to the analysis. Eccentric peak power, peak ground reaction force, peak impulse and peak velocity were the variables which were included to show the effect of using ER on eccentric jumping performance. The overall effect obtained from 78 males, all trained with a minimum of six months of strength-training

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**Table 1. Details of the studies included in the meta-analysis.** Acronyms: CMJ: countermovement jump, ACMJ: augmented CMJ, FCMJ: free CMJ, DJ: drop jump, ADJ: augmented DJ, FDJ: free DJ, M: males, F: females, BW: body weight, RT: resistance trained, ER: elastic resistance, RRM: randomized repeated measure, PP: peak power, PV: peak velocity, VGRF: vertical ground reaction force, RFD: rate of force development. * indicates that in these studies the elastic bands were released at the beginning of concentric phase.

<table>
<thead>
<tr>
<th>Study Name</th>
<th>Study type</th>
<th>N (M/F)</th>
<th>Age (±SD) (years)</th>
<th>Trained level</th>
<th>Intervention</th>
<th>Measurements used in the Meta-analysis</th>
<th>Other Measurements of the study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aboodarda et al</td>
<td>RRM</td>
<td>15 M</td>
<td>22.6 ± 5.3</td>
<td>Trained with RT experience &gt; 1 year</td>
<td>FCMJ (control) ACMJ 20% BW ACMJ 30% BW</td>
<td>Eccentric PP Concentric PP</td>
<td>VGRF, Impulse, Jump height</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aboodarda et al</td>
<td>RRM</td>
<td>15 M</td>
<td>24.7 ± 5.7</td>
<td>Trained with RT experience &gt; 5 years</td>
<td>FDJ ADJ 20%BW ADJ 30% BW</td>
<td>Eccentric impulse Concentric impulse</td>
<td>RFD Take of velocity Duration Jump height</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argus et al</td>
<td>RRM</td>
<td>8 M</td>
<td>27.5 ± 5.5</td>
<td>Trained with RT experience &gt; 6 month</td>
<td>FCMJ ACMJ</td>
<td>Eccentric GRF Concentric PP</td>
<td>Peak velocity Peak force</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cronin et al</td>
<td>RRM</td>
<td>10 M</td>
<td>24.2 ± 2.3</td>
<td>Trained with RT experience &gt; 3 years</td>
<td>CMJ on isoinertial (ISO) supine squat machine</td>
<td>Eccentric PV Concentric PV</td>
<td>Mean velocity Time to peak Velocity EMG</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Markovic &amp; Jaric</td>
<td>RRM</td>
<td>15 M</td>
<td>23.5 ± 3.4</td>
<td>Trained with RT experience &gt; 1 year</td>
<td>FCMJ ACMJ 15% BW ACMJ 30% BW</td>
<td>Concentric PP</td>
<td>Concentric Mean power Momentum PV Duration</td>
</tr>
</tbody>
</table>

RRM= repeated measures , M= males, RT= resistance training, FCMJ= free countermovement jump, ACMJ= augmented countermovement jump, FDJ= free drop jump, ADJ= augmented drop jump, ER= elastic resistance, PP= peak power, GRF= ground reaction force, PV= peak velocity, VGRF= vertical ground reaction force, EMG= electromyography
experience, demonstrated that augmented jumps provided greater eccentric loading compared to free jumps (Hedges’s g ES = 0.237, CI: 0.025 to 0.448, \( p = 0.028 \)) (Table 2). The data presented in Figure 2 showed large CIs for each estimate, which indicate a poor precision for each study (i.e. large intra-study variance). However there was very small inter-study variation between different estimates (Q-value = 0.738, \( p = 0.981 \), \( I^2 < 0.001 \)), which suggest that there was no heterogeneity between the observed effect sizes. In other words, the true effect sizes between studies were almost identical and 98% of the inter-study variation was due to sampling error that could be attributed to variables such as smaller sample size, biased sampling, targeting an available population and other factors.

**Concentric jumping performance**

Table 3 presents data from the five studies met the inclusion criteria for the meta-analysis. Eight ESs (from the five studies) were included in the analysis of concentric peak power,\(^{27,28,35}\) peak impulse\(^{36}\) and peak velocity\(^{26}\) variables. The overall effect obtained from 108 males, all trained with a minimum of six months of strength-training experience, demonstrated that augmented jumps with ER impaired concentric performance compared to free jumps (Hedges’s g ES = -0.776, CI: -1.528 to -0.023, \( p = 0.043 \)) (Table 3). The data presented in Figure 3 exhibited a high inter-study dispersion between different estimates, which suggests that there was a very high heterogeneity between the effect sizes of the included studies (Q-value = 79.088, \( p < 0.001 \), \( I^2 = 91.149 \)).

<table>
<thead>
<tr>
<th>Study Name</th>
<th>Hedges’s g</th>
<th>Standard error</th>
<th>Variance</th>
<th>Lower limit</th>
<th>Upper limit</th>
<th>Z-Value</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aboodarda(^{28}), 20% BW, CMJ</td>
<td>0.209</td>
<td>0.247</td>
<td>0.061</td>
<td>-0.275</td>
<td>0.693</td>
<td>0.845</td>
<td>0.398</td>
</tr>
<tr>
<td>Aboodarda(^{28}), 30%BW, CMJ</td>
<td>0.346</td>
<td>0.252</td>
<td>0.064</td>
<td>-0.148</td>
<td>0.840</td>
<td>1.372</td>
<td>0.170</td>
</tr>
<tr>
<td>Aboodarda(^{36}), 20%BW, DJ</td>
<td>0.129</td>
<td>0.245</td>
<td>0.060</td>
<td>-0.352</td>
<td>0.609</td>
<td>0.525</td>
<td>0.599</td>
</tr>
<tr>
<td>Aboodarda(^{36}), 30%BW, DJ</td>
<td>0.343</td>
<td>0.252</td>
<td>0.064</td>
<td>-0.151</td>
<td>0.837</td>
<td>1.362</td>
<td>0.173</td>
</tr>
<tr>
<td>Cronin(^{26}), 20-30 kg, CMJ</td>
<td>0.120</td>
<td>0.290</td>
<td>0.084</td>
<td>-0.449</td>
<td>0.690</td>
<td>0.415</td>
<td>0.678</td>
</tr>
<tr>
<td>Argus(^{27}), 20%BW, CMJ</td>
<td>0.260</td>
<td>0.321</td>
<td>0.103</td>
<td>-0.369</td>
<td>0.889</td>
<td>0.810</td>
<td>0.418</td>
</tr>
<tr>
<td>Overall</td>
<td>0.237</td>
<td>0.108</td>
<td>0.012</td>
<td>0.025</td>
<td>0.448</td>
<td>2.195</td>
<td>0.028</td>
</tr>
</tbody>
</table>

BW= body weight, CMJ= countermovement jump, DJ= drop jump

![Figure 2. Forest plot presenting the results of the Hedges’s g ES and 95% CIs for the eccentric performance. Six effect sizes were included in the analysis. Eccentric peak power,\(^{27,28}\) peak impulse\(^{36}\) and peak velocity\(^{26}\) were the variables which included in the analysis. The augmented jumps with ER provided a greater eccentric loading compared to free jumps (Hedges’s g ES = 0.237, CI: 0.025 to 0.448, \( p = 0.028 \)). The horizontal line demonstrates the lower and the upper limits of the effect at a 95% CI. The filled square (■) indicates the ES for each study. The filled diamond (◇) indicates the pooled effect size.](image-url)
### Table 3. Results of the four studies included in the meta-analysis measuring concentric performance

<table>
<thead>
<tr>
<th>Study Name</th>
<th>Groups by</th>
<th>Hedges’s $g$</th>
<th>Standard error</th>
<th>Variance</th>
<th>Lower limit</th>
<th>Upper limit</th>
<th>Z-Value</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argus*, 20% BW, CMJ</td>
<td>With bands</td>
<td>-1.928</td>
<td>0.575</td>
<td>0.331</td>
<td>-3.056</td>
<td>-0.800</td>
<td>-3.351</td>
<td>0.001</td>
</tr>
<tr>
<td>Cronin*, 20-30 kg, CMJ</td>
<td>With bands</td>
<td>0.035</td>
<td>0.289</td>
<td>0.084</td>
<td>-0.532</td>
<td>0.602</td>
<td>0.122</td>
<td>0.903</td>
</tr>
<tr>
<td>Markovic and Jeric**, 15% BW, CMJ</td>
<td>With bands</td>
<td>-4.255</td>
<td>0.814</td>
<td>0.663</td>
<td>-5.850</td>
<td>-2.659</td>
<td>-5.225</td>
<td>0.000</td>
</tr>
<tr>
<td>Markovic and Jeric**, 30% BW, CMJ</td>
<td>With bands</td>
<td>-6.556</td>
<td>1.222</td>
<td>1.492</td>
<td>-8.950</td>
<td>-4.161</td>
<td>-5.367</td>
<td>0.000</td>
</tr>
<tr>
<td>Subgroup pooled data</td>
<td></td>
<td>-2.440</td>
<td>0.597</td>
<td>0.357</td>
<td>-3.611</td>
<td>-1.270</td>
<td>-4.085</td>
<td>0.000</td>
</tr>
<tr>
<td>Aboodarda*, 20% BW, CMJ</td>
<td>Without bands</td>
<td>0.059</td>
<td>0.244</td>
<td>0.060</td>
<td>-0.420</td>
<td>0.538</td>
<td>0.241</td>
<td>0.809</td>
</tr>
<tr>
<td>Aboodarda*, 30% BW, CMJ</td>
<td>Without bands</td>
<td>0.493</td>
<td>0.260</td>
<td>0.068</td>
<td>-0.017</td>
<td>1.003</td>
<td>1.894</td>
<td>0.058</td>
</tr>
<tr>
<td>Aboodarda**, 20% BW, DJ</td>
<td>Without bands</td>
<td>0.285</td>
<td>0.250</td>
<td>0.062</td>
<td>-0.204</td>
<td>0.774</td>
<td>1.142</td>
<td>0.254</td>
</tr>
<tr>
<td>Aboodarda**, 30% BW, DJ</td>
<td>Without bands</td>
<td>0.758</td>
<td>0.281</td>
<td>0.079</td>
<td>0.208</td>
<td>1.308</td>
<td>2.701</td>
<td>0.007</td>
</tr>
<tr>
<td>Subgroup pooled data</td>
<td></td>
<td>0.397</td>
<td>0.501</td>
<td>0.251</td>
<td>-0.586</td>
<td>1.379</td>
<td>0.792</td>
<td>0.429</td>
</tr>
<tr>
<td>Overall</td>
<td></td>
<td>-0.776</td>
<td>0.384</td>
<td>0.147</td>
<td>-1.528</td>
<td>-0.023</td>
<td>-2.020</td>
<td>0.043</td>
</tr>
</tbody>
</table>

BW = body weight, CMJ = countermovement jump, DJ = drop jump

---

**Figure 3.** Forest plot presenting the results of the Hedges’s $g$ ES and 95% CIs for the concentric performance. Eight effect sizes were included in the analysis. Concentric peak power,$^{27,28,35}$ peak impulse$^{26}$ and peak velocity$^{26}$ were the variables which included in the analysis. The overall effect demonstrated that augmented jumps with ER impaired concentric performance compared to free jumps (Hedges’s $g$ ES = -0.776, CI: -1.528 to -0.023, p = 0.043). There was a significant impairment for those studies which the bands were kept attached (Hedges’s $g$ ES = -2.440, CI: -3.611 to -1.270, p < 0.001); however, no performance decrement was observed for those studies which the bands were released (Hedges’s $g$ ES = 0.397, CI: -0.586 to 1.379, p = 0.429). The horizontal line demonstrates the lower and the upper limits of the effect at a 95% CI. The filled square ($■$) indicates the ES for each study. The grey diamonds ($♦$) indicates the pooled effect size for the two subgroup studies (with bands vs. without bands). The black diamond ($♣$) indicates the pooled effect size.
Further analysis of the two subgroups of studies in which elastic bands were kept attached during concentric phase of jump and those during which the bands were released at the beginning of concentric phase produced distinctive results. Interestingly, there was a significant impairment in the concentric performance for those studies during which the bands were kept attached (Hedges’s g ES= -2.440, CI: -3.611 to -1.270, \( p <0.001 \)); however, no performance decrement was observed for those studies during which the bands were released (Hedges’s g ES= 0.397, CI: -0.586 to 1.379, \( p = 0.429 \)). Furthermore, there was a large heterogeneity between the effect sizes of those studies, which did not release the bands (Q-value = 52.022, \( p <0.001 \), \( I^2 = 94.233 \)) and moderate heterogeneity was evident between studies in which the bands were released (Q-value = 3.870, \( p = 0.276 \), \( I^2 = 22.479 \)).

**DISCUSSION**

The most important findings of the current meta-analysis were that the addition of ER to the CMJs and DJs could significantly increase the eccentric loading, as measured by eccentric peak power, peak impulse and peak velocity. However, this greater eccentric loading could lead to decreases in concentric performance if the bands were not released at the beginning of concentric phase. In light of this observation, releasing the force exerted by elastic resistance, at the beginning of concentric phase, seems to be critical to avoiding impairment of acute concentric performance.

The sequencing of fast eccentric (stretching) and concentric (shortening) actions has been shown to enhance jumping performance.\(^{29,31-33}\) The rationale for augmenting explosive exercises such as CMJ and DJ with ER is to take advantage of the physiological components associated with the SSC mechanism in order to increase concentric power output.\(^{28,32,34,40}\) In addition to the SSC reflexive component,\(^{41,42}\) the visco-elastic characteristic of the musculotendinous tissues as well as the fiber cross-bridges may store elastic energy during an initial rapidly performed eccentric movement after which release of the stored energy may improve concentric performance.\(^{29,43,44}\)

The six effect sizes (from the four studies) used to examine the effect of augmented jumps on eccentric responses indicated that the additional ER improved eccentric loading evident in eccentric peak power, GRF, impulse and velocity. Although this finding was in line with the authors’ expectation, only a small effect size was observed for this improvement (ES= 0.237), which could be attributed to 1) the small magnitude of elastic load utilized during augmented jumps (15 to 30% bodyweight), 2) the large intra-study variance observed for the included ESs (Figure 2). Nonetheless, a small inter-study variance was observed for the overall ES (variance = 0.012), which indicates that the increased eccentric loading was a consistent phenomenon between the six included studies.

However, contrary to the hypothesis that a faster and greater eccentric loading can improve concentric jumping output, the results of this meta-analysis indicate that the concentric performance was diminished or impaired during augmented jumps compared to the control condition. More specifically, the results of this meta-analysis demonstrated a large negative effect size (ES= -2.440) for the acute concentric performance measured by concentric peak power, impulse, and velocity for those studies in which equal magnitude of ER was applied during both concentric and eccentric phases.\(^{27,35}\) However, interestingly, no impairment was observed in concentric performance (ES = 0.397) when the elastic bands were released at the beginning of concentric phase.\(^{28,36}\) In other words, as presented in Figure 3, the large negative ESs from the studies by Markovic and Jeric\(^{35}\) and Argus et al\(^{27}\) studies contributed significantly to shift the overall effect toward a negative value. The study by Cronin et al\(^{26}\) seems to be an exception to this trend because although they used downward tensile load during both eccentric and concentric phases of CMJs, they did not observe any impairment in concentric peak velocity. Although the actual reason for the disparity between these findings is unclear, there are a number factors that could diminish the beneficial effects of adding elastic resistance to explosive exercises such as CMJ and DJ.

Whereas elastic resistance can increase eccentric velocity and VGRF possibly facilitating reflexive and mechanical SSC responses, the additional load during the concentric phase could hinder take-off velocities. In line with this explanation, the two studies...
which demonstrated the highest impairment in concentric jumping performance\textsuperscript{27,35} reported significant decreases in peak concentric velocity when compared to no additional ER. The concept of specificity of training velocity\textsuperscript{45,46} indicates that the training velocity should match as closely as possible to the competition or event velocity, thus, a decreased concentric velocity might adversely affect training responses. In order to address this difficulty, Aboodarda and colleagues\textsuperscript{28} modified the augmented CMJ with ER by releasing the elastic bands immediately prior to the concentric phase. They demonstrated that this technique could enhance jump height performance and takeoff velocity as measured with a force plate and motion analysis system. However, the release of the elastic bands immediately before the concentric phase of DJs did not change the takeoff velocity and concentric impulse compared to the control condition.\textsuperscript{36} Unfortunately, few studies have employed the release of ER method to enhance jumping performance; therefore, further research is required to investigate effectiveness of using ER during different modalities of augmented jumps.

Other potential explanations for failure in transfer of greater eccentric loading to concentric jumping performance could be: 1) the timing and magnitude of muscle preactivation before the start of the eccentric phase, 2) the prolonged length of eccentric phase and 3) the protracted amortization period between eccentric and concentric phase.\textsuperscript{47} In order to achieve greatest possible jump height, it is important to perform the eccentric phase of jump with an adequate muscle pre-activation in order to generate an optimal level of leg stiffness.\textsuperscript{48,49} Athletes develop an optimal strategy to pre-activate muscles for different type of activities. This anticipatory strategy has been demonstrated with DJs,\textsuperscript{50,51} hopping,\textsuperscript{31} jumping drills,\textsuperscript{52} and maximum sprinting.\textsuperscript{53} The increased eccentric loading during augmented jumps may disrupt the pre-activation strategy and provide a dampening effect on muscle stiffness. Aboodarda et al\textsuperscript{36} showed no change or slightly shorter eccentric durations of DJs in response to the addition of elastic resistance. Subjects demonstrated earlier onset of EMG activity for all studied muscle groups during loaded DJs suggesting an increased leg stiffness response to additional eccentric loading by ER. The purpose of this anticipatory modulation of muscle activation patterns is to decelerate and eventually terminate the joint rotations and to provide adequate muscle tension for absorption of the impact force.\textsuperscript{54,55} The increased elastic resistance load may have caused Aboodarda’s subjects to focus more on impact absorption and therefore less on explosiveness during the concentric phase. More specifically, excessive eccentric loading may necessitate a greater amount of joint excursion in order to absorb the higher VGRF which can elongate the delay between the eccentric and concentric contraction phases and result in dissipation of the stored elastic in the form of heat.\textsuperscript{56}

Excessive eccentric loading might also increase Golgi tendon inhibitory Ib afferent responses minimizing muscle activation benefits associated with SSC mechanism.\textsuperscript{57-59} Fetz et al\textsuperscript{60} reported that in addition to possible Ib afferent inhibition, that the inhibition of motoneurons may also be evoked from homonymous and synergistic Ia muscle spindle afferents. Aboodarda et al\textsuperscript{36} contradicted the hypothesis that augmented DJs would increase muscle spindle stretch reflex activity leading to increased motoneuronal output\textsuperscript{30,58} with their report of no significant EMG differences between loaded and unloaded DJs during the concentric phase. Aboodarda’s findings were in line with those reported by Bobbert et al\textsuperscript{38} that did not exhibit higher EMG values for the knee extensors and plantar flexors despite larger knee and ankle moments in DJs with faster eccentric loading. These findings might be related to the population used in these three studies as it is possible that highly motivated and trained individuals are at or close to their maximum potential and thus there is minimal contribution from an already fully activated stretch reflex system.

The major limitation of this meta-analysis is the few comparable studies available. The low number of total subjects would also contribute to the high inter-study variability. Furthermore, instructions to participants regarding jump technique (particularly during landing phase) could have differed between studies leading to significant differences in concentric and eccentric performance. In addition, a variety of elastic materials were used in the included studies, which could have provided different resistance and loading patterns.

CONCLUSIONS
The results of this meta-analysis suggest that the addition of ER to the CMJs and DJs can signifi-
cantly increase the eccentric loading; however, greater eccentric loading may not be translated to an enhanced concentric performance. In particular, the concentric responses may considerably be impaired if the elastic bands are not released at the beginning of concentric phase. The authors postulated that the excessive eccentric loading might trigger reflex inhibition (Ia and Ib afferents), alter the anticipatory EMG responses affecting muscle stiffness, increase downward displacement of the hip and dissipate mechanical recoil properties. It’s worth noting that the current results should only be interpreted in the context of the acute effects on eccentric and concentric jumping performances. Therefore, the possible potential benefits of augmented jumps with ER as an effective technique for increasing eccentric loading and the long-term effects of ER for enhancing concentric performance needs to be studied.

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ABSTRACT

Background/Purpose: Identifying an athlete’s functional capacity is an important consideration in determining when to allow an athlete to return to competition following injury. Establishing normative data for lower extremity functional assessment is valuable for comparison when making decisions regarding the high school athlete returning to play after injury. Therefore, the purpose of this study was to compare functional performance and strength between American high school football players of both skilled and non-skilled positions.

Methods: Forty-nine high school football players (30 skilled; 19 non-skilled) completed a single-session of testing consisting of a Figure of 8 test (F-8), single-leg vertical jump (SLVJ), single-leg broad jump (SLBJ), and isokinetic knee strength assessment. Pearson correlation coefficients were used to determine the relationships between the results of functional testing and isokinetic strength measures. Paired t-tests were used to determine the differences in functional performance and isokinetic muscle strength between skilled and non-skilled athletes.

Results: Knee extension peak torque/body weight (BW) was moderately correlated ($p < .01$) with SLBJ ($r = .54-.61$), SLVJ ($r = .39-.48$), and F-8 run times ($r = -.50$) for all athletes. Similar relationships were observed between knee flexion peak torque/BW and SLBJ ($r = .48-.49$), SLVJ ($r = .28-.46$), and the F-8 run times ($r = .41-.52$) for all subjects. No differences were observed between groups when examining raw peak torque values for knee flexion and extension ($p > .05$), however, skilled players did demonstrate greater peak torque/BW ratios ($p < .05$) for both knee extension and knee flexion at 60 and 240 degrees/sec. Skilled players also displayed faster F-8 times (9.4 sec ± .3; $p < .01$) and greater SLBJ ($p < .05$) on both the dominant (81.0 in ± 9.3) and non-dominant (83.0 in ± 7.6) limbs ($p < .01$) when compared to non-skilled players.

Conclusions: Overall, skilled football players displayed greater peak torque/BW ratios and functional performance when compared to non-skilled players. Furthermore, isokinetic peak torque/BW appears to be related to functional performance. This relationship is affected by position, with skilled players showing a stronger association. Limb dominance did not influence these functional and strength metrics. It is recommended that clinicians and coaches consider the positional differences in strength and functional performance when managing patients and athletes.

Keywords: Football, functional assessment, isokinetic strength assessment

Level of Evidence: 4 – Cross-sectional Case Series
INTRODUCTION

Functional assessment of athletes has increased in recent years. With the high prevalence of knee injuries in high school athletes, identification of the functional level of an injured athlete is an important consideration in determining readiness for return to play. In addition to a basic physical exam and the time after surgery, functional testing and isokinetic assessment of muscle strength are often used to make the determination of when a patient is ready to return to sport.1 Knowing which functional tests most closely correlate with traditional isokinetic testing provides greater insight into achieving the most informed clinical judgments regarding patient functional status.

Given that quadriceps strength is an important factor in restoring proper biomechanics and reducing recurrence of injury, determining the magnitude of strength deficits that lead to abnormal mechanics is critical.2 In order to objectively measure an athlete’s lower extremity strength, isokinetic testing has been used to provide quantitative data on force production of the involved limb relative to both the uninvolved limb, and to normal values. Authors have specifically examined the peak torque of both the quadriceps and hamstrings, as compared to the uninvolved leg.2,3 The measure of peak torque has been used to develop criteria that should be met before allowing athletes to participate in sporting activities. Although isokinetic testing has been accepted as an important part of clearance for return to sport activity, strength measures alone fail to encompass all of the requirements necessary for functional movements and sport-specific activities.4

Similarly, self-reported questionnaires have been used to assess functional capacity and subjective performance in athletes. Although questionnaires are useful in assessing the history and other subjective information, they give little objective evidence of the functional status of an athlete.

Functional tests that are performed under clinical supervision provide data to objectively measure an athlete’s performance. A combined approach using both subjective and objective functional data has been recommended to determine an athlete’s ability to return to play.4 While both have been recommended, the reported relationships between functional and isokinetic strength testing have been conflicting in recent years. Specifically, several authors have reported no correlation between isokinetic peak torque and functional testing, while others have found strong positive correlations.1,3,5 Most of these studies examined ACL reconstructed knees and included various isokinetic testing protocols that ranged from speeds of 60 deg/sec to 450 deg/sec.8 Considering these conflicting results and varying methodologies, additional study is required to elucidate these relationships among healthy athletes. Therefore, the purpose of this study was to compare functional performance and isokinetic strength in healthy high school American football players of both skilled and non-skilled positions.

MATERIALS AND METHODS

Participants

Informed consent was obtained from each participant in this study. A sample of convenience including forty-nine healthy male high school football players (age 16.2 yrs ± 1.4) was recruited from ten different high schools to participate in this study (30 skilled and 19 non-skilled). Inclusion criteria for participation were: males, ages 15-19 and active participation in all team activities. The exclusion criterion for participation was a recent injury (within the prior three months) that prevented usual participation from any team activities. Players were grouped into skilled and non-skilled positions based on most common playing position. Skilled positions were defined as quarterbacks, running backs, receivers, and defensive backs, while non-skilled positions were considered lineman and linebackers.

Study Design

Using information described by Daniel et al,9 the authors developed a three part functional protocol for this cross-sectional study. Each subject participated in a single-session of functional and isokinetic strength testing that required approximately 20 minutes to complete. The functional assessment consisted of three tests: a single leg broad jump (SLBJ), a single leg vertical jump (SLVJ), and a 40-yard figure of 8 test (F-8).3 In addition to performing functional testing, players completed an isokinetic assessment at 60 and 240 degrees per second, bilaterally. Participants were also asked to determine limb dominance by denoting the primary leg used for jumping.
**Functional Assessment**

The SLBJ was performed as described by Daniel et al.\(^9\) with the athlete standing on one leg, jumping forward as far as possible while landing on the same leg. In order to constitute a valid jump, the athlete had to demonstrate control by maintaining balance after landing (no shifting or repositioning of the involved leg) for at least two seconds. Three measurements were taken, and the test was repeated on the opposite extremity. The SLVJ was performed by measuring the distance from the floor to the end of the player's extended hand on the wall. A measuring tape was affixed to the wall. Three measurements were recorded for three jumps after a three repetition warm-up was performed. The distance attained during the jump was subtracted from the initial reach, to obtain the vertical jump distance. The average of all three test trials were used for both jump tests and calculated as a ratio according to dominance: non-dominant (ND)/dominant (D) \(\times 100 = \) dominance ratio.

The 40-yard shuttle run in Daniel's study\(^8\) was modified to a 40-yard figure of 8 test (F-8). The F-8 is preferred because while turning around the cones, the subject is required to pivot twice on the involved extremity. The F-8 (Figure 1) was constructed using two 12-inch standard cones separated by a distance of 10 yards. The athlete began at point A, ran to point B, pivoted around the pylon and returned to pivot around point A. Without hesitation, the athlete returned to point B, pivoted around the pylon and sprinted across the finish line at point A. The athlete was required to use the non-dominant knee to pivot around point B, which would require two pivot maneuvers.

**Strength Assessment**

A Cybex II+® isokinetic dynamometer with Humac software® (CSMI, Boston, MA, USA) was used for all isokinetic strength testing. The isokinetic dynamometer was calibrated prior to all testing procedures. Participants completed six repetitions of knee flexion and extension at 60 degrees per second and fifteen repetitions at 240 degrees per second. The peak torque to body weight (BW) ratio was calculated by dividing peak torque by the athletes' BW, and expressed as a percentage. A limb symmetry ratio was calculated for each speed by the following: non-dominant (ND)/dominant (D) \(\times 100 = \) dominance ratio.

**Statistical Analysis**

SPSS 22® (IBM, Armonk, New York) was used for all statistical analyses. Pearson's correlation coefficients \((r)\) were analyzed to determine the relationships between average isokinetic knee strength measures (flexion and extension) and the functional performance tests (SLBJ, SLVJ, and F-8). Independent t-tests were used to examine the differences between groups (skilled versus non-skilled) for all dependent variables of function (SLBJ, SLVJ, and F-8) and strength (peak knee extension and flexion torque; and peak knee flexion and extension torque / BW). Statistical significance was set \(a \text{ priori} at \alpha = .05\) for all correlational and mean comparison statistics.

**RESULTS**

Ninety one percent of the participants (30 skilled and 19 non-skilled) were considered starting players for their teams. Data for mean strength comparisons (Table 1) indicate that no differences existed between...
groups when examining raw peak torque values for knee flexion and extension ($p > 0.05$). However, when comparing peak torque/BW between groups, skilled players consistently displayed greater peak torque/BW for both knee flexion and extension at $60^\circ$/sec and $240^\circ$/sec ($p < 0.05$). These differences indicate that skilled players are able to generate more torque when standardizing to bodyweight than are non-skilled position players. 

Means and group results for the functional performance tests are listed in Table 2. An average F-8 time of 9.5 seconds was established for the 49 high school football players in the current study. In general, skilled athletes exhibited faster time for the F-8 and greater jump distance for the SLBJ ($p < 0.05$). No differences were observed for the SLVJ between groups, however the results for this measure trended towards significance ($p = 0.07$). During the F-8, sta-
Statistically significant differences were found between groups, with skilled players displaying faster average times (9.4 sec ± 0.3, \( p < 0.01 \)) when compared to non-skilled athletes (9.9 sec ± .03). For SLBJ, skilled players on average jumped farther on both the dominant (4.2 in, \( p = 0.5 \)) and non-dominant (7.3 in, \( p = 0.01 \)) limbs than non-skilled athletes.

The relationships between the isokinetic knee torque/BW (flexion and extension) and functional performance are presented in Table 3. Overall, there were moderate to strong correlations between knee extension peak torque/BW and SLBJ (\( r = .54-.61, p < 0.01 \)), SLVJ (\( r = .39-.48, p < 0.01 \)), and the F-8 (\( r = -.50, p < 0.01 \)). Moderate correlations were also observed between knee flexion peak torque/BW and SLBJ (\( r = .48-.49 \)), SLVJ (\( r = .28-.46 \)), and the F-8 (\( r = .41-.52 \) (\( p < 0.05 \)). Being a skilled position player was moderately related to having greater peak torque/BW ratios at 60°/sec for knee flexion (\( r = .41, p < 0.01 \)) and extension (\( r = .46, p < 0.01 \)) when compared to non-skilled positions. Similarly, greater peak torque/BW ratios at 240°/sec were positively related to being a skilled position player for both knee flexion (\( r = .47, p < 0.01 \)) and extension (\( r = .38, p < 0.01 \)) during functional testing, being a skilled position player was associated with greater SLBJ distance (\( r = .34, p < 0.01 \)) and faster F-8 times (\( r = .57, p < 0.01 \)) than in a non-skilled player.

**DISCUSSION**

The primary results of this study show that significant relationships exist between functional performance testing and isokinetic strength tests, and that playing position likely influences an athletes' performance on these tests. This is in agreement with prior research examining patients with ACL reconstructed or ACL deficient knees and suggests that muscle strength is a contributing factor for functional performance.\(^1,3,5,6\) Specifically, Wilk et al\(^8\) reported a positive correlation between knee extension peak torque and the single leg hop for distance test. Additionally, Daniel et al\(^9\) were among the first to report functional data as a follow-up after ACL reconstruction. The tests performed by Daniel et al\(^9\) established a normative shuttle run time and symmetry patterns for dominant and non-dominant lower extremities when performing the single leg hop for distance. Daniel’s population was comprised of general orthopedic patients. Noyes and Mangine\(^10\) established normative values for a group of professional soccer players. Because the high school athlete is a commonly seen patient in the sports medicine setting, the authors sought to record normal values for the studied functional tests. In this study, no between limb differences were observed for either group, indicating that limb dominance does not appear to significantly influence functional performance during single leg

**Table 3. Correlations between Strength and Function for Total Sample (n = 49)**

<table>
<thead>
<tr>
<th>Functional Variable</th>
<th>Strength Variable</th>
<th>Pearson’s ( r ) (( p )-Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL Broad Jump</td>
<td>Extension Peak Torque/BW (60°/sec)</td>
<td>.54 (0.00)*</td>
</tr>
<tr>
<td></td>
<td>Flexion Peak Torque/BW (60°/sec)</td>
<td>.49 (0.00)*</td>
</tr>
<tr>
<td></td>
<td>Extension Peak Torque/BW (240°/sec)</td>
<td>.61 (0.00)*</td>
</tr>
<tr>
<td></td>
<td>Flexion Peak Torque/BW (240°/sec)</td>
<td>.48 (0.00)*</td>
</tr>
<tr>
<td>SL Vertical Jump</td>
<td>Extension Peak Torque/BW (60°/sec)</td>
<td>.39 (0.01)*</td>
</tr>
<tr>
<td></td>
<td>Flexion Peak Torque/BW (60°/sec)</td>
<td>.28 (0.05)*</td>
</tr>
<tr>
<td></td>
<td>Extension Peak Torque/BW (240°/sec)</td>
<td>.48 (0.00)*</td>
</tr>
<tr>
<td></td>
<td>Flexion Peak Torque/BW (240°/sec)</td>
<td>.46 (0.00)*</td>
</tr>
<tr>
<td>40-yard Figure of Eight</td>
<td>Extension Peak Torque/BW (60°/sec)</td>
<td>-.50 (0.00)*</td>
</tr>
<tr>
<td></td>
<td>Flexion Peak Torque/BW (60°/sec)</td>
<td>-.41 (0.01)*</td>
</tr>
<tr>
<td></td>
<td>Extension Peak Torque/BW (240°/sec)</td>
<td>-.50 (0.00)*</td>
</tr>
<tr>
<td></td>
<td>Flexion Peak Torque/BW (240°/sec)</td>
<td>-.52 (0.00)*</td>
</tr>
</tbody>
</table>

SL= Single limb; BW= Body weight. * Statistically significant at \( p \leq .05 \)
functional tests in a healthy, high school population. Therefore, assessing football athletes for limb dominance may not be of added value when evaluating functional and strength metrics.

The isokinetic strength results from this study suggest that skilled position players produce higher peak torque/BW for both knee extension and flexion when compared to non-skilled position players. When left unstandardized to body weight, no differences were observed in isokinetic peak torque values, highlighting the importance of including body weight within the assessment of isolated muscle strength. The associations between playing position and peak torque/BW are likely related to the physical demands and performance characteristics of their respective positions. For example, while having higher body mass is likely beneficial to a non-skilled player for purposes of leverage (i.e. offensive lineman) it may be detrimental to skilled position players (i.e. defensive back) where speed is more of a determining factor to successful performance. Therefore, establishing an athlete's playing position (skilled or non-skilled) may be helpful when setting goals and expectations for participation and/or return to play. Furthermore, future investigators should consider these differences when managing healthy athletes, and continue to explore these relationships among injured populations.

This study examined strength and functional relationships within a healthy population, however, there appears to limited available evidence guiding clinicians for objectively assessing an injured athlete ability to return to play. A systematic review by Westin and Noyes in 2011 showed that of 264 studies involving varying athlete populations following anterior cruciate ligament reconstruction, only 13% of these studies noted objective criteria for determining readiness of return to play. The objective criteria in these studies included muscle strength, thigh circumference, a general knee exam, single leg hop tests, Lachman testing, and validated subjective questionnaires. While these are valid metrics, the low number of available studies utilizing objective criteria for determining readiness for play provides little evidence to guide clinicians and physicians in the decision-making of when to safely return an athlete to the competition. The data from this study may help future researchers establish more tailored objective criteria based on playing position and body mass, and potentially reinjury.

Clinically, the combination of the SLBJ, SLVJ, and F-8 may be a practical method of testing the functional capacity of a high school athlete, and these results suggest that differences likely exist between skilled and non-skilled position players. The SLBJ may be performed in any clinic, as the space and equipment requirements are minimal. The F-8 test is an original test designed by the authors to force pivoting and turning on the involved extremity. There are no known previous published studies on the F-8 40 yard run. The F-8 test allows the clinician to observe the patient in a functional mode, which consists of running and cutting, and forces the athlete to pivot on the involved extremity twice. By contrast, when performing a shuttle run, the athlete may involuntarily choose the stronger leg on which to pivot as they retrieve the shuttlecock. It is encouraged that parents and coaches observe the athlete during all of these functional tests as they can assist the athlete and others to recognize inadequacies that may be present.

Considering that functional training and testing involves multiple muscle groups and body systems, it may be difficult to detect deficits in functional performance with the strength of an isolated muscle group. The significant but weak correlations observed in this study would support these conclusions and suggest that other variables likely influence an athlete's performance during functional tests (such as neuromuscular control, balance, and other factors). Wilk and Escamilla reported that many closed kinetic chain exercises produce a co-contraction of the hamstring and quadriceps muscles, which help decrease shear forces in the knee. The magnitude of the co-contraction activity depends on trunk position relative to the knee joint and the application of force and knee flexion angle. This suggests that proper functional training and awareness may reduce shear forces in the knee via quad, hamstring, hip and core co-activation. Theoretically, an athlete may have the ability to perform well on a functional test with present deficits in muscle strength due to the multiple muscle involvement, and the lack of development of a specific functional test that emphasizes quadriceps function.
Decreased torque/BW ratios may also be a significant predictor of kinesiophobia and successful return to play within an injured setting. Lentz et al\textsuperscript{12} demonstrated that despite lower average pain ratings, patients with high fear avoidance scores were less likely to return to preinjury sports participation. In the group that failed to return to sport, International Knee Documentation Committee (IKDC) scores were associated with poor quad torque/BW ratio at six months and one-year post surgery. Anecdotally, decreased quad torque/BW ratios may have a significant influence on an athletes’ overall fear of movement and ability to successfully return to preinjury participation. A systematic review by Arden et al\textsuperscript{13} of studies following patients after anterior cruciate ligament reconstruction reported return to preinjury level rate of 64%, with only 56% of athletes returning to competitive sports. In these studies, fear of re-injury was the most commonly cited reason for not returning to pre-injury participation levels. In light of these relationships, future investigators should consider the influence of peak torque/BW on pain-related fear of movement/reinjury.

It is important to consider the limitations of this study when interpreting these results. The isokinetic testing and functional performance tests were selected based upon previous work and translational feasibility to a clinical setting. While past studies have primarily focused on isokinetic peak torque,\textsuperscript{4} other variables such as hamstring/quadriceps ratios, average power, and/or total work may be more strongly associated with the performance of function-based activities. Additional research is needed to determine if other strength variables, as previously mentioned, have a higher correlation to functional performance than those that were currently investigated. Lastly, this study included only high-school American football athletes, and should not be extrapolated to other field sports, age ranges, or demographics.

**CONCLUSION**

This results of study suggest that skilled position players demonstrate greater knee extension and flexion peak torque when standardized to bodyweight, longer SLBJ distances, and faster F-8 run times when compared to non-skilled positions. In light of these findings, investigators should consider the potential differences that may exist between skilled and non-skilled athletes when using functional tests and isokinetic strength assessments. Additionally, the relationships between isokinetic peak torque/BW and functional testing may be useful when assessing an athletes’ capacity to perform functional movements. No significant differences were observed for limb dominance and performance of functional testing.

**REFERENCES**


ABSTRACT

**Background:** Shoulder pain is common in competitive young swimmers. A relationship between shoulder strength and shoulder soreness in competitive young swimmers may indicate need for strengthening.

**Purpose:** To determine if a shoulder exercise program will improve shoulder strength and decrease pain in competitive young swimmers.

**Study Design:** Randomized control

**Methods:** Participants (10 control, 11 experimental), randomly assigned to a control or experiment group, completed the 12 week program. Strength was measured prior to the study for shoulder flexion, abduction, external rotation, internal rotation, and extension on the dominant arm using handheld dynamometry. The experimental group was then assigned exercises to be performed three times per week. The control group was instructed not to perform the exercises. All participants were re-tested at six and twelve weeks following initiation of the study.

**Results:** The changes in strength for each muscle group and pain were compared between groups using a mixed design two-way ANOVA. The experimental group significantly increased external rotation strength compared to the control group. Shoulder soreness was not significantly different between groups.

**Conclusion:** Adolescents who perform shoulder strengthening significantly increased their external rotation strength compared to adolescents who only participated in a regular swimming regimen.

**Key words:** Competitive swimmer, rotator cuff strength, soreness, adolescent, external rotation. Randomized controlled trial
INTRODUCTION
Swimming is an activity that is growing in popularity as a competitive sport in the United States\textsuperscript{1,2} with registered swimmers in the USA Swimming Association reaching 349,000 as of 2014.\textsuperscript{3} Due to this increasing interest, sport-related injuries are also on the rise. Competitive year round swimmers cover 6,000 to 14,000 meters (m) a day in practice, while some distance swimmers cover as far as 24,000 m a day during practice.\textsuperscript{4-8} Practices are generally held five to seven days per week, oftentimes twice daily up to 3 times per week. This equates to roughly 60,000 to 80,000m of total swimming distance per week.\textsuperscript{4-8} This exercise volume can result in the development of shoulder pain. Shoulder pain is among the most frequent complaints of competitive swimmers with the incidence of shoulder pain in competitive swimmers ranging between 3-80%.\textsuperscript{1,4,8-13} Swimmers’ shoulder is a common term used to describe anterior shoulder pain that occurs during swimming or after workouts.\textsuperscript{12} More recently the term swimmers’ shoulder has been thought to indicate the underlying cause of pain, not just anterior shoulder pain in general. These causes may be benign such as general post workout soreness or may include more serious pathology such as tendonitis, glenohumeral instability and laxity, impingement, rotator cuff tears, labral tears, symptomatic os acromiale, scapular dyskinesis, and increased glenohumeral range of motion.\textsuperscript{14-20} The authors speculated that weakness or muscular imbalance of the rotator cuff and shoulder muscles are possible reasons for the shoulder pain in competitive swimmers. There is evidence in non-athlete populations that rotator cuff strengthening decreases shoulder pain. With increased shoulder strength, self-reported shoulder pain levels decrease. McClure, et al\textsuperscript{21} implemented a six-week strength and stretching training program to study the relationship between shoulder strength changes and pain in non-swimming patients with impingement syndrome. Interventions to strengthen rotator cuff and scapular stabilizers and to increase flexibility resulted in decreased pain during external and internal rotation, as well as increased strength in these motions. However, others have found no relationship or difference between shoulder pain and strength when comparing swimmers who experience pain and those who do not.\textsuperscript{5,16,22} Ramsi, et al suggested that shoulder pain in collegiate-level swimmers could be the result of muscular imbalance developed during training and competition in adolescence.\textsuperscript{23} Insufficient research has been conducted regarding the effect of competitive swimming on younger swimmers who are still developing their skills and gaining height, weight, and muscle mass. Previous authors have examined shoulder pain and its relationship to selected variables in college-age swimmers.\textsuperscript{5,22,24} No studies have examined subjects whose mean age was below the age of 14. Bak et al reported that some swimmers (mean age 18.5 years) on the Danish National team started competitive swimming as early as age 11.\textsuperscript{22} Dry-land strength training is used for performance enhancement and injury prevention.\textsuperscript{25} Krabak et al surveyed coaches/trainers of randomly selected US swim clubs and found that dry-land training rates increased with age. Of those swimmers \( \leq 10 \) years of age, 54% participated in dry-land training. By 15-18 years, 93% participated. No studies have examined the effects of dry-land training in adolescent swimmers.

The purpose of this study was to evaluate changes in shoulder strength and discomfort or soreness in a group of adolescent competitive swimmers who took part in a dry-land shoulder strengthening program and a group of swimmers who did not. It was hypothesized that no interaction would occur between experimental and control groups in shoulder strength over time and that no relationship would be found between the groups concerning changes in strength and pain levels.

METHODS
Participants
Forty-three volunteers were interviewed for participation. They were recruited from a sample of convenience from the Aqua Shocks swim team (Wichita, KS) who practiced at a local university's pool. Subjects were excluded if they had been injured or had surgery within the last six months. No volunteers met the exclusion criteria. All participants were under the age of 18, and therefore required parental consent and participant assent according to the Wichita State University’s Institutional Review Board that approved this study.
Instrumentation
A hand-held dynamometer (HHD), the Lafayette Manual Muscle Test System (Lafayette Inc, Lafayette IN) was used to test each participant's isometric shoulder strength. An HHD was used because of its versatility with testing muscles at several different angles and for its portability, and proven validity and reliability for measuring muscle strength in kilograms.26,27 A pilot study showed examiner’s test-retest reliability for measuring strength of shoulder flexion, abduction, extension, internal rotation, and external rotation was high (Table 1).

Procedure
Prior to study inclusion each participant filled out a questionnaire describing history of injury and rating their current shoulder soreness on a visual analog scale (0-10). Participants were randomly assigned to either an experimental or a control group with the role of a dice. Isometric force (in kg) was measured in the dominant arm using an HHD. Dominant arm was determined by asking swimmers which arm they would use to throw a small ball. Isometric strength of shoulder flexors, abductors, extensors, internal and external rotators was tested. Each muscle group was tested using three repetitions according to procedures described by Kendall et al.28 A mean of the three scores was used for analysis. Testing occurred before the intervention began, and then was repeated at six weeks, and twelve weeks after onset of the exercise program. To prevent bias, the researcher testing muscle strength was blinded to group assignment throughout the study. None of the researchers was affiliated with the swimming team and, therefore, was not present at all training sessions.

After initial testing, the control group was released back to regular swim practice and instructed to continue their normal swimming regimen. The experimental group was instructed on five resistance band exercises for strengthening the shoulder and rotator cuff muscles. Exercise band resistance ranged from least resistance, yellow, to most resistance, gray. Experimental group participants were assigned a specific color depending on their initial strength assessment. Participants tried bands starting with yellow progressing as tolerated until they found a band that created difficulty between a 6 and 10 difficulty with zero being “nothing at all” to ten being “very, very hard”.

Exercises for selected muscles groups were developed based on recommendations from studies demonstrating high EMG activity.29-32 The experimental group was given handouts with explicit written instructions and pictures for exercises to strengthen shoulder flexors (Figure 1), abductors (Figure 2), extensors (Figure 3), internal (Figure 4) and external rotators (Figure 5) (Table 2). These were performed bilaterally because swimming uses both arms.

<table>
<thead>
<tr>
<th>Table 1. Intratester reliability</th>
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<tbody>
<tr>
<td>Motion</td>
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<tr>
<td>Flexion</td>
</tr>
<tr>
<td>Abduction</td>
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<tr>
<td>Internal Rotation</td>
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<tr>
<td>External Rotation</td>
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<tr>
<td>Extension</td>
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</table>

Figure 1. Exercise position for shoulder flexion
Figure 2. Exercise position for shoulder abduction

Figure 3. Exercise position for shoulder extension

Figure 4. Exercise position for shoulder internal rotation

Figure 5. Exercise position for shoulder external rotation
Exercises were performed prior to swim practice 2-3 times per week, 2 sets of 15 repetitions. Researchers reviewed correct exercise performance every other week. To know when to increase the resistance band being used, participants rated their difficulty on the same scale described above. Participants began using a band with the next higher resistance when they rated their current exercise difficulty at < 6 out of ten. Pain was rated using the Wong-Baker scale at baseline, 6 weeks and 12 weeks.

Data analysis
Strength scores were not adjusted to bodyweight. The three repetitions of strength measurements taken at each time were averaged. Strength data were analyzed using a mixed design two-way ANOVA. Change in strength was analyzed using univariate analysis between groups with pain at the end of the study (time 3) as the covariate. The dependent variables were isometric strength measurements (kgs) and pain scores. The independent variable was group (experimental or control). Pain ratings were analyzed between groups over time using contingency coefficients. The alpha level was set at 0.05. SPSS V. 19 was used to analyze the data.

RESULTS
Twenty-one participants completed the 12-week program. Characteristics were not different for the 43 who were initially tested and the remaining participants (Table 3). Table 3 also includes characteristics of both groups who completed the program. Twenty-two participants were lost to different swim clubs or school teams over the 12-week training program and therefore, did not complete the program. No one left the study due to injury or pain from any of the prescribed exercises.

No differences were found between groups at the 6-week measurement timeframe in any of the analyses; therefore, tables do not include these data. For those in both groups who completed the 12-week program, strength in external rotation increased significantly between baseline and 12 weeks. The experimental group gained a greater percentage of strength in each motion, however, only gains in external rotation were statistically significant (Table 4). Ratios of external to internal rotation strength remained at approximately 0.60:1 and were not different between groups over time (data not shown).

No differences in baseline pain rating or pain ratings over time were demonstrated between those participants who completed the program and those who did not. (Table 5) To account for any pain that may have interfered with strength training, pain was used in the analysis of variance when determining if strength changes were significantly different between the control and experimental groups at the

Table 2. Strengthening exercises with starting and ending positions

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Starting Position</th>
<th>Ending Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder flexors (Figure 1)</td>
<td>Shoulder at 0° abduction</td>
<td>Shoulder at 90° flexion</td>
</tr>
<tr>
<td>Shoulder abductors (Figure 2)</td>
<td>Shoulder at 0° abduction with elbow bent 90°</td>
<td>Shoulder at 90° abduction with elbow bent 90°</td>
</tr>
<tr>
<td>Shoulder extensors (Figure 3)</td>
<td>Shoulder at 45° flexion</td>
<td>Shoulder 5-10° extension</td>
</tr>
<tr>
<td>Shoulder internal rotators</td>
<td>Shoulder at 0° abduction, laterally rotated 10°, with elbow bend 90°</td>
<td>Shoulder at 0° abduction, medially rotated 50-60°, with elbow bend 90°</td>
</tr>
<tr>
<td>(Figure 4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder external rotators</td>
<td>Shoulder at 0° abduction, medially rotated 50-60°, with elbow bent 90°</td>
<td>Shoulder at 0° abduction, laterally rotated 10°, elbow bent 90°</td>
</tr>
<tr>
<td>(Figure 5)</td>
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Table 3. Mean (SD) for participant characteristics by group

<table>
<thead>
<tr>
<th></th>
<th>Participants at baseline (n=43)</th>
<th>Participants who completed 12 week program (n=21)</th>
<th>Participants who did not complete 12 week program (n=22)</th>
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<tbody>
<tr>
<td></td>
<td>Experimental group (n=23)</td>
<td>Control group (n=20)</td>
<td>Experimental group (n=11)</td>
</tr>
<tr>
<td></td>
<td>Control group (n=10)</td>
<td></td>
<td>Control group (n=12)</td>
</tr>
<tr>
<td>Height in centimeters</td>
<td>147.56 (16.10)</td>
<td>150.33 (15.10)</td>
<td>147.04 (16.81)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>148.45 (16.61)</td>
<td>147.95 (16.28)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>152.76 (11.24)</td>
<td></td>
</tr>
<tr>
<td>Weight in kilograms</td>
<td>44.54 (15.44)</td>
<td>44.84 (12.14)</td>
<td>49.10 (21.15)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>43.78 (8.48)</td>
<td>41.27 (12.03)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45.00 (14.58)</td>
<td></td>
</tr>
<tr>
<td>Age in years</td>
<td>11.37 (2.01)</td>
<td>12.03 (2.27)</td>
<td>11.20 (2.44)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.31 (2.24)</td>
<td>11.52 (1.61)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12.83 (2.12)</td>
</tr>
</tbody>
</table>

Table 4. Mean (SD) for isometric strength measures (in kilograms) for the experimental group and the control group, mean (SD) difference within groups and mean (95% confidence interval (CI) differences between groups. Strength is reported for the right upper extremity.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Strength in kg</th>
<th>Change within groups</th>
<th>Difference between groups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exp</td>
<td>Con</td>
<td>Exp</td>
</tr>
<tr>
<td></td>
<td>Week 0</td>
<td>Week 12</td>
<td>Week 12 minus Week 0</td>
</tr>
<tr>
<td>Flexion</td>
<td>N=11</td>
<td>N=10</td>
<td>N=11</td>
</tr>
<tr>
<td>Extension</td>
<td>5.23 (2.06)</td>
<td>5.69 (2.37)</td>
<td>5.63 (2.05)</td>
</tr>
<tr>
<td>Abduction</td>
<td>11.57 (4.49)</td>
<td>11.49 (3.51)</td>
<td>13.81 (4.99)</td>
</tr>
<tr>
<td>Internal rotation</td>
<td>4.88 (1.97)</td>
<td>4.96 (1.91)</td>
<td>5.12 (1.71)</td>
</tr>
<tr>
<td>External rotation</td>
<td>9.37 (4.04)</td>
<td>9.65 (3.64)</td>
<td>10.97 (3.90)</td>
</tr>
</tbody>
</table>

Exp=experimental group
Con=control group

Table 5. Frequency of pain ratings of participants (choices were 0-10, in intervals of 2)

<table>
<thead>
<tr>
<th>Pain rating</th>
<th>Participants who completed 12 week program (n=21)</th>
<th>Participants who did not complete 12 week program (n=22)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experimental group (n=11)</td>
<td>Control group (n=10)</td>
</tr>
<tr>
<td>0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>12-week</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
end of the project. Only change in external rotation strength was significantly increased between groups (Table 4). There were no significant relationships between pain ratings and strength ratings over the 12 week study.

**DISCUSSION**

This is the first study to examine the effects of a dry-land strengthening program on swimmers under the mean age of 14. Strength improved in both groups in all muscles tested. However, only external rotation strength improved significantly for the experimental group over the course of the study.

Because of the role of the pectoralis major and latissimus dorsi in swimming strokes, internal rotation musculature is stronger than that of the external rotation musculature in competitive swimmers because repetitive concentric contractions are required during propulsion. The results of the current study agree with these reports. At all measurement times, internal rotation strength was greater than external rotation. Ramsi et al found internal rotation and external rotation strength increased over time depending on side and gender, however experimental and control groups were not used as this was a cohort study who followed 27 varsity swimmers across a season. With high volumes of practice yardage, it is not uncommon for the anterior shoulder to become overdeveloped leading to strength imbalances between the anterior and posterior shoulder.

The only significant strength gains that occurred in the experimental group were of the external rotators. These gains, albeit limited, may be due to the experimental group's performance of dry-land exercises to increase the strength of these muscles. In contrast to the internal rotators, strength of the external rotators is consistently weaker in both college and masters-level swimmers. This has been attributed to the lesser role of the external rotators during swimming; external rotation is the least used motion. The external rotators primarily function eccentrically to decelerate the humerus throughout the swim stroke.

Pink et al found that the subscapularis is active throughout the freestyle stroke; while the supraspinatus, infraspinatus, and teres minor are only active during small portions of stroke and at a lower level of muscular activation. According to Scovazzo et al, the infraspinatus demonstrates a significantly higher level of muscular activation when shoulder pain occurs with swimming. Weak external rotators in swimmers has been recognized as a contributor to common shoulder conditions such as impingement, tendinitis and instability. Thus, an increase in external rotation strength may decrease a swimmer’s chance of developing impingement.

Strength gains by all participants were anticipated over 12 weeks as the act of swimming by nature should create a physical response to gain shoulder strength or endurance. However, it was expected that experimental group members would demonstrate strength increases in more than just the external rotation. McClure et al recruited subjects with impingement syndrome from a university swim team. Their strengthening and stretching program for rotator cuff and scapular stabilizers resulted in strength gains over six weeks. Hibberd et al conducted a 6-week strengthening and stretching program on shoulder and scapular-stabilizer strength and found no change in strength in flexion, extension, internal and external rotation between the experimental and control groups. However, shoulder extension and internal rotation strength significantly increased in all subjects regardless of group assignment. Swanik et al found no significant isokinetic strength differences between control and intervention groups after a 6-week functional training program that included rubber-tubing, dumbbell, and body-weight exercises. Researchers attributed lack of significant changes in strength variables between groups to preseason conditioning. Despite lack of strength changes between groups, the experimental group reported fewer injuries and reduced rate of increased shoulder pain. Swanik et al suggest that although strength did not improve, the program was a success.

Controversy remains regarding the assessment of strength ratios. Some researchers report higher internal rotator/external rotator ratios in competitive swimmers. Internal to external rotation strength ratios approximate 3:2 in both non-athletes and athletes, including college and masters level swimmers. Bak et al examined strength ratios by evaluating both concentric and eccentric external rotation/internal rotation ratios. In those elite swimmers with one symptomatic and one nonsymp-
tomic shoulder or control, strength ratios were 0.66 to 0.83. Bak et al agree with Beach and colleagues, who found similar strength ratios of 0.64 in elite collegiate swimmers. Control subjects in other studies had an external/internal concentric isokinetic strength ratio of 0.75. The current results conflict with those of Ramsi et al who found an approximate 1:1 ratio between internal rotation/external rotation strength in competitive high school swimmers throughout the swimming season. Magnusson et al also observed at 1:1 strength ratio between internal rotation/external rotation strength in masters level swimmers. There are at least two reasons for the current findings of external rotation/internal rotation strength of 0.60:1 in both groups. First, all of the swimmers were adolescent competitive swimmers who may not yet have achieved significantly stronger internal rotation strength. Substantial strength changes may take months or years to develop. Second, while the experimental group's strength in external rotation increased significantly, both groups' external rotation strength improved the current participants made statistically significant gains in external rotation strength, which may limit a change in the ratio.

Baseline pain ratings were not different between those participants who completed the program and those who did not, nor were differences found between experimental and control groups over time. When pain at 12 weeks was used as the covariate, only change in external rotation strength was significantly increased between groups. Change in pain rating and strength were not related (data not shown). This is somewhat surprising as shoulder pain in competitive swimmers has been reported to be present at all participation levels. The participants in the present study were adolescent competitive swimmers who may not have participated in sufficient practice/competition to develop shoulder pain. Studies describing shoulder pain usually have examined high school age or older swimmers. High reports of swimmers with shoulder pain may be misleading and give a false impression that even younger competitive swimmers suffer shoulder pain.

This study was not without limitations. The largest was the small sample size. Only 21 of 43 the original participants completed the study. More than half of the initial participants left near the end of the season to join other swim teams. Swimmers did not keep training logs; it was assumed that experimental group members were performing the exercises at least two to three times per week per instructions. Swim coaches indicated they reminded swimmers to perform exercises before each practice. Use of the Wong-Baker pain scale may have forced participants to pick a pain rating in even numbers to correspond to the faces depicted on the scale. Future studies should use a more typical visual analog scale presented in centimeters to be more accurate and not inadvertently lead participants to a certain pain rating. Lastly this study examined strengthening in younger adolescent male and female swimmers. Most previous studies have utilized older (high school and collegiate) competitive swimmers. Although the present study assessed competitive swimmers, obvious differences exist between a preteen competitive swimmer and a 22-year-old collegiate competitive swimmer. These differences could explain the current findings. The participants were younger; therefore, their pain level was likely lower due to a less demanding training schedule based upon participant's age. The strengthening program may have produced effects that are more robust if it lasted the entire season rather than only 12 weeks. Swimmers are often taught that shoulder pain is normal in their sport, therefore, it is possible that subjects who were experiencing shoulder pain under-reported their symptoms. Lastly, individual effort could not be assessed. Although the exercise program was clearly explained and researchers visited every two weeks to evaluate tubing resistance and exercise form, some participants may have chosen tubing that did not sufficiently challenge them and, thus, did not create a training effect.

Future research should examine injury prevention of adolescent swimmers using both a strengthening and a stretching program. Larger sample sizes and higher reports of pain and soreness will be important to finding any possible relationship between pain and strength in this age group.

**CONCLUSION**

Strength training is common in swimmers. Younger swimmers are now asked to perform dry land
strength training. Adolescents who perform shoulder strengthening significantly increased their external rotation strength compared to adolescents who only participated in a regular swimming regimen. Increasing strength of external rotators in swimmers may be helpful as a preventative measure to help decrease injury risk.

REFERENCES


ABSTRACT

Background: High school cross country runners have a high incidence of overuse injuries, particularly to the knee and shin. As lower extremity strength is modifiable, identification of strength attributes that contribute to anterior knee pain (AKP) and shin injuries may influence prevention and management of these injuries.

Purpose: To determine if a relationship existed between isometric hip abductor, knee extensor and flexor strength and the incidence of AKP and shin injury in high school cross country runners.

Materials/Methods: Sixty-eight high school cross country runners (47 girls, 21 boys) participated in the study. Isometric strength tests of hip abductors, knee extensors and flexors were performed with a handheld dynamometer. Runners were prospectively followed during the 2014 interscholastic cross country season for occurrences of AKP and shin injury. Bivariate logistic regression was used to examine risk relationships between strength values and occurrence of AKP and shin injury.

Results: During the season, three (4.4%) runners experienced AKP and 13 (19.1%) runners incurred a shin injury. Runners in the tertiles indicating weakest hip abductor (chi-square = 6.140; p=0.046), knee extensor (chi-square = 6.562; p=0.038), and knee flexor (chi-square = 6.140; p=0.046) muscle strength had a significantly higher incidence of AKP. Hip and knee muscle strength was not significantly associated with shin injury.

Conclusions: High school cross country runners with weaker hip abductor, knee extensor and flexor muscle strength had a higher incidence of AKP. Increasing hip and knee muscle strength may reduce the likelihood of AKP in high school cross country runners.

Level of Evidence: 2b

Keywords: Lower extremity muscle strength, medial tibial stress syndrome, patellofemoral pain syndrome, running

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INTRODUCTION

Cross country is a popular high school sport in the U.S. as reflected by the growth of over 25% in participation level for high school cross country in the past decade. However, a consequence of the increased participation is the corresponding high rate of injury in cross country, with 29-38.5% of runners expected to experience an injury during an interscholastic cross country season. Injuries to the knee (including anterior knee pain [AKP] which refers to any issue at the anterior aspect of the knee and may include bursitis, tendinitis, and patellofemoral pain syndrome [PFPS]) and shin are common, together comprising 48% of new injuries and 59% of re-injuries.

Evidence on the relationships between lower extremity strength and running-related injuries has focused primarily on recreational runners. In cross-sectional studies of recreational runners, reduced hip abductor and knee extensor strength have been observed in runners with overuse injuries, including PFPS, when compared with asymptomatic runners. Females with PFPS displayed hip abductor and extensor weaknesses and increased hip internal rotation motion while running compared with controls. Hip and knee strengthening exercises are commonly used for the treatment of injured runners to address areas of impaired strength and biomechanics associated with injury.

Along with their use in rehabilitation, strengthening exercises have been suggested for the prevention of common running injuries. However, as most studies have used a cross-sectional study design to examine the association between lower extremity muscle weakness and running-related injury, it is unclear whether weakness is a risk factor or occurs secondary to the injury. Presently, there are few prospective investigations that have assessed the role of lower extremity muscle strength impairment as a risk factor for AKP or shin injury risk in adult runners. A study of over 600 novice recreational runners found runners with higher eccentric hip abductor strength had a lower risk of developing PFPS. In contrast, a prospective study of 77 novice female recreational runners noted hip strength values for extensors, flexors, abductors, adductors, external and internal rotators were not associated with the development of patellofemoral dysfunction during a training program.

In a prospective study of 125 collegiate cross country runners, Bennett et al observed that lesser isotonic ankle plantar flexor endurance was not significantly associated with exercise related leg pain. In a prospective investigation of 111 track and field athletes 17-26 years old, females with stress fractures, most frequently of the tibia, were found to have less lean mass in their lower limb and smaller calf girth than female track and field athletes who did not incur a stress fracture. Track and field athletes with a one cm decrease in corrected calf girth were also four times more likely to incur stress fracture. Verrelst et al found that decreased hip abductor strength predicted the development of exertional medial tibial pain while running in a prospective study of 95 female collegiate physical education students.

A systematic review on hip strength and PFPS indicated that while many cross sectionally-designed studies reported hip muscle weakness in those with PFPS, few prospective studies have found hip muscle weakness as a significant risk factor. The authors concluded that hip muscle weakness may be the result of knee pain rather than the cause. In contrast, peak isometric strength for knee extensors and flexors in adolescents with patellofemoral pain did not vary from symptom-free adolescents. However, the isometric knee extensor and flexor muscle strength values were based on a general adolescent population, thus were not specific to runners.

The identification of modifiable risk factors may allow implementation of screening and preventative measures for running-related injuries. The value of hip and knee strength screening in adolescent runners is not known as it is unclear whether decreased strength at either the hip or knee are risk factors for or a result of injury. Prospective evidence on the relationship between lower extremity strength and running injury risk in high school runners is limited. In a study of 98 high school cross country and track runners, Finnoff et al reported that runners with lower pre-injury hip external to internal rotator strength ratios were more likely to develop AKP.

As high school runners have a high incidence of knee and shin injury, the purpose of this study was to determine if a relationship existed between isometric hip abductor, knee extensor and flexor strength and the incidence of AKP and shin injury in high school cross
country runners. The authors hypothesized that runners with higher hip and knee strength values would have a significantly lower incidence of AKP and shin injury than runners with lower strength values. A secondary purpose was to explore hip and knee strength values and injury incidence between girls and boys.

METHODS

Subjects and Setting
This study used a prospective cohort design. An a priori power analysis was performed using an alpha value of 0.05, power of 0.80, and 20% incidence values for AKP and shin injury based on seasonal injury incidence of 38.5% and 52% of injuries affecting the knee and shin. With a conservative expected estimate of 15% of non-injured runners with low strength, an expected estimate of 30% of injured (shin injury or AKP) runners with low strength, an odds ratio of 3.0 (corresponding relative risk of approximately 2.0), a sample of 121 runners was indicated to show a statistically significant relationship between strength and shin injury or AKP.

Runners from a Northeast Wisconsin high school were invited to participate in this study. To be included in the study, the runner had to be a member of the boys’ or girls’ cross country teams, not present with signs or symptoms of a current running-related injury, and be cleared for athletic participation. All runners provided informed consent and guardian/parental consent (for runners less than 18 years of age). The study was approved by the Rocky Mountain University of Health Professions Institutional Review Board.

Data Collection

Isometric strength tests

A MicroFET II® handheld dynamometer (Hoggan Scientific, LLC, Salt Lake City, UT) was used to collect bilateral peak isometric strength values for: 1) hip abductors, 2) knee extensors (quadriceps), and 3) knee flexors (hamstrings). Prior to testing, the device was calibrated by the manufacturer. Hip abductor strength was measured with the participant in sidelying (Figure 1). The non-test limb was positioned in 30-45° of hip flexion and 90° of knee flexion. The pelvis was stabilized to the table using a strap and the test hip was in 0° of extension and abducted to parallel with the table. Resistance was placed just proximal to the lateral malleolus on the test limb. Knee extensors were tested with the participant seated at the end of a table with the test knee at 45° of flexion (Figure 2). A stabilizing strap was placed around the thighs and table with resistance applied to the anterior aspect of the tibia 5 cm proximal to the ankle joint. Knee flexor testing occurred with the participant in prone and the test knee flexed to 45° (Figure 3). A stabilizing strap was placed around the pelvis and table with resistance applied to the posterior aspect of the tibia 5 cm proximal to the ankle joint.

Peak isometric strength values (N) for two separate trials were collected for each muscle group, with the muscle groups tested in the following order: knee...
extensors, knee flexors, and hip abductors. The runners were given five seconds between trials and 30 seconds between muscle groups. During each test, the runners were instructed to “take one to two seconds to reach the maximal effort and then maintain this level for three seconds” pushing as hard as they could. The maximum value (N) of the two trials from each muscle group was multiplied by the length of the resistance moment arm (m) and normalized to the participants’ body mass (kg). Moment arm length for knee flexors and extensors was from the medial knee joint line to medial malleolus less five cm and moment arm length for the hip abductors was from the anterior superior iliac spine to the medial malleolus less five cm.

Prior to the main study, inter-rater reliability for each isometric strength test was assessed with 10 participants with 30 seconds to reposition the dynamometer between tests. Inter-rater reliability was determined using intraclass correlation coefficient (ICC3,1) and standard error of measurement (SEM) for each muscle group: hip abductors (ICC3,1, 0.83; SEM, 1.15N / 0.017 Nm/kg), knee extensors (ICC3,1, 0.51; SEM, 3.71N / 0.024 Nm/kg) and flexors (ICC3,1, 0.76; SEM, 2.60N / 0.017 Nm/kg).

Injury surveillance
Runners were followed during the interscholastic season to identify occurrences of AKP and shin injury. Prior to the season, team coaches and athletic trainers were instructed in the use of the Daily Injury Report to record occurrences and non-occurrences of injury. An injury was defined as a medical problem resulting from athletic participation that required an athlete to be removed from a practice or competitive event or to miss a subsequent practice or competitive event. Runners who were able to return to full, unrestricted participation prior to the end of cross country practice or meet were not considered injured in this study. Coaches and athletic trainers recorded absences or limitations due to injury and also specified the injured body part.

If a runner reported knee or shin pain, a licensed physical therapist or licensed athletic trainer examined the athlete to determine whether criteria for AKP [1) Pain around the anterior aspect of the knee, 2) insidious onset, and 3) no evidence of trauma (e.g., falls, twists)] or shin injury [1) Continuous or intermittent pain in the tibial region, 2) exacerbated with repetitive weight-bearing activity, and 3) localized pain with palpation along the tibia] were met.

Data Analysis
The incidence of AKP and shin injury was calculated for all runners and by sex. Mean strength values (average of right and left) for hip and knee muscle groups were used for the injury analysis. As applicable, bivariate logistic regression was used to determine univariate odds ratios (ORs) and 95% confidence intervals (CI) for AKP and shin injuries based on strength tertiles (weakest, middle, strongest) for each muscle group tested. The tertile with the strongest strength values was considered the referent (comparison) group. Separate univariate ORs and 95% CIs were also calculated for girl and boy runners to allow for comparison to published papers that reported sex-specific results. An alpha level of 0.05 was used to determine statistical significance for all tests. SPSS Version 22.0 (SPSS Inc, Chicago, IL) was used for all statistical analyses.

RESULTS
Of the 154 runners who participated in the 2014 cross country season, 68 (44.2%) high school cross country runners enrolled in and completed the study (47 girls and 21 boys; age = 16.2 ± 1.3 yrs, mass = 59.6 ± 9.0 kg, height = 168.1 ± 8.7 cm) (Table 1). During the season, 4.4% (n=3) experienced AKP and 19.1% (n=13) of the runners experienced a shin injury (Table 2). The percent of AKP occurrence was

Figure 3. Test position for knee flexors
similar for girl and boy runners. Boy runners had a significantly higher percent of shin injury than girls (p=0.003).

Runners in the weakest tertile for hip abductor (p=0.046), knee extensor (p=0.038), and flexor strength (p=0.046) had a higher incidence of AKP than those in the strongest tertile (Table 3). As all AKP injuries occurred among runners in the tertile with the weakest tertile values, the likelihood of AKP (i.e., odds ratio) could not be appropriately calculated for each muscle group area. Using the strongest tertile as the reference group, hip and knee muscle strength were not significantly associated with shin injury (Table 4). Within gender, a significant association was found between weaker knee extensor strength and increased occurrence of shin injury (p=0.01) in girls, but no association was found between knee extensor strength and shin injury in boys. No other significant gender-specific associations were found between shin injury and knee flexor or hip abductor muscle strength.

### Table 1. Baseline Characteristics (Mean ± SD) of High School Cross-Country Runners

<table>
<thead>
<tr>
<th></th>
<th>Total (n=68)</th>
<th>Girls (n=47)</th>
<th>Boys (n=21)</th>
<th>p-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>16.2 ± 1.3</td>
<td>16.2 ± 1.3</td>
<td>16.3 ± 1.5</td>
<td>0.82</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>168.1 ± 8.7</td>
<td>164.3 ± 6.3</td>
<td>176.5 ± 7.1</td>
<td>0.000</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>59.6 ± 9.0</td>
<td>57.1 ± 7.5</td>
<td>65.0 ± 9.8</td>
<td>0.001</td>
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<td>BMI (kg/m²)</td>
<td>21.0 ± 2.7</td>
<td>21.1 ± 2.1</td>
<td>20.9 ± 3.7</td>
<td>0.81</td>
</tr>
<tr>
<td>Muscle strength (Nm/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right hip abductors</td>
<td>0.25 ± 0.08</td>
<td>0.25 ± 0.08</td>
<td>0.25 ± 0.07</td>
<td>0.89</td>
</tr>
<tr>
<td>Left hip abductors</td>
<td>0.25 ± 0.07</td>
<td>0.26 ± 0.07</td>
<td>0.25 ± 0.08</td>
<td>0.77</td>
</tr>
<tr>
<td>Right knee extensors</td>
<td>0.29 ± 0.05</td>
<td>0.28 ± 0.04</td>
<td>0.31 ± 0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Left knee extensors</td>
<td>0.28 ± 0.05</td>
<td>0.28 ± 0.05</td>
<td>0.30 ± 0.05</td>
<td>0.11</td>
</tr>
<tr>
<td>Right knee flexors</td>
<td>0.21 ± 0.04</td>
<td>0.20 ± 0.03</td>
<td>0.22 ± 0.06</td>
<td>0.07</td>
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<tr>
<td>Left knee flexors</td>
<td>0.20 ± 0.05</td>
<td>0.20 ± 0.04</td>
<td>0.21 ± 0.06</td>
<td>0.17</td>
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<tr>
<td>$\text{Mean hip abductors}$</td>
<td>0.25 ± 0.07</td>
<td>0.26 ± 0.07</td>
<td>0.25 ± 0.07</td>
<td>0.83</td>
</tr>
<tr>
<td>$\text{Mean knee extensors}$</td>
<td>0.29 ± 0.05</td>
<td>0.28 ± 0.40</td>
<td>0.30 ± 0.53</td>
<td>0.07</td>
</tr>
<tr>
<td>$\text{Mean knee flexors}$</td>
<td>0.20 ± 0.04</td>
<td>0.20 ± 0.03</td>
<td>0.22 ± 0.06</td>
<td>0.10</td>
</tr>
</tbody>
</table>

BMI, body mass index.
*Two sample t-test of differences of means for boys and girls.
$\text{Average value of Right and Left.}$

### Table 2. Distribution of Anterior Knee Pain and Shin Injuries by Sex

<table>
<thead>
<tr>
<th>Injury type</th>
<th>Total (n=68)</th>
<th>Girls (n=47)</th>
<th>Boys (n=21)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>%</td>
<td>N</td>
</tr>
<tr>
<td>Anterior Knee Pain</td>
<td>3</td>
<td>4.4</td>
<td>2</td>
</tr>
<tr>
<td>Shin Injury</td>
<td>13</td>
<td>19.1</td>
<td>4</td>
</tr>
</tbody>
</table>

N= Number of runners with injury.
DISCUSSION
The primary purpose of this study was to examine whether hip and knee strength were associated with AKP and shin injury among high school cross country runners. While the findings of this current study support the hypothesis that runners with stronger hip abductor, knee extensor and flexor muscle strength had a lower incidence of AKP injury, the results did not support the same hypothesis for shin injury.

In this study, high school cross country runners with weaker hip abductor, knee extensor and knee flexor strength values had a higher incidence of AKP. The findings are consistent with those reported by Ramskov et al in recreational runners, who found runners with higher values for eccentric hip abduction strength had a lower incidence of AKP. Finnoff et al also found a similar incidence (5.1%) of AKP among high school runners. In contrast to the findings of the current study, they found that runners with higher baseline hip abduction strength values were at a five-fold risk of developing AKP. This finding was contrary to what was expected. The higher strength values observed may have been an adaptation to increased hip adduction moments in the injured group during early and mid-stance phases of gait due to their higher weights relative to the uninjured group.28 As few studies have prospectively evaluated the relationship between hip abductor muscle strength and AKP, further studies are needed to help determine whether greater strength serves as a risk factor or a protective role in high school runners.

With respect to the overall sample in this study, runners with the weakest knee extensor and flexor muscle strength values were not at a significantly higher risk of shin injury than those with strongest knee extensor and flexor muscle strength values. In fact, runners with knee extensor strength values in the middle tertile had the lowest injury incidence of shin injury. While these results were contrary to what was expected, when sex-specific distributions were examined, girls with knee extensor muscle strength values in the weakest tertile indeed had the highest incidence of shin injury. This was not true for boy runners. The reasons for this sex-

<table>
<thead>
<tr>
<th>Table 3. Relationships Between Selected Lower Extremity Muscle Group Strength and Anterior Knee Pain (AKP)</th>
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<tbody>
<tr>
<td><strong>Total (N=68)</strong></td>
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<td></td>
</tr>
<tr>
<td><strong>Hip Abductor</strong></td>
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<td>T1 (weakest)</td>
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<td>T3 (strongest)</td>
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</table>

N, Number of runners at risk for AKP; OR, Odds Ratio; CI, Confidence interval; T1, weakest tertile; T2, middle tertile; T3, strongest tertile; NA, Non-applicable
specific difference, or for why no relationship exists between knee flexor muscle strength, is not known and future study is recommended.

There was no significant relationship between hip abductor strength and shin injury. This is in contrast to Verrelst et al who prospectively observed that increased isometric hip abduction strength was protective for exertional medial tibial pain in female physical education students.25 This relationship could be sex-specific; the lack of association between hip strength and shin injury in the present study may be related to the boys having a higher distribution of incidence of shin injury in the weakest tertile than girls comparatively to those in the tertile with the strongest muscle values.

Bennell et al reported that greater muscle mass was protective for stress fractures injuries in elite club track and field athletes.23 Corrected calf girths and lower limb lean mass were positively correlated with tibial and fibular bone density suggesting strength may provide defense for bone injuries in runners.38 However, their study focused on stress fractures while our injury definition included all shin injury types.

A strength of this study is the prospective design which allowed assessment of strength values prior to injury occurrence. This minimized the risk of measurement and recall bias.3,39 Further, the prospective design provided the opportunity to appropriately determine whether the strength values were a causative rather than resultant factor.

Limitations of this study include a small sample size and a limited number of AKP cases. While information on body mass index and history of prior running injury was collected on participants, adjustments for the possible effects of these potential confounding variables could not be appropriately evaluated due to the small sample size. The associations found between hip and knee strength and AKP occurrence were significant but with few runners experiencing AKP, the associations may be partially due to Type II error. However, the fact that all injuries were in those with muscle strength in the weakest tertile provided some additional confidence in the current findings. Another potential limitation was that the strength measurements were assessed isometrically using a handheld dynamometer. Considering that running

| Table 4: Relationships Between Selected Lower Extremity Muscle Group Strength and Shin Injury |
|---------------------------------|---------------------------------|---------------------------------|
|                                 | Total (N=68)                    | Girls (N=47)                    | Boys (N=21)                     |
| N at risk | % injured | OR (95% CI) | N at risk | % injured | OR (95% CI) | N at risk | % injured | OR (95% CI) |
| Hip Abductor Strength |
| T1 (weakest) | 23 | 26.1 | 2.35 | 0.5-10.9 | 14 | 7.1 | 1.23 | 0.7-21.6 | 9 | 55.6 | 1.25 | 0.2-9.9 |
| T2 | 22 | 18.2 | 1.48 | 0.3-7.5 | 16 | 12.5 | 2.28 | 0.2-28.0 | 6 | 33.3 | 1.00 | NA |
| T3 (strongest) | 23 | 13.0 | 1.00 | Ref | 17 | 5.9 | 1.00 | Ref | 6 | 33.3 | 1.00 | Ref |
| Knee Extensor (Quadriceps) Strength |
| T1 (weakest) | 22 | 31.8 | 1.24 | 0.3-4.5 | 16 | 25.0 | NA | NA | 6 | 50.0 | 0.83 | 0.1-6.1 |
| T2 | 24 | 0.0 | NA | NA | 20 | 0.0 | NA | NA | 4 | 0.0 | NA | NA |
| T3 (strongest) | 22 | 27.3 | 1.00 | Ref | 11 | 0.0 | 1.00 | Ref | 11 | 54.5 | 1.00 | Ref |
| Knee Flexor (Hamstring) Strength |
| T1 (weakest) | 23 | 21.7 | 0.74 | 0.2-2.9 | 17 | 11.8 | 1.33 | 0.1-16.7 | 6 | 50.0 | 1.20 | 0.2-8.8 |
| T2 | 23 | 8.7 | 0.25 | 0.1-1.4 | 19 | 5.3 | 0.55 | 0.1-9.9 | 4 | 25.0 | 0.40 | 0.1-5.2 |
| T3 (strongest) | 22 | 27.3 | 1.00 | Ref | 11 | 9.1 | 1.00 | Ref | 11 | 45.5 | 1.00 | Ref |

N, Number of runners at risk for shin injury; OR, Odds Ratio; CI, Confidence interval; T1, weakest tertile; T2, middle tertile; T3, strongest tertile; NA, Non-applicable
requires concentric and eccentric muscle contrac-
tions, the construct validity of isometric strength as
it pertains to running has been fairly questioned.26,40
Messier et al reported strength values were similar
among recreational runners ages 16-50 with and
without PFPS, but the runners with PFPS tended
to have increased knee flexor and decreased knee
extensor endurance bilaterally measured with an
isokinetic dynamometer compared with controls
despite unilateral symptoms.41 Lastly, as this study
only included runners from one high school, the
generalizability is limited to other high school run-
ners competing across the U.S.

CONCLUSION
In summary, high school runners who developed AKP
during the cross country season had weaker muscle
strength values for hip abductors, knee extensors
and flexors. No significant relationships between hip
and knee strength values and shin injury occurrence
were detected. Local muscle strength is a modifi-
cable risk factor and based on this sample, improving
hip and knee strength may reduce the likelihood of
developing AKP. Future studies with larger samples
sizes are warranted to assess whether interventions
to improve hip and knee strength reduce the inci-
dence of AKP and shin injury in runners.

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runners initiating a self-structured running program:


ORIGINAL RESEARCH
EFFECTIVENESS OF A MOTOR CONTROL THERAPEUTIC EXERCISE PROGRAM COMBINED WITH MOTOR IMAGERY ON THE SENSORIMOTOR FUNCTION OF THE CERVICAL SPINE: A RANDOMIZED CONTROLLED TRIAL

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ABSTRACT

Background: Motor control therapeutic exercise (MCTE) for the neck is a motor relearning program that emphasizes the coordination and contraction of specific neck flexor, extensor, and shoulder girdle muscles. Because motor imagery (MI) improves sensorimotor function and it improves several motor aspects, such as motor learning, neuromotor control, and acquisition of motor skills, the authors hypothesized that a combination of MCTE and MI would improve the sensorimotor function of the cervical spine more effectively than a MCTE program alone.

Purpose: The purpose of this study was to investigate the influence of MI combined with a MCTE program on sensorimotor function of the cranio cervical region in asymptomatic subjects.

Study Design: This study was a single-blinded randomized controlled trial.

Methods: Forty asymptomatic subjects were assigned to a MCTE group or a MCTE+MI group. Both groups received the same MCTE program for the cervical region (60 minutes), but the MCTE+MI group received an additional intervention based on MI (15 minutes). The primary outcomes assessed were cranio cervical neuromotor control (activation pressure value and highest pressure value), cervical kinesthetic sense (joint position error [JPE]), and the subjective perception of fatigue after effort.

Results: Intra-group significant differences were obtained between pre- and post interventions for all evaluated variables (p<0.01) in the MCTE+MI and MCTE groups, except for cranio cervical neuromotor control and the subjective perception of fatigue after effort in the MCTE group. In the MCTE+MI group a large effect size was found for cranio cervical neuromotor control (d between -0.94 and -1.41), cervical kinesthetic sense (d between 0.97 and 2.14), neck flexor muscle endurance test (d = -1.50), and subjective perception of fatigue after effort (d = 0.79). There were significant inter-group differences for the highest pressure value, joint position error (JPE) extension, JPE left rotation, and subjective perception of fatigue after effort.

Conclusion: The combined MI and MCTE intervention produced statistically significant changes in sensorimotor function variables of the cranio cervical region (highest pressure value, JPE extension and JPE left rotation) and the perception of subjective fatigue compared to MCTE alone. Both groups showed statistically significant changes in all variables measured, except for cranio cervical neuromotor control and the subjective perception of fatigue after effort in the MCTE group

Level of Evidence: 1b

Key Words: Cervical disorders, motor imagery, motor control, therapeutic exercise.

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INTRODUCTION

Neck pain is one of the most frequent musculoskeletal disorders, with a one-year prevalence of around 37%, and a significant problem in healthcare. Neck pain has a high prevalence in triathletes and cyclists, especially recreational athletes. Fortunately, athletic neck pain is usually the result of minor injury and most athletes can return to full activity. Therapeutic exercise is an effective intervention in neck pain management in both the short (<1 month) and intermediate (1-6 months) terms. One of the most interesting approaches used to manage neck pain is therapeutic exercise with a focus on motor control; some authors describe altered movement patterns (e.g., less flexible movement patterns, reduced range motion, and/or poor accuracy in maintaining maximal voluntary isometric contraction) in the cervical spines of patients with neck pain. Motor control can be defined as the capacity of how the central nervous system produces useful movements that are coordinated and integrated with the rest of the body and the environment. Thus, motor control therapeutic exercises (MCTE) are relevant to improve the status of patients with neck pain. In fact, MCTE have been demonstrated to increase motor control and reduce pain and disability in patients with neck pain. Changes in motor control that could cause pain or dysfunction require practitioners to work on the components of motor learning for a successful intervention capable of producing satisfactory motor learning and retention. Such an intervention requires repetitive training.

Alternatively, motor imagery (MI), defined as the mental representation of movement without any body movement, can be employed to improve motor performance and learn motor tasks. This technique has usually been used in sports, but recent researchers show that it is also effective in treating patients with neurological diseases or chronic pain. By inducing the activation of different cortical areas, MI is useful for influencing the central nervous system and causing plastic changes in the brain. Thus, this method should be considered for use in rehabilitation, because its goals include the improvement of motor performance and learning.

Considering that MI improves sensorimotor function and it improves several motor aspects, such as motor learning, neuromotor control, and acquisition of motor skills, the authors hypothesized that a combination of MCTE and MI would improve the sensorimotor function of the cervical spine more effectively than a MCTE program alone. Thus, the purpose of this study was to investigate the influence of MI combined with a MCTE program on sensorimotor function of the craniocervical region in asymptomatic subjects.

METHODS

Study Design

This study was a single-blind, randomized, and controlled trial; the assessor responsible for obtaining the study outcomes was blinded to intervention group allocation. This study was planned and conducted in accordance with the CONSORT requirements (Consolidated Standards of Reporting Trials).

Recruitment of Participants

A convenience sample of asymptomatic volunteers was obtained from a university campus and the local community through flyers, posters, and social media. Subjects were recruited between February and May 2014. The inclusion criteria were healthy subjects between 18 and 65 years old. The exclusion criteria included the following: a) subjects who experienced neck pain in the previous 6 months; b) subjects who had been treated for neck pain in the previous 6 months; c) subjects with other chronic pain conditions; and d) subjects with difficulty in communication or understanding.

Informed consent was obtained from all subjects before inclusion. All participants received an explanation about the procedures of the study, and each one completed a questionnaire with demographic data. All of the procedures were planned under the ethical norms of the Declaration of Helsinki and were approved by the ethics committee of the Center for Advanced Studies University La Salle.

Randomization

Randomization was performed using a computer-generated random-sequence table with a two-balanced block design (GraphPad Software, Inc., CA, USA). A statistician generated the randomization list, and a member of the research team who was
not involved in the assessment or treatment of the participants was in charge of the randomization and maintained the list.

Once the initial assessment and inclusion of the participants were complete, the included were randomly assigned to either of the two groups (MCTE alone or MCTE-MI) using the random-sequence list, ensuring concealed allocation.

Blinding
The assessor was blinded to the condition of the healthy subjects being assessed. The subjects were told to freely comment to the researcher in charge of performing the allocation about how they were feeling or regarding the intervention itself. Additionally, the subjects were asked not to make any comments to the assessor.

Interventions
MCTE in isolation (MCTE)
The subjects in the MCTE group received a prescription for MCTE for the cervical region. A physiotherapist instructed the participants regarding the MCTE program in one one-to-one session that lasted approximately 60 minutes. In this session, participants were taught each exercise and all the details of the training program were explained (sets, repetitions, rest periods, frequency, and common mistakes in the exercises). To ensure proper motor control, the session ended with the participant performing the entire training program supervised by a physiotherapist.

The MCTE used for this research is based on retraining the cervical muscles and included the following exercises:15 1) craniocervical flexor exercise (Figure 1, Exercise 1); 2) craniocervical extensor exercise (Figure 1, Exercises 2A-2B); 3) co-contraction of flexors and extensors (Figure 1, Exercise 3); and 4) a synergy exercise for retraining the strength of the deep neck flexors (Figure 1, Exercises 4A-4B). Each of these four exercises was performed for three sets of 10-12 repetitions, taking an approximate total duration of 10 to 20 minutes. The subjects were asked to practice the MCTE program at home once a day, 5 days a week, for 30 days.

![Figure 1](image_url). Exercises that were used in the motor control therapeutic exercise program: 1) Craniocervical flexor exercise, 2) Craniocervical extensor exercise [a = start, b = end], 3) Co-contraction of neck flexors and extensors, 4) Synergy exercise for deep neck flexors [a = start, b = end].
The subjects in the MCTE-MI group underwent the MCTE program and also received an additional intervention based on MI. The MI intervention was explained at the end of the MCTE session and instruction lasted approximately 15 minutes. The objective of the MI program was to modify the MCTE program. The four phases of the MI intervention were performed one after the other, in order, for 4 weeks: a) kinesthetic imagery (first week); b) visual imagery (second week); c) movement observation therapy plus MI (third week); and d) exercise execution with mirror feedback (fourth week).

All participants (both groups) also received a booklet with written information about the indications and exercises to be practiced at home to ensure that the training program was performed properly. Each week, participants received messages by email and phone to remind and motivate them to undertake the exercise program as scheduled.

**Procedure**

Outcomes were obtained twice in each group, and participants were supplied with a battery of self-report questionnaires before the intervention. The neuromotor assessment of subjects in both groups was performed before and 30 days after the intervention. The measurements performed included: 1) cervical range of motion (ROM) measurements; 2) craniocervical flexion test (CCFT); 3) joint position error (JPE) test; 4) the deep neck flexor endurance test; and 5) assessment of perception of fatigue after the deep neck flexors endurance test.

**Self-report outcomes**

After consenting to the study, recruited healthy subjects were given a battery of questionnaires to complete on the day of the first measurement. These included various self-reports for sociodemographic and psychological variables, collecting information about gender, age, height, and weight, and included the validated Spanish versions of the Pain Catastrophizing Scale (PCS),27 the Tampa Scale for Kinesiophobia (TSK-11),28 the Hospital Anxiety and Depression Scale (HADS),29,30 and the International Physical Activity Questionnaire (IPAQ).31 Each of these tools has acceptable validity and reliability.

**Outcome Measures**

**Primary Outcome Measures**

*Craniocervical neuromotor control.* The CCFT has been described as a neuromotor control test that evaluates the activation and isometric endurance of the deep neck flexors.15 The CCFT is performed with the subject in a supine position, with 45° of hip flexion and 90° of knee flexion. A feed-back device “stabilizer” (Chattanooga Group, Inc., Hixson, TN, USA) was applied under the suboccipital region and inflated to 20 mmHg of pressure; subjects were verbally instructed to bend their heads, as if saying “yes,” to obtain a craniocervical flexion movement. A correct pattern movement of craniocervical flexion was required and had to be verified by the evaluator.
during the CCFT. Craniocervical flexion is described as flexion of the head over the upper cervical region without any flexion of the middle or lower cervical region. The movement was considered incorrect when activation of the sternocleidomastoid and anterior scalenus was palpable, a movement quickly took place, and/or head retraction was performed instead of craniocervical flexion. Each of these compensations were assessed by both observation and palpation. The movement was taught to each participant and practiced before the test to ensure that the craniocervical flexion was performed correctly, and the evaluator highlighted the importance of precision rather than force.32

With the CCFT, two items were measured in two phases, respectively:

1) Activation pressure value (APV): the highest pressure a subject could achieve and maintain for 10 seconds while properly performing the CCFT, less the baseline 20 mmHg (registered in mmHg). This first part was undertaken to determine the contractile capacity of the deep neck flexors when performing the correct movement pattern. Intra-rater reliability for this measure was very high [ICC = 0.91; 95% CI (0.85 to 0.96)].33

2) Highest pressure value (HPV): the highest target pressure that a subject could achieve and hold for 10 seconds, starting at a baseline of 20 mmHg and increasing by 2 mmHg at each phase, with a total of five phases and a top value 30 mmHg (target pressures of 22, 24, 26, 28, and 30 mmHg). The feed-back device provided information to the subjects regarding the performance of the target pressure during the ten second hold, and a 30 second rest was given between phases. This second part was undertaken to determine the pressure (registered in mmHg) that the asymptomatic subject could achieve with the correct movement held for ten seconds. When the subject could not perform the correct movement, the test finished and the pressure registered was the greatest pressure at which the subject performed the correct movement without substitution, which corresponded to the previous phase. The reported intra- and inter-rater reliability for this test was high [ICC = 0.82, 95% CI (0.67 to 0.91)]; the minimal detectable change (MDC) was 4.70 mmHg.34

- Cervical kinesthetic sense. JPE tests were used (in four motions) to assess this variable. JPE is an objective measure of neck reposition sense and can quantify the alteration of neck proprioception.35,36 This measure is based on the ability to relocate the natural head posture (anatomic position) after performing several cervical movements.37 For this, a laser pointer, mounted onto a light-weight headband, was used. The test procedure was as follows: the subjects were placed in a sitting position with the head in a resting position. A target was positioned against a wall 90 cm away from the subject's head (Figures 2A & 2B). Once the device was placed on the subject, subjects were blindfolded and asked to perform the neck movement being tested within comfortable limits and to return as accurately as possible to the starting position. The linear distance (assessed in cm) between the center and the end positions was measured and recorded. Four movements were evaluated: flexion, extension, and left and right rotations; starting each time with the patient repositioned to the center position before performing the tested movement. Regarding the reliability, the ICC for this test has been reported to range from 0.35 to 0.44, with a good agreement between days;38 and the MDC ranged from 7 to 10 mm.34

Secondary Outcome Measures

- Cervical ROM: Cervical ROM was measured with a cervical goniometer called CROM (Performance Attainment Associates, Lindstrom, MN). This device has three inclinometers, one in each plane of movement. A plastic support piece houses two inclinometers, which allow for the measurement of flexion, extension, and lateral flexion of the neck. The third inclinometer and magnets around the neck allow for rotation measurement39 (Figure 2C, 2D, & 2E). This device is valid and reliable for test-retest measures [r = 0.98, 95% CI (0.95 to 0.99)], with MDC for flexion of 2.2°, extension 2.8°, left rotation 2.1°, right rotation 2.6°, left lateral flexion 1.8°, and right lateral flexion 1.6°.40

-Neck Flexor Muscle Endurance Test. The aim of this test was to assess neck flexor endurance, isometrically against gravity. The participants laid in a supine position with the knees and hips bent to 45°. The test consisted of a craniocervical flexion position maintained isometrically followed by a lift of the head 2.5
cm above the plinth while the chin was maintained in the retracted position. The subjects were instructed to bend their chin and lift their head up and hold it. To check whether the subject had failed, one researcher’s hand was placed under the head to monitor when the participant failed to maintain the head lift, and visual monitoring was used to establish when the chin had lost its retracted position; either event meant the test was over. The outcome of the test was time in seconds that the subject could maintain the correct craniocervical flexion position. The ICC value for inter-rater reported reliability for this test ranged from 0.57 to 1.0 and the MDC was 6.4 seconds.

- Subjective perception of fatigue after effort. The visual analogue fatigue scale (VAFS) was used to quantify fatigue after performing the neck flexor endurance test. The VAFS consists of a 100-mm vertical line on which the bottom represents “no fatigue” (0 mm) and the top represents “maximum fatigue” (100 mm). After the neck flexor endurance test, the subject was instructed to mark on the line the level of fatigue felt after the effort of performing the test. The researcher recorded the mark in millimeters.

Sample Size Calculation
The necessary sample size was estimated using G*Power 3.1.7 for Windows (G*Power©, University of Dusseldorf, Germany). The sample size calculation was considered as a power calculation to detect between-group differences in the primary outcome measures (craniocervical neuromotor control and cervical kinesthetic sense). To obtain 80% statistical power (1-β error probability) with an α error level probability of 0.05, we used repeated-measured analysis of variance (ANOVA), within-between interaction, and a medium effect size of 0.25 to consider two groups and two measurements for primary outcomes, generating a sample size of 17 participants per group (total sample size of 34 subjects). Allowing a dropout rate of 15% and aiming to increase the statistical power of the results, the authors planned to recruit at least 40 participants to provide sufficient power to detect significant group differences.

Statistical Analysis
The Statistical Package for Social Sciences (SPSS 21, SPSS Inc., Chicago, IL, USA) software was used for statistical analysis. The normality of the variables...
was evaluated by the Shapiro-Wilk test. Descriptive statistics were used to summarize the data for continuous variables and are presented as mean ± standard deviation (SD), 95% confidence interval (CI), and median (interquartile interval), and categorical as absolute (number), and relative frequency (percentage). A chi-squared test with residual analysis was used to compare categorical variables. Student’s t-test and two-way repeated-measures ANOVA were used to compare continuous outcome variables. The factors analyzed were group (MCTE in isolation, MCTE in conjunction with MI) and time (pre-intervention, post-intervention). The time x group interaction, which is the hypothesis of interest, was also analyzed. Partial eta-squared ($\eta^2_p$) was calculated as a measure of effect size (strength of association) for each main effect and interaction in the ANOVAs and 0.01-0.059 represented a small effect, 0.06-0.139 a medium effect, and > 0.14 a large effect.\textsuperscript{45} Post hoc analysis with Bonferroni correction was performed in the case of significant ANOVA findings for multiple comparisons between variables. Effect sizes ($d$) were calculated according to Cohen’s method, in which the magnitude of the effect was classified as small (0.20 to 0.49), medium (0.50 to 0.79), or large (0.8).\textsuperscript{46}

For variables with non-normal distributions, the Mann-Whitney U test was utilized. The Wilcoxon signed-rank test was used to analyze the change from the intra-group results. The $\alpha$ level was set at 0.05 for all tests.

**RESULTS**

Forty healthy subjects were included in this research, and were randomly allocated in two groups of 20 subjects per group. There were no adverse events or drop-outs reported in either group. A CONSORT flow diagram is provided in Figure 3. No statistically significant differences were present pre-intervention between groups in demographic data and self-reported variables ($p > 0.05$), meaning the groups were not significantly different from each other. The demographic data and self-reported variables are shown in Table 2. The Shapiro-Wilk test confirmed that the data were normally distributed ($p > 0.05$), except for age and cervical ROM.
Primary Outcomes

**Craniocervical neuromotor control.** Statistically significant differences were found for CCFT revealing differences for the group x time interaction [APV (F = 9.85, p = 0.003; \( \eta^2_p = 0.21 \); HPV (F = 10.18, p = 0.003; \( \eta^2_p = 0.21 \)] and for the time factor [APV (F = 7.54, p = 0.009; \( \eta^2_p = 0.16 \); HPV (F = 43.56, p < 0.001; \( \eta^2_p = 0.53 \)]. Pre-post intervention differences were observed in APV and HPV in the MCTE-MI group and between groups differences in the HPV at the post-intervention measure, all with large effect sizes (p < 0.001; Table 3).

**Cervical kinesthetic sense.** The were no significant group x time interaction differences for any of the measures of JPE; however, statistically significant differences were observed for the time factor in all ROMs measured for JPE (flexion: [F = 38.52, p < 0.001; \( \eta^2_p = 0.50 \]); extension: [F = 24.53, p < 0.001; \( \eta^2_p = 0.39 \]);

<table>
<thead>
<tr>
<th>Measure</th>
<th>MCTE (n=20)</th>
<th>MCTE+MI (n=20)</th>
<th>p-value of independent samples ( \chi^2 ) test, Mann-Whitney U test or t-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>33.66±10.47</td>
<td>33.05±12.87</td>
<td>0.49†</td>
</tr>
<tr>
<td>Gender</td>
<td></td>
<td></td>
<td>0.20**</td>
</tr>
<tr>
<td>Female</td>
<td>6 (30)</td>
<td>10 (50)</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>14 (70)</td>
<td>10 (50)</td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>1.72±0.72</td>
<td>1.69±0.78</td>
<td>0.22*</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>70.60±11.55</td>
<td>66.40±8.42</td>
<td>0.20*</td>
</tr>
<tr>
<td>PCS (points)</td>
<td>6.15±5.61</td>
<td>8.45±7.25</td>
<td>0.27*</td>
</tr>
<tr>
<td>TSK-11 (points)</td>
<td>18.30±5.92</td>
<td>19.85±6.56</td>
<td>0.44*</td>
</tr>
<tr>
<td>Anxiety</td>
<td>2.55±1.79</td>
<td>2.80±1.96</td>
<td>0.68*</td>
</tr>
<tr>
<td>Depression</td>
<td>6.05±3.36</td>
<td>4.30±4.03</td>
<td>0.14*</td>
</tr>
<tr>
<td>IPAQ (points)</td>
<td></td>
<td></td>
<td>0.44**</td>
</tr>
<tr>
<td>Slow</td>
<td>4 (20)</td>
<td>6 (30)</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>11 (55)</td>
<td>7 (35)</td>
<td></td>
</tr>
<tr>
<td>Vigorous</td>
<td>5 (25)</td>
<td>7 (35)</td>
<td></td>
</tr>
</tbody>
</table>

MCTE= motor control therapeutic exercise; MI= motor imagery; PCS= Pain Catastrophizing Scale; TSK-11, Tampa Scale of Kinesiophobia; HADS= Hospital Anxiety and Depression Scale; IPAQ= International Physical Activity Questionnaire;  
* t-test.  
** \( \chi^2 \) test.  
† Mann-Whitney U test.
right rotation: \[F = 28.84, \ p < 0.001; \ \eta^2_p = 0.43\]; left rotation: \[F = 19.12, \ p < 0.001; \ \eta^2_p = 0.33\]. The post hoc analysis revealed differences between the pre- and post-intervention results in both groups for all the movements \(p < 0.05\), but not between groups.

The greatest effect sizes were found in the MCTE-MI group in all measures; the largest effect size that equates to a large effect size was for the JPE extension measure \(d = 2.14\). The descriptive data and multiple comparisons are presented in Table 3.

### Table 3. Descriptive data and multiple comparisons of the primary variables.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Group</th>
<th>Mean ±SD</th>
<th>Mean difference (95%CI); Effect size (d).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>APV</td>
<td>MCTE</td>
<td>5.80±1.94</td>
<td>5.70±1.87</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>5.00±1.78</td>
<td>6.50±1.43</td>
</tr>
<tr>
<td></td>
<td>Mean difference (95%CI); Effect size (d).</td>
<td>0.80 (-0.39 to 1.99)</td>
<td>-0.80 (-1.87 to 0.27)</td>
</tr>
<tr>
<td>HPV</td>
<td>MCTE</td>
<td>24.10±1.77</td>
<td>24.80±1.64</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>23.90±1.77</td>
<td>26.30±1.63</td>
</tr>
<tr>
<td></td>
<td>Mean difference (95%CI); Effect size (d).</td>
<td>0.20 (-0.94 to 1.34)</td>
<td>-1.50 (-2.55 to -0.45)**</td>
</tr>
<tr>
<td>JPEFlex</td>
<td>MCTE</td>
<td>6.64±2.38</td>
<td>4.20±1.70</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>5.80±1.94</td>
<td>3.70±1.26</td>
</tr>
<tr>
<td></td>
<td>Mean difference (95%CI); Effect size (d).</td>
<td>0.84 (-0.56 to 2.23)</td>
<td>0.50 (-0.56 to 1.46)</td>
</tr>
<tr>
<td>JPEExt</td>
<td>MCTE</td>
<td>6.10±3.11</td>
<td>4.25±1.53</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>6.02±2.09</td>
<td>3.03±0.70</td>
</tr>
<tr>
<td></td>
<td>Mean difference (95%CI); Effect size (d).</td>
<td>0.09 (-1.61 to 1.78)</td>
<td>1.23 (0.47 to 1.99)**</td>
</tr>
<tr>
<td>JPERotL</td>
<td>MCTE</td>
<td>5.79±2.86</td>
<td>4.18±1.49</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>5.72±2.76</td>
<td>3.43±0.65</td>
</tr>
<tr>
<td></td>
<td>Mean difference (95%CI); Effect size (d).</td>
<td>0.08 (-1.73 to 1.88)</td>
<td>0.75 (0.01 to 1.49)*</td>
</tr>
<tr>
<td>JPERotR</td>
<td>MCTE</td>
<td>6.35±2.10</td>
<td>4.68±1.68</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>5.38±1.96</td>
<td>3.73±1.46</td>
</tr>
<tr>
<td></td>
<td>Mean difference (95%CI); Effect size (d).</td>
<td>0.98 (-0.33 to 2.28)</td>
<td>0.95 (-0.06 to 1.96)</td>
</tr>
</tbody>
</table>

MCTE= motor control therapeutic exercise; MI= motor imagery; APV= activation pressure value; HPV= highest pressure value; JPEFlex= joint position error flexion; JPEExt= joint position error extension; JPERotL= joint position error left rotation; JPERotR= joint position error right rotation. 

*\(p<0.05\)

**\(p<0.001\)
Secondary Outcomes

Cervical ROM. Statistically significant differences in cervical ROM were found in both groups when the pre-intervention data was compared with the post-intervention data; however, the Mann-Whitney U-test showed no statistically significant differences between groups. The descriptive data and multiple comparisons are presented in Table 4.

Neck flexor endurance and fatigue perception. Statistically significant differences in group x time interaction were found for only for VAFS (F = 10.38, p = 0.03; $\eta^2_p = 0.22$). Regarding pre- to post- interaction for both groups, statistically significant differences were found for the deep neck flexor endurance test (F = 119.80, p < 0.001; $\eta^2_p = 0.75$) and VAFS (F = 4.2, p = 0.047; $\eta^2_p = 0.1$). Post hoc analysis revealed differences between pre- and post-intervention in both groups but not between groups (p<0.001) for the deep flexor endurance test; however, there were differences between groups post-intervention in the VAFS (p<0.001) and only pre-post differences in the MCTE-MI group (p<0.001). The effect sizes were greatest in the MCTE-MI group in both measures, especially in the neck flexor endurance test ($d = 1.50$). The descriptive data and multiple comparisons are presented in Table 5.

DISCUSSION

This study was designed to determine the effect of MI combined with a MCTE program on the cervical region in asymptomatic subjects. This study provides new evidence of the effects of MI and MCTE on sensorimotor variables measured in the cervical region in asymptomatic subjects. An intervention of MCTE combined with MI was effective in improving

<table>
<thead>
<tr>
<th>Measure</th>
<th>Group</th>
<th>Median (1 and 3 quartile)</th>
<th>p-values from Wilcoxon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>Flex</td>
<td>MCTE</td>
<td>46.50 (42.50 &amp; 64.63)</td>
<td>51.75 (47.25 &amp; 69.38)</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>51.25 (47.88 &amp; 64.63)</td>
<td>55 (50 &amp; 67.25)</td>
</tr>
<tr>
<td></td>
<td>p-values from Mann-Whitney U test</td>
<td>0.33</td>
<td>0.48</td>
</tr>
<tr>
<td>Ext</td>
<td>MCTE</td>
<td>75 (62.88 &amp; 79.75)</td>
<td>76 (70.25 &amp; 81.5)</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>71.25 (70 &amp; 79)</td>
<td>78.75 (72.38 &amp; 81.75)</td>
</tr>
<tr>
<td></td>
<td>p-values from Mann-Whitney U test</td>
<td>0.81</td>
<td>0.39</td>
</tr>
<tr>
<td>Rot</td>
<td>MCTE</td>
<td>132.75 (126.63 &amp; 139)</td>
<td>135 (130.5 &amp; 153.63)</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>132.75 (119.13 &amp; 148.88)</td>
<td>147 (132.88 &amp; 157.38)</td>
</tr>
<tr>
<td></td>
<td>p-values from Mann-Whitney U test</td>
<td>0.97</td>
<td>0.36</td>
</tr>
<tr>
<td>Lat. flex</td>
<td>MCTE</td>
<td>89.25 (75.25 &amp; 101.5)</td>
<td>95 (78.5 &amp; 107)</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>93.25 (83.75 &amp; 111.75)</td>
<td>104.5 (90.5 &amp; 114.75)</td>
</tr>
<tr>
<td></td>
<td>p-values from Mann-Whitney U test</td>
<td>0.20</td>
<td>0.20</td>
</tr>
</tbody>
</table>

MCTE= motor control therapeutic exercise, MI= motor imagery, Flex= flexion, Ext= extension, Rot= rotation, Lat. Flex= lateral flexion.

* p < 0.05
** p < 0.01
craniocervical neuromotor control and the subjective perception of fatigue after effort, while MCTE in isolation did not produce changes for these same variables.

The results of the JPE, cervical ROM, and deep neck flexor endurance tests showed no statistically significant differences between groups, but statistically significant changes were observed within each group for these variables. The reported effect sizes (d) of the differences obtained in most of these variables are larger in the combined intervention group than in the MCTE group in isolation. Previous research supports the theoretical argument regarding the changes in the variables related to the cervical region for both study groups, and MI seems to have an additional effect on sensorimotor variables, such as cervical neuromotor control, perceived fatigue, and kinesesthetic sense in the normal subjects studied.

Craniocervical Neuromotor Control and Cervical Kinesthetic Sense

The main measures of this study assessed the cervical kinesthetic sense and craniocervical neuromotor control, measured by the ability to activate the deep cervical flexor muscles. These two variables serve an important proprioceptive role in the integration of sensorimotor control. Previous evidence has shown that MCTE can improve JPE,47 and the current results agree, based on the observation that both groups improved in this variable; however, MI may enhance outcomes beyond MCTE alone, since it has been studied in other investigations that MI may contribute to improving the precision of movement48,49 and integrating relevant proprioceptive information.50 It is important to note that extensive evidence supports MI practice and its effects on motor behavior and motor recovery.51–58 MI has been useful in patients that have had a stroke, have Parkinson's disease, have sustained spinal cord injury, and those who have had an amputation. In the case of post stroke rehabilitation, MI has demonstrated changes in cerebral activation observed with neurophysiological recordings and improvements in the performance of the paretic limb, increasing functionality.52,54

At present, the recovery strategies for cervical neuromotor control are based mainly on models of motor learning using therapeutic exercise, but there is no previous evidence on the use of MI to improve craniocervical neuromotor control. The current results show promising findings about improving craniocervical neuromotor control with the combination of MI and MCTE. Consistent with these results, several authors have demonstrated that MI combined with physical practice is effective in improving motor function.51,59,60 Adding the mental rehearsal (MI) to the practice of physical exercise resulted in much bet-

<table>
<thead>
<tr>
<th>Measure</th>
<th>Group</th>
<th>Mean±SD Pre</th>
<th>Mean±SD Post</th>
<th>Mean difference (95% CI); Effect size (d).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexors Endurance Test</td>
<td>MCTE</td>
<td>17.90±8.91</td>
<td>31.90±13.35</td>
<td>-14.00 (-17.88 to -10.12)**; d=-1.26</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>21.40±8.90</td>
<td>37.05±12.00</td>
<td>-15.65 (-19.53 to -11.77)**; d=-1.50</td>
</tr>
<tr>
<td>Mean difference (95% CI); Effect size (d)</td>
<td></td>
<td>-3.50 (-9.20 to 2.20)</td>
<td>-5.15 (-13.28 to 2.98)</td>
<td>d=-0.39</td>
</tr>
<tr>
<td>VAFS</td>
<td>MCTE</td>
<td>45.50±19.66</td>
<td>49.00±17.21</td>
<td>-3.50 (-12.05 to 5.05); d=-0.19</td>
</tr>
<tr>
<td></td>
<td>MCTE+MI</td>
<td>46.00±19.97</td>
<td>30.25±12.92</td>
<td>15.75 (7.20 to 24.30)**; d=0.79</td>
</tr>
<tr>
<td>Mean difference (95% CI); Effect size (d)</td>
<td></td>
<td>-0.50 (-13.19 to 12.19)</td>
<td>18.75 (9.01 to 28.49)**</td>
<td>d=-0.02</td>
</tr>
</tbody>
</table>

MCTE= motor control therapeutic exercise; MI= motor imagery; VAFS= visual analog fatigue scale.
*p<0.05
**p<0.001
ter performance and reduced movement time execution when performing a specific task with the upper limb.51 Also, MI is an effective method for motor learning24,25,61,62 and the acquisition of new motor skills.24

Unlike other studies, craniocervical neuromotor control did not improve in the group that performed the MCTE alone, possibly because the MCTE program was performed at home without any supervision, which could have led to subjects performing the exercise with less precision. It is important to note that most studies of MCTE programs are conducted under the supervision of a physiotherapist. The authors believe that the combined intervention improved neuromotor control, because the MI provided more information for motor learning and sensorimotor integration and promoted retention and acquisition of motor skills,63–66 and suggest that this may be helpful when practicing at home without supervision to achieve a better performance.

Cervical Range of Movement
Prior scientific evidence has shown that MCTE improves cervical ROM.67,68 Thus, it is assumed that the improvement observed in the cervical ROM was a result of the MCTE program performed by both groups. Therefore, MI does not produce a significant effect on ROM, and for that reason, no significant differences between groups were found in this variable. Unlike the current results, other authors have found positive effects in improving flexibility through the combination of MI and physical practice in healthy athletes.55,69 For example in a study by Guillot et al55 that included MI in flexibility training, ROM improved after training. In present study, the subjects were healthy non-athletes; therefore, the improvements observed by Gillot et al55 may have been due to the high learning ability of the athletes in terms of MI training.70

Muscular Endurance and Fatigue Perceived
No statistically significant differences were observed between the groups for the variable neck flexor endurance, but there were differences in the pre- and post-intervention results in each group, which could be due to the practice or performance of the exercise program. These results suggest that MI does not influence increases in muscular endurance. The current results differ from many studies that show changes in muscle strength and voluntary torque production after MI alone or in combination with physical activity.71–74 When MI was compared to no intervention in those studies, an improvement of endurance was observed74,75 while in the current study the non statistically significant improvement could be due to the exercise itself, being not enough 4 weeks of intervention to obtain the results that other studies have when combining with exercise.73,75 One of the main differences between the previous studies and the current study is the areas of the body where the intervention was focused: the current focus on the neck muscles, while previous studies focused on the muscles of the upper and lower limbs. These areas of the body have a greater cortical representation (particularly the hands and ankles) than neck muscles,76 and this might make it difficult to achieve significant differences in strengthening in present sample.

Regarding the perception of fatigue as measured by the VAFS, the results showed a decrease only for the group that used a combination of MCTE and MI. In support of this, Catalan et al75 showed that a treatment to improve motor planning based on MI was effective in reducing fatigue in patients with multiple sclerosis. Also, Rozand et al77 recently showed that MI combined with physical practice does not exacerbate neuromuscular fatigue.

Practical and Scientific Implications
This is the first study investigating the effect of MI in combination with a MCTE program for the cervical region. The results of this research are promising with regard to the sensorimotor improvements obtained, but these data should be interpreted with caution because the study was conducted with asymptomatic subjects. It is not acceptable to extrapolate the results to patients with chronic neck pain. The authors of this study believe that the investigation of this type of intervention applied to symptomatic patients could generate additional information therapeutic alternatives for those with neck pain. Moreover, having found differences in asymptomatic subjects, the combination of MI with an MCTE program may be recommended as a useful preventive treatment in the fight against chronic neck pain.

Both of the intervention programs used in this research could be considered cost-effective since
there was only one supervision session, and the rest of the program was performed individually at home for 30 days, for an average of 10 to 20 minutes per session. Beinart et al\(^8\) disclosed in their systematic review that a large proportion of MI programs (focused on motor skills, performance, or strength improvement, and applied to all ages) have a total duration of 34 days and a duration of on average 17 minutes per session. Unlike the program used in the current study however, the MI programs in most other studies were conducted under professional supervision.\(^\text{78}\) The method seems to be a safe intervention, and so far, no author has reported adverse effects after its completion.\(^\text{79}\)

In this study, therapeutic exercise was combined with a MI program consisting of several activities related to different mental tasks, such as kinesthetic imagery, visual imagery, movement observation therapy, and MI plus exercise execution with mirror feedback. The authors believe that the combination of these mental tasks enhances motor learning, enabling better results in the combined intervention group. This study is the first to integrate all these mental tasks with physical practice.

### Study Limitations

This study has several limitations. The first and most important is that the subjects' ability to generate motor images has not been quantified. This is a factor to take into consideration, as there are validated instruments to measure this variable in healthy subjects with restricted mobility.\(^\text{80-82}\) It is important to consider since it may influence the efficiency of generating images.\(^\text{83}\)

Secondly, variables were measured in only the short term, so it is necessary to measure the impact in the medium and long terms. Also, it could be considered a limitation that there was not a control group. It would also be interesting to include an experimental group with a supervised exercise program.

Another limitation is that our study did not measure exercise compliance, and the authors recommend that compliance be measured in future studies. Various mental tasks may produce an improvement in the acquisition of motor learning and skills and influence adherence to the program. However, this is speculation since a validated tool was not utilized to quantify the level of adherence. However, the authors did include motivation to increase compliance with the program, which is an important aspect of promoting adherence with exercise programs at home.\(^\text{84}\)

Finally, although there were no statistical differences between the sexes, the MCTE group was only 30% female, while the MCTE plus MI group was 50% female. Along these lines, recent studies investigated the differences between males and females in sensorimotor cortical representation, and there is much we do not know about how the female body is represented in the brain or how it might change with different reproductive systems, hormones, or experiences.\(^\text{85}\)

### CONCLUSIONS

The results of the current study show that combining MI with MCTE produced statistically significant changes in sensorimotor function variables of the craniocervical region and the perception of subjective fatigue. Both interventions showed statistically significant changes in all variables measured, except for craniocervical neuromotor control and the subjective perception of fatigue after effort in the MCTE group. However, APV (craniocervical neuromotor control), JPE flexion and JPE right rotation (cervical kinesthetic sense), cervical ROM, and neck flexor muscle endurance were not significantly different between the two groups. These findings must be interpreted with caution because the study population was comprised of asymptomatic subjects. Future studies should be directed toward performing the same study protocol for patients with neck pain in order to check whether the combination of MI and MCTE is more effective than MCTE alone for ameliorating their neck pain.

### REFERENCES

31. Medina C, Barquera S, Janssen I. Validity and reliability of the International Physical Activity


ABSTRACT

**Purpose/Background:** Assessment of postural sway with force plates can be affected by type of measurement and various clinical parameters such as age and activity level of the individual person. For this reason, variability is detected in postural reactions of healthy subjects without balance impairment. Test-retest reliability of postural sway in adolescent athletes has been measured using a force plate and additional test-retest studies have been suggested for subjects of different age groups with different activity levels. Therefore, the purpose of this research was to assess test-retest reliability of Tetra® Static Posturography in young adults with low physical activity level, and examine the relationship between posturography results and low activity level.

**Methods:** Young adults older than 18 years of age were included in the study. Demographic characteristics of the cases were recorded including age, weight, height, body mass index (BMI, kg/m²) and dominant extremity. Number of falls in the previous six months, lower body endurance (sit to stand test) and single-leg eyes closed stance test were recorded. Activity level of participants was determined according to the International Physical Activity Questionnaire (IPAQ). Posturographic evaluation of all volunteers was completed using the Tetra® Interactive Postural Balance System (Sunlight Medical Ltd, Israel). Fall risk and general stability index (SI) calculated by the Tetra® were recorded. Following the first test, measurements were repeated 24 to 48 hours later for reliability purposes.

**Results:** Sixty-five subjects (28 male, 37 female; mean age 22.2 ± 1.1 years, mean BMI 22.6±3.3 kg/m²) were evaluated. All participants were classified as minimally active according to mean IPAQ score (1042.1 ± 517.7 [231 – 2826] MET- minutes per week). ICC scores between the first and second tests for fall index and total stability index were excellent (ICC²,1 = 0.858, 0.850, respectively). Fall risk determined by using the Tetra® device was negatively correlated with lower body endurance (p = 0.001, r = -0.446), vigorous activity score (p = 0.011, r = -0.312) and total activity score (p = 0.029, r = -0.271), and positively correlated with single leg stance score (p = 0.001, r = 0.606). There was a weak correlation between fall risk history and the fall risk determined by using Tetra® device (p = 0.04, r = 0.255). There were no correlations between fall risk and height, weight, and BMI (p > 0.05).

**Conclusions:** The results demonstrated the high test-retest reliability of Tetra® interactive balance system in young healthy adults with low physical activity level. Future studies are needed to determine the effectiveness of increasing physical activity level on postural control.

**Keywords:** Balance, physical activity level, static posturography

**Level of Evidence:** III

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**ORIGINAL RESEARCH**

**TEST-RETEST RELIABILITY OF TETRA® STATIC POSTUROGRAPHY SYSTEM IN YOUNG ADULTS WITH LOW PHYSICAL ACTIVITY LEVEL**

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Nur Doğanlar²
Emine Çelik²
Ayş Sümeysra Engin²
Semih Akkaya, MD³
Harun R. Gungör, MD³
Füsun Şahin, MD¹

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INTRODUCTION

Postural stability requires complex integration of multiple inputs from the vestibular, visual, and somatosensory organs in the central and peripheral nervous systems. Adults with high postural sway and diminished postural control fall more frequently and due to these falls may have a higher fracture risk than subjects with good postural control. Falls resulting in fracture or other musculoskeletal injury have personal, economic, and social consequences along with immobilization and morbidity.\(^{1,4}\) Although postural stability disorders are diagnosed more frequently in the older population, higher fall risk and fracture incidence have been reported in the literature that examines young adults with poor postural stability and excessive postural sway.\(^{4,6}\) In addition, more than 97% of most frequently encountered upper extremity fractures in young adults have been reported to occur due to falls.\(^{5}\) Diagnosis of postural disorders, prevention of falls, and rehabilitation of postural stability are all important issues in decreasing health expenses.

Several methods are used for evaluation of postural control in clinical practice including static and dynamic posturography.\(^{7}\) Static or dynamic computerized posturography gives quantitative data while evaluating the vestibular, visual and somatosensory systems. Therefore, sensitivity and specificity of this evaluation method is higher than the other methods in terms of diagnosis of specific organ systems causing postural stability disorders.\(^{8}\) On the other hand, static computerized posturography has an advantage of shorter evaluation period and less expensive equipment compared to dynamic computerized posturography devices.\(^{7}\) However, intrinsic variability of the body’s center of pressure (COP), age of the patient, and equipment used in testing are all variables affecting reliability and validity of this method for obtaining quantitative measurements.\(^{7,9}\)

It has been reported that type of the measurement, age of the patient, comorbidities, and difficulty levels of balance tasks all affect posturography results.\(^{10}\) For this reason, variability in results of posturography measurements are seen in the postural reactions of healthy subjects without balance impairment. This variability results in unreliable outcomes, and there is limited and inconclusive research available regarding the test-retest reliability of posturography devices.\(^{10-12}\) Therefore, it has been suggested that while evaluating test-retest reliability, homogenous groups of subjects in specific age groups should be utilized in studies to decrease inter-subject variability in balance reactions.\(^{13-15}\)

Test-retest reliability of postural sway evaluation measured with force plates in adolescent athletes has been reported and further test-retest studies have been suggested for different age groups and for subjects with a variety of activity levels.\(^{16}\) The Tetrax® Interactive Static Posturography System (Tetrax®) (Sunlight Medical Ltd, Israel) has been used to measure postural stability in several previous studies evaluating different age groups and various patient populations.\(^{17-21}\) However, to the authors’ knowledge, the Tetrax® device has not been tested for reliability in young adults with low physical activity level. Therefore, the purpose of this research was to assess test-retest reliability of Tetrax® Static Posturography in young adults with low physical activity level, and examine the relationship between posturography results and low activity level.

MATERIALS AND METHODS

Young adults older than 18 years of age who were minimally physical active as defined by the International Physical Activity Questionnaire (IPAQ) were included in the study.\(^{22}\) The IPAQ short version was used to define daily activity levels and frequency of activities of the subjects. The questionnaire includes information about vigorous physical activity duration (soccer, basketball, aerobic, fast bicycling, weight lifting, heavy labor, etc.), moderate physical activity duration (light weight laboring, moderate bicycling, traditional dancing, dancing, bowling, table tennis, etc), duration of daily walking, and duration of daily sitting in minutes. Total physical activity score as a basal metabolic equivalent (Metabolic Equivalent Task-MET minutes per week) can be calculated according to the data obtained from IPAQ. Total physical activity score of participants was classified as inactive (less than 600 MET minutes per week), minimally active (between 600 to 3000 MET minutes per week), and active (more than 3000 MET minutes per week) according to recommendations in the IPAQ.\(^{22}\)

Exclusion criteria included history of inflammatory disease, inner ear disorder impairing postural
stability, history or current complaint of vertigo or dizziness, marked visual impairment, orthopedic disability or history of surgery related to lower limbs, neurological disorders and peripheral neuropathy, and athletic participation in sports (participation in any type of sports, including recreational exercise at least 4 days/week). Ethical approval was obtained from ethical committee of Pamukkale University Medical Faculty.

Volunteers who met the aforementioned inclusion/exclusion criteria were enrolled in the study. Demographic and anthropometric characteristics of the subjects were recorded including age, weight, height, body mass index (BMI) in kg/m², occupation, and dominant extremity. Number of falls in the prior six months was recorded. A fall was defined as an unintentional episode of a fall to the ground. Falls which were the result of fainting, dizziness, loss of consciousness, sustaining a violent blow, or other overwhelming external factor were excluded. Sleep quality of the subjects were also recorded using Sleep Quality Numeric Rating Scale that assesses the quality of sleep in the previous 24 hours on a numeric rating scale ranging from 0 (best possible sleep) to 10 (worst possible sleep).

Functional status of the participants was evaluated with lower body endurance (sit to stand test) and single-limb stance test. Lower-body endurance was tested with the subject sitting on a stable chair with the seat height of approximately 43 cm with arms crossed over the chest, and then asked to perform as many sit to stand repetitions as possible in 30 seconds. Total number of stands executed was used as the test value. Higher values indicate better lower body endurance.

For the single limb stance test, participants were asked to stand as long as possible on their extended dominant leg with eyes closed. During this test, the knee of the non-dominant side was fully flexed and fixed on gluteal region by ipsilateral hand. When the subject lost balance, he or she was allowed to touch contralateral foot to the ground. Loss of balance was defined as the touch of contralateral foot to the ground. The number of balance losses in 30 seconds was recorded, therefore higher values indicated worse results. After each break, the same position was repeated until the 30 seconds session was completed for the single limb stance test.

Postural control assessment was performed before functional tests in order to prevent the possibility of fatigue. Posturographic evaluation was performed with the Tetrax®. This system involves evaluation of static postural balance by recording vertical pressure fluctuations in four different power plates when the subject is standing barefoot on the device with the arms freely hanging next to the body. Hand pieces are present on both sides of the device that allows subjects to use these metal bars for stability when needed. The Tetrax® has a computer and dedicated software system, from which all the data were obtained. (Figure 1) Input from the plates is integrated and processed by a computer. Subjects were instructed to begin by placing their feet side by side on lined places of plates in shape of feet, not to speak and move during task. Measurements are made in eight different conditions, each with the same technique, sequence, and directions (each position takes about 40 seconds): (i) head straight, eyes open, on hard ground; (ii) head straight, eyes closed, on hard ground; (iii) head straight, eyes open, on soft ground (foam under feet); (iv) head straight, eyes closed, on soft ground; (v) head turned to the right, eyes closed, on hard ground; (vi) head turned to the left, eyes closed on hard ground; (vii) neck fully extended, eyes closed, on hard ground; and (viii) neck fully flexed, eyes closed, on hard ground. Vestibular, visual and somato-sensorial inputs are recorded in each of the eight different positions to evaluate static postural balance and fall risk.

Measurements were performed at the same time period during the day (around 11:00 am). Following the first test, measurements are repeated 24 to 48 hours later. For each subject, fall risk and general stability index (SI) as calculated by the Tetrax® were recorded. Higher stability index and fall risk shows poorer postural performance. Fall risk obtained from the Tetrax® is a numerical value in between 0 and 100 (low fall risk, 0-35; moderate fall risk, 36-57; high fall risk, 58-100).

Data were analyzed with Statistical Package for Social Sciences software (SPSS Version 17, Chicago, IL, USA). Descriptive statistics (including mean ± stan-
standard deviation, frequency, and percentage) were calculated. Intra-class correlation coefficient (ICC with the confidence interval 95%) was used to examine test-retest reliability of postural balance data from the device. ICC score in the range of 0.00-0.49 was considered poor, 0.50-0.74 moderate and 0.75-1.00 excellent reliability. Spearman correlation analysis was used to examine the correlation between fall risk and clinical variables. Statistical significance was set at p < 0.05. An a priori power analysis revealed that 65 subjects should be included in the study for 80% power (D=0.015, β=20, α=0.05).

RESULTS
Sixty-five subjects (28 male, 37 female; mean age 22.2 ± 1.1 years, mean height 1.70±0.1 meters, mean weight 65.9±13.4 kg, mean BMI 22.6±3.3) were included in the study. In 56 (86.2%) of the subjects, dominant extremity was right side. Mean total physical activity score of the subjects was 1042.1±517.7 (MET-minutes per week) and mean sitting duration was 661.8±105.5 (minute per day). Demographic and clinical characteristics of the patients are summarized in Table 1.

ICC’s between first and second tests for fall index (0.858) and total stability index (0.850) were excellent. ICC values of first and second measurements for fall index, total SI, and ICC values of stability index of eight different positions of the subjects are presented in Table 2.

Relationships between fall risk obtained from posturographic evaluation and clinical parameters are summarized on Table 3. Fall risk determined by using Tetrax® device in minimally active young adults was weakly negatively correlated with lower body endurance (p=0.001, r=-0.446), vigorous activity score (p=0.011, r=-0.312) and total activity score (p=0.029, r=-0.271), and moderately positively correlated with single limb stance score (p=0.001, r=0.606). There was a weak correlation between fall risk history and the fall risk determined by using Tetrax® device (p=0.04, r=0.255). There were no correlations between fall risk and height, weight, and BMI (p>0.05).

DISCUSSION
The most important finding of this study is that test-retest reliability of Tetrax® Static Posturography...
Table 1. **Demographic, clinical and posturographic data of the subjects**

<table>
<thead>
<tr>
<th></th>
<th>Mean ± Standard Deviation (Min-Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>N= 65</strong></td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>22.2 ± 1.1 (20 - 25)</td>
</tr>
<tr>
<td>Height (meters)</td>
<td>1.70 ± 0.1 (1.55 - 1.94)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>65.9 ± 13.4 (43 - 95)</td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>22.6 ± 3.3 (16.2 - 31.9)</td>
</tr>
<tr>
<td>Sleep Quality in previous 24 hours</td>
<td>3.1 ± 1.9 (0 - 10)</td>
</tr>
<tr>
<td>Fall number in previous 6 months</td>
<td>0.1 ± 0.3 (0 - 2)</td>
</tr>
<tr>
<td>Sit to stand test (Number of stands/30 sec.)</td>
<td>18.9 ± 3.4 (14 - 28)</td>
</tr>
<tr>
<td>Single limb stance test (Number of balance losses/30 sec.)</td>
<td>1.4 ± 1.4 (0 - 5)</td>
</tr>
<tr>
<td>Vigorous physical activity (MET-min/week)</td>
<td>113.2 ± 266.0 (0 - 1140)</td>
</tr>
<tr>
<td>Moderate physical activity (MET-min/week)</td>
<td>126.5 ± 224.6 (0 - 720)</td>
</tr>
<tr>
<td>Walking activity (MET-min/week)</td>
<td>802.4 ± 418.2 (231 - 2772)</td>
</tr>
<tr>
<td>Total physical activity (MET-minutes per week)</td>
<td>1042.1 ± 517.7 (231 - 2826)</td>
</tr>
<tr>
<td>Sitting duration (min/day)</td>
<td>661.8 ± 105.5 (480 - 900)</td>
</tr>
</tbody>
</table>

**MET=** Metabolic Equivalent Task

Table 2. **Fall index and stability index values of cases in first and second posturographic tests**

<table>
<thead>
<tr>
<th></th>
<th>First Posturography</th>
<th>Second Posturography</th>
<th>p</th>
<th>ICC, (min-max)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>N= 65</strong></td>
<td>Total Fall Index</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>47.9 ± 26.6 (2-100)</td>
<td>48.6 ± 25.5 (6-100)</td>
<td>0.001</td>
<td>0.858 (0.768-0.914)</td>
</tr>
<tr>
<td><strong>Total Stability Index</strong></td>
<td>185.3 ± 46.7 (108.4-341.2)</td>
<td>180.7 ± 45.0 (107.0-362.7)</td>
<td>0.001</td>
<td>0.850 (0.755-0.909)</td>
</tr>
<tr>
<td><strong>NO SI</strong></td>
<td>18.8 ± 6.3 (10.4-37.5)</td>
<td>17.9 ± 5.1 (10.8-38.6)</td>
<td>0.001</td>
<td>0.746 (0.583-0.845)</td>
</tr>
<tr>
<td><strong>NC SI</strong></td>
<td>22.2 ± 6.1 (13.1-40.9)</td>
<td>21.4 ± 5.6 (13-41)</td>
<td>0.001</td>
<td>0.818 (0.702-0.889)</td>
</tr>
<tr>
<td><strong>PO SI</strong></td>
<td>19.1 ± 4.6 (12.7-34.7)</td>
<td>19.2 ± 6.3 (8.4-54.4)</td>
<td>0.006</td>
<td>0.470 (0.132-0.677)</td>
</tr>
<tr>
<td><strong>PC SI</strong></td>
<td>26.9 ± 5.4 (17.1-41.7)</td>
<td>26.3 ± 7.3 (16.3-50.2)</td>
<td>0.001</td>
<td>0.740 (0.574-0.841)</td>
</tr>
<tr>
<td><strong>HR SI</strong></td>
<td>23.9 ± 6.1 (13.4-42.5)</td>
<td>24.1 ± 6.8 (11.2-57.4)</td>
<td>0.001</td>
<td>0.832 (0.724-0.897)</td>
</tr>
<tr>
<td><strong>HL SI</strong></td>
<td>23.3 ± 7.2 (9.4-54.2)</td>
<td>24.3 ± 9.7 (11.5-80.7)</td>
<td>0.001</td>
<td>0.679 (0.474-0.804)</td>
</tr>
<tr>
<td><strong>HB SI</strong></td>
<td>24.7 ± 7.8 (12.7-46.6)</td>
<td>24.9 ± 8.0 (11.2-54.4)</td>
<td>0.001</td>
<td>0.863 (0.775-0.916)</td>
</tr>
<tr>
<td><strong>HF SI</strong></td>
<td>23.6 ± 7.4 (12.2-51.1)</td>
<td>22.4 ± 6.6 (7.9-39.8)</td>
<td>0.001</td>
<td>0.864 (0.777-0.917)</td>
</tr>
</tbody>
</table>

**NO=** Head straight, eyes open, on hard ground; **NC=** Head straight, eyes closed, on hard ground; **PO=** Head straight, eyes open, on soft ground; **PC=** Head straight, eyes closed, on soft ground; **HR=** Head turned to right, eyes open, on hard ground; **HL=** Head turned to left, eyes closed, on hard ground; **HB=** Cervical extension, eyes closed, on hard ground; **HF=Cervical flexion, eyes closed, on hard ground. **SI= Stability index; higher values indicate worse postural stability. **ICC= Intraclass correlation coefficient.
System is high for output values for fall risk and stability index in young adults with low physical activity level. According to the results of this study, as the lower body endurance, vigorous activity score, and total activity score increase, Tetrax® measured fall risk decreases. Additionally, significant positive correlation was detected between score of single limb stance (number of balance losses in 30 seconds) and Tetrax® measured fall risk, indicating that greater losses of balance occur there is a greater fall risk.

In previous studies, postural control has been evaluated with force plates, and validity of test-retest reliability in young athletes has been reported. However, test-retest reliability of Tetrax® static posturography system in young adults with low physical activity level has not been previously investigated. Test-retest reliability of postural stability scores with Tetrax® has been demonstrated with no learning effect in older women and autistic children. Similarly, there was no significant difference between the first and second evaluation of fall risk with Tetrax® in young adults with low physical activity level. This supports the theory that learning effect does not influence the results in this system. Fall risk determined by using Tetrax® device in sedentary young adults was weakly negatively correlated with lower body endurance, vigorous activity score and total activity score. In addition, only a weak correlation between fall risk and number of falls at last six months existed in healthy young adults with low activity in our study. The weak correlation between number of falls in the previous six months and fall risk may be attributed to the low population size that reported falls in the previous six months in this group of subjects. Therefore, investigation of the effects of increasing physical activity level on fall risk in young adults in further prospective randomized studies using this reliable assessment method will provide additional results, which could assist in planning rehabilitation programs for prevention of fall risk.

In addition to specific vestibular or central disorders causing postural stability disturbances, visual problems and other sensorimotor problems due to aging have been described as resulting in deterioration of balance. However, there was no correlation between fall risk and age of the subjects in our study. Strict exclusion criteria, and homogenous distribution of the young adults in terms of age might have resulted in this finding. Larger groups with more heterogeneous distribution of age of the subjects in future studies will allow for evaluation of the correlation between fall risk and age.

Postural stability of healthy subjects before and after a 24-hour sleepless period was evaluated in a previous study, and it was reported that fatigue due to sleeplessness might affect the postural stability. Therefore, all of the current subjects were evaluated at almost the same time of day, in order to minimal-

<table>
<thead>
<tr>
<th>Table 3. Relationships between fall risk and clinical parameters</th>
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<tbody>
<tr>
<td>N= 65</td>
</tr>
<tr>
<td>Fall Risk – Age</td>
</tr>
<tr>
<td>Fall Risk – Height</td>
</tr>
<tr>
<td>Fall Risk – Weight</td>
</tr>
<tr>
<td>Fall Risk – Body Mass Index</td>
</tr>
<tr>
<td>Fall Risk – Sleep Quality</td>
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<tr>
<td>Fall Risk – Number of falls in last 6 months</td>
</tr>
<tr>
<td>Fall Risk – Previous Fall history</td>
</tr>
<tr>
<td>Fall Risk – Sit to stand test</td>
</tr>
<tr>
<td>Fall Risk – One leg stance</td>
</tr>
<tr>
<td>Fall Risk – Vigorous activity score</td>
</tr>
<tr>
<td>Fall Risk – Moderate activity score</td>
</tr>
<tr>
<td>Fall Risk – Walking score</td>
</tr>
<tr>
<td>Fall Risk – Total Physical activity score</td>
</tr>
<tr>
<td>Fall Risk – Daily sitting duration</td>
</tr>
<tr>
<td>*: p&lt;0.05</td>
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</table>
ize the potential effect of sleeplessness. The mean sleep quality of the subjects in the current study was approximately 3 (0 = best possible sleep, 10 = worst possible sleep). No relationship was detected between sleep quality and fall risk. This is likely due to homogenous distribution of the subjects in terms the overall good sleep quality experienced by the whole group.

One of the limitations of the current study is that data for fall frequency was recorded according to subjects’ recall over the prior six months. Another limitation of the current study is that the study population consisted of only young (20-25 years of age) healthy adults with sedentary life styles, the results cannot be generalized to other age groups and patients with balance disorders or to more active young adults. Repeating the study in wider and heterogeneous group of patients will provide more detailed information about fall risk in different age groups and in specific disorders.

**CONCLUSIONS**

This results of this study demonstrate the high test-retest reliability of Tetrax® interactive balance system for testing postural stability in young healthy adults with low physical activity levels. Correlations between performance measures related to endurance, activity level, and postural stability and fall risk exist.

**REFERENCES**


ABSTRACT

Background: Runners sustain high injury rates. As greater numbers of individuals continue to run past the age of 60, normal physiological changes that occur with aging may further contribute to injuries. Male and female runners demonstrate different mechanics and injury rates. However, whether these mechanics further diverge as runners age and whether or not this potential divergence in mechanics may or may not be associated with a potential for increased injury risk is unknown.

Hypothesis/Purpose: The purpose of this study was to compare measures of loading and lower extremity coupling during running with respect to age and sex. It was hypothesized that males and females would demonstrate increasingly diverging mechanics with increased age.

Methods: Forty-one subjects were placed in four groups: younger males (n = 13), younger females (n = 6), older males (n = 16), and older females (n = 6). Ten running trials were collected and analyzed for each subject. Kinematic data were collected and reconstructed using a nine-camera motion analysis system and commercial software. Vertical loading rate (VLR), initial (GRF₁) and peak vertical ground reaction force (GRF₂) and lower leg joint coupling were calculated for each subject. Analysis was performed using a 2-factor ANOVA (sex X age) to determine differences between groups during the stance phase of running.

Results: Compared to younger subjects, older subjects demonstrated higher GRF₁ per body weight (Y: 1.70 (0.19), O: 1.96 (0.23), p < 0.01), higher VLR in body weight/second (Y: 44.17 (6.73), O: 52.76 (8.39), p < 0.01) and lower GRF₂ per body weight (Y: 2.47 (0.18), O: 2.35 (0.18), p = 0.04). However, no differences existed between males and females or further diverged in the older subjects. There were no differences between or within groups in joint coupling. Finally, no significant differences were seen between sexes and no interactions were found between any variables in the current study.

Conclusions: Older runners experience greater GRF₁ and VLR and lower GRF₂. These are factors previously associated with tibial loading and stress fractures. Males and females do not differ on these factors suggesting older female runners may be at no greater risk than younger runners or male runners for lower extremity bony injury based on normal mechanics.

Key words: Aging, coupling, loading, running, sex

Level of Evidence: 3

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INTRODUCTION

Participation in long-distance running has steadily increased in the past 30 years, with the greatest increases seen in Master's age groups (≥ 50 years old).1,6 Women in this age group have shown the most dramatic increases in participation and demonstrated greater improvement in race time compared to their male counterparts.1,6 Participation in running results in many health benefits including improved cardiovascular health, muscle strength, psychological health, and decreased risk of death.7-11 However, older runners are more frequently injured and may require more time to recover from injury when compared to younger runners.12-14 Due to physiological and mechanical changes with aging, biomechanical contributors to the increased injury rate in older runners may differ from those in the younger population.

Declines in muscular strength and flexibility that occur with aging have been reported and may contribute to particular biomechanical changes observed in the aging runner.15-18 Runners who are typically categorized into the “older” group are over age 50. A direct relationship exists between increasing age and increasing peak impact force and maximal loading rate at a controlled running speed.19 Furthermore, as age increases, sagittal plane knee range of motion decreases.19,20 Older runners land in greater knee flexion but experience less sagittal plane knee excursion during stance phase thus decreasing their force-absorbing capability.19,20 Finally, older runners undergo less transverse plane tibial range of motion and demonstrate decreased time to peak rearfoot eversion.20 In older females, knee internal rotation motion, ankle eversion motion, and knee adduction moment are decreased during running while loading rate is increased.21 Additionally, older runners experience increased loading rate and reduced propulsive peak vertical ground reaction force as well as reduced hip, ankle, and trunk sagittal plane excursions.22 While differences exist in running mechanics as individuals age, it is unclear whether these changes are consistent between the sexes.

Several differences have been identified in running mechanics between uninjured younger (typically under 40 years of age) adult males and females. Specifically, peak hip adduction, knee abduction, and hip internal rotation excursion are increased in females.23 Additionally, kinetic differences exist in negative work at the hip in the frontal and transverse planes. Younger adult uninjured females also exhibit decreased knee flexion angle and increased knee valgus angle during running.24 The physiological and structural changes that occur with aging differ between uninjured younger adult males and females. These include loss of bone density,25 muscle strength and flexibility.26 For these reasons, in part, it is plausible that each sex could demonstrate differing biomechanics with aging. Although numerous studies have evaluated differences in running mechanics related to aging and sex independently, only a single study exists that has evaluated the potential interactions between age and sex.27 Results from this study establish that differences exist between older males and females in frontal plane hip, knee, and ankle motion, with females demonstrating greater range of motion than males. These findings are consistent with those seen in younger adult female runners. However, there have been no studies to date that have evaluated kinetic differences between older males and females. It is unknown if ground reaction force variables or lower limb joint coupling differences exist between older males and females.

The purpose of this study was to compare measures of loading and lower extremity coupling during running with respect to age and sex. The authors hypothesize that males and females will manifest different age-related changes when comparisons are made based on vertical ground reaction force characteristics and joint coupling. Specifically, an increase in vertical loading rate, initial impact peak vertical ground reaction force, and a decrease in propulsive vertical ground reaction force in the older runners, with older females demonstrating the greatest increases. It was hypothesized that lower leg joint coupling will decrease in the older runners, with sex differences seen in younger runners persisting in the older runner.

METHODS

Thirteen younger males (age 33.6 ± 5.2 yrs), six younger females (age 33.1 ± 5.2 yrs), 16 older males (age 63.8 ± 3.8 yrs), and six older females (age 63.2 ± 3.4 yrs) volunteered for this cross-sectional study. The older group was between the ages of 60-74
years, while the younger group was between 20-39 years. These age ranges are consistent with previous studies that evaluated younger and older runners.19,20 A series of a priori power analyses based on each of the variables of interest ($\alpha = 0.05$, $\beta = 0.80$, $\delta = 0.5$) revealed the need for a range of 3-13 subjects per group. Because there were a limited number of older female runners available to recruit for the current study, six subjects were included in both the female groups. Mass and height were similar between groups (Table 1). All subjects ran greater than six miles per week and at least two days per week. All subjects were absent of lower extremity injury at the time of and for the six weeks prior to data collection. Injury was defined as musculoskeletal pain that prevented the subject from running for three consecutive training days within one week. Subjects with significant musculoskeletal, neurological and cardiovascular compromise or injury were also excluded. All included subjects provided written informed consent prior to participation. The study was approved by the East Carolina University and Medical Center Institutional Review Board.

A nine-camera OQUS 3 Qualisys Motion Capture System (Qualisys AB, Gothenberg, Sweden) was used to collect and reconstruct the three-dimensional coordinates of the retroreflective markers at 240 Hz. A custom marker set consisting of clusters of markers were attached to the pelvis, thigh, shank, and rearfoot of bilateral lower extremities (Figure 1).23

Table 1. Subject Characteristics: Mean (+/-sd)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mass in kilograms</th>
<th>Height in meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young</td>
<td>74.42 (13.57)</td>
<td>1.74 (0.09)</td>
</tr>
<tr>
<td>Old</td>
<td>72.16 (10.76)</td>
<td>1.76 (0.09)</td>
</tr>
<tr>
<td>Male</td>
<td>78.24 (10.20)</td>
<td>1.79 (0.07)</td>
</tr>
<tr>
<td>Female</td>
<td>61.36 (6.09)</td>
<td>1.66 (0.05)</td>
</tr>
<tr>
<td>Young Males</td>
<td>79.08 (12.6)</td>
<td>1.78 (0.06)</td>
</tr>
<tr>
<td>Young Females</td>
<td>62.31 (6.50)</td>
<td>1.65 (0.07)</td>
</tr>
<tr>
<td>Old Males</td>
<td>76.57 (8.58)</td>
<td>1.79 (0.07)</td>
</tr>
<tr>
<td>Old Females</td>
<td>60.40 (6.07)</td>
<td>1.66 (0.02)</td>
</tr>
</tbody>
</table>

Figure 1. Retroreflective marker placement for lower extremity model. Tracking markers are placed on the pelvis, bilateral thighs, bilateral lower legs and bilateral calcanei. Markers to determine joint centers and segment lengths are placed over greater trochanters, medial and lateral knees, medial and lateral malleoli and medial and lateral forefoot.

Subjects ran overground and were tested at a controlled running speed of 3.3 ± 0.2 m/s. Running speed was determined using photocells positioned 6 meters apart. Running speed was selected based on patient fitness and speeds reported in a previous
study comparing runners of different age groups. Subjects all wore the same running shoes (New Balance 825, New Balance 114 Athletic Shoe Inc., Boston, MA) provided by the lab. After allowing time for warm-up, subjects were given as many practice trials as needed to familiarize themselves with the laboratory setting and marker placement. Subjects were instructed to run without targeting the force plate. Ten successful trials on each leg were analyzed with a successful trial defined as the entirety of the subject’s foot making contact with the force plate, a running speed of 3.1 – 3.5 m/s, and the subject reporting that they were exhibiting their typical running pattern. All runners naturally ran with a rearfoot strike pattern confirmed by ground reaction force curves and foot-ground angle review.

Visual 3-D (C-Motion, Germantown, MD) was used to process the kinetic and kinematic data. Joint rotations were calculated via Cardan sequencing, where motion about the local z (vertical) axis at the knee was defined as internal/external rotation. The y and z axes are rotated 90° for the foot segment. Therefore, motion about the local y (vertical) axis at the rearfoot/tibia was defined as internal/external rotation. Mean curves were created for each group for tibia and knee motions and vertical GRF for the right lower extremity. A single AMTI force plate (AMTI, Watertown, MA) was used to collect force data at 1200 Hz. The force plate was located in the middle of a 25-meter runway.

The mean of the 10 trials for each subject was used for analysis of each dependent variable. Two-way analyses of variance (sex X age) were performed using JMP 9 software (SAS, Cary, NC) to assess for statistically significant differences between sex and age groups, and the interaction between the two. Post-hoc Student’s t tests (p≤0.05) were employed for comparisons on main effects and if interactions existed. The hypotheses that rearfoot coupling kinematics would decrease in the older runners was partially confirmed. VLR was calculated by dividing the GRF1 by the time after heel strike, in seconds, that GRF1 occurred.

RESULTS

Differences were found between older and younger runners in GRF1, GRF2, and VLR. Older subjects demonstrated higher GRF1 (Y: 1.70 (0.19), O: 1.96 (0.23) body weights (BW), p< 0.01), lower GRF2 (Y: 2.47 (0.18), O: 2.35 (0.18) BW, p=0.04) and a higher VLR (Y: 44.17 (6.73), O: 52.76 (8.39) BW/s, p< 0.01) than younger subjects (Figure 2). No significant differences were found between age groups in EV/TIR.

Interestingly, no significant differences were found between sexes on any variables. No significant interactions were found between any of the variables selected for analysis (Table 2).

DISCUSSION

The purpose of this study was to examine the effect of normal aging and sex on specific kinetic and kinematic variables. The hypotheses that vertical loading rate, impact peak, and propulsive peak of the vertical ground reaction force were partially confirmed. VLR and impact peak were increased in the older runners, regardless of sex, while propulsive peak was decreased. However, no sex differences in the ground reaction force variables were found to be significantly different. The hypotheses that rearfoot coupling kinematics would decrease in the older run-
ners and that sex differences would be maintained was not confirmed as no significant differences were found. Based on the results, differences exist in the loading response and force absorption characteristics between younger and older runners and no differences were found in loading response and force absorption characteristics between the sexes. Older runners demonstrate significant increases in GRF₁ and VLR while demonstrating decreased GRF₂. With increased age, changes were most evident in the GRF₁, GRF₂, and VLR. Older runners experienced a greater GRF₁ than younger runners. This result has been reported in previous studies and current values are similar to those previously reported. GRF₁ is important and has been correlated to increased incidence of tibial stress fracture as GRF₁ is associated with direct bone loading. Bone and ligament, the passive structures of the lower extremity, are responsible for absorbing the GRF₁. Older runners in the current study demonstrated a greater initial peak and although not measured in the current study, are more likely to have developed lower bone mineral density. Changes in bone health in the presence of higher loads during running may place these individuals at risk for lower extremity stress injuries such as tibial stress fractures. Other gait parameters such as stride length and stride frequency tend to reduce impact peaks and loading rate. During running, stride length tends to decrease with age and is thought to be a possible protective adaptation that reduces loading rate. Stride length and stride frequency were not collected in this study due to the subjects running over ground and not on an instrumented treadmill. However, it is important to note that an increase in VLR and GRF₁ were seen in the current sample. Thus, changes in stride frequency or stride length may not have existed in the current cohort, or if they did, did not result in reductions of force parameters. Furthermore, differences in foot strike position relative to the center of mass and dorsiflexion angle at foot strike were not analyzed and could also influence the ground reaction force variables.

| Table 2. Coupling and Ground Reaction Force Comparison between groups: Mean (+/-sd) |

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age</th>
<th>Interactions</th>
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</thead>
<tbody>
<tr>
<td>EV/TIR</td>
<td>M: 1.80 (1.18)</td>
<td>Y: 2.01 (1.42)</td>
</tr>
<tr>
<td></td>
<td>F: 2.38 (1.61)</td>
<td>O: 1.93 (1.27)</td>
</tr>
<tr>
<td>p = 0.28</td>
<td>p = 0.84</td>
<td>p = 0.62</td>
</tr>
<tr>
<td>GRF₁ (BW)</td>
<td>M: 1.82 (0.22)</td>
<td>Y: 1.70 (0.19)</td>
</tr>
<tr>
<td></td>
<td>F: 1.87 (0.33)</td>
<td>O: 1.96 (0.23)</td>
</tr>
<tr>
<td>p = 0.44</td>
<td>p &lt; 0.01</td>
<td>p = 0.38</td>
</tr>
<tr>
<td>GRF₂ (BW)</td>
<td>M: 2.41 (0.18)</td>
<td>Y: 2.47 (0.18)</td>
</tr>
<tr>
<td></td>
<td>F: 2.39 (0.22)</td>
<td>O: 2.35 (0.18)</td>
</tr>
<tr>
<td>p = 0.64</td>
<td>p = 0.04</td>
<td>p = 0.38</td>
</tr>
<tr>
<td>Loading Rate (BW/sec)</td>
<td>M: 47.50 (7.87)</td>
<td>Y: 44.17 (6.73)</td>
</tr>
<tr>
<td></td>
<td>F: 51.86 (10.23)</td>
<td>O: 52.76 (8.39)</td>
</tr>
<tr>
<td>p = 0.07</td>
<td>p &lt; 0.01</td>
<td>p = 0.99</td>
</tr>
</tbody>
</table>

EV/TIR = Eversion to tibial internal rotation ratio, GRF₁ = initial peak vertical ground reaction force, GRF₂ = maximum peak vertical ground reaction force, M = Males, F = Females, Y = Young, O = Old, YM = Younger Males, YF = Younger Females, OM = Older Males, OF = Older Females
Although not significantly different, there were notable differences in the increase of the GRF between sexes that may be clinically significant. Males increased 13% from younger to older while females increased by 21%. Females are also diagnosed with osteopenia or osteoporosis at a higher rate than males, and their bones may be less able to meet the higher demands from a higher initial peak.

While bone and ligament are responsible for absorbing the initial force peak during running, muscles absorb the active force peak created during GRF<sub>2</sub>. Interestingly, the opposite response is seen when examining GRF<sub>2</sub> as younger subjects experience a greater GRF<sub>2</sub> than older subjects. Similar results have been recognized in other studies examining the effects of age on running. While we did not directly measure muscle strength, it is likely that the older runners are weaker than the younger runners. Considering sarcopenia and declines in muscle strength with aging are well-documented, this result is expected as the first half of stance requires the quadriceps and gluteal musculature to eccentrically control the vertical center of mass displacement. This reduction in GRF<sub>2</sub> may be a neuromuscular accommodation to reduce the demands on the muscles responsible for controlling the descent of the center of mass during the first half of the stance phase. Vertical displacement was not calculated in this sample but could have influenced GRF<sub>2</sub>.

Differences in age are also seen in VLR where the older runners demonstrated a significantly higher VLR than younger runners. Loading rate, like GRF<sub>1</sub>, is related to bone loading and the potential for tibial stress fractures. Due to the anticipated decreased in bone mineral density and the faster loading rate experienced by older runners, they may be more likely than younger runners to experience bony injuries. However, one study found that there was no increased risk for stress fracture in older runners beyond what was expected based on other risk factors including vitamin D insufficiency, Type 2 diabetes, nicotine abuse, and others. Females experienced a faster loading rate than males and older females experienced the fastest rate of all the groups with a value of 58.26 BWs/s. Actual values for loading rate have been reported previously and vary between 50 and 130 BWs/sec. There is currently no evidence to suggest that there is a threshold in loading rate that corresponds with injury in human runners. Animal and finite-element models have been applied to determine a possible etiology. However, no consistent threshold for loading, loading frequency, or loading rate has been established.

No differences were seen in EV/TIR coupling between groups. Despite lack of significant findings, there are graphical differences between groups. Young females demonstrate a different movement pattern when compared to the other groups (Figure 3). Initially, rearfoot motion is dominated by tibial internal rotation before converting into almost exclusively eversion motion. This may suggest a “bottom-up” pronation pattern in which distal rearfoot eversion contributes to proximal lower extremity motion, leading to additional knee abduction, hip internal rotation, and hip adduction. Although, hip and knee kinematics were not reported in this manuscript, increased excursion of these positions during the stance phase of running has been linked to an increased incidence of anterior knee pain in female runners. Interestingly, the movement patterns are more similar between the older males and females than the younger runners, indicating a possible convergence of joint coupling with increased age. Whether this convergence is a positive or negative adaptation is unknown and calls for further study into its potential influence on injury risk.

This study is limited by the cross-sectional design and small female sample size. The current sample size is consistent with participation characteristics of runners as females make up 20-22% of participants in ultramarathons, 41% in marathons, and females older than 55 years old accounting for only 7% of all finishers in 2011. However, the small number of females in both the younger and older group may have reduced the power, particularly for vertical loading rate where the p value was 0.07. A post hoc power analysis suggests that 15 subjects would have been appropriate to detect differences. Future studies should attempt to recruit a greater number of older females to determine if differences exist in vertical loading rate between younger and older runners. Additionally, the external validity is limited to recreational runners participating at fairly low training loads per week. Finally, studies investigating...
potential differences in proximal kinematics and kinetics in older runners are warranted given relation to the risk of developing knee injuries.  

CONCLUSIONS

The findings of this study suggest that initial vertical ground reaction force and vertical loading rate are increased in both older adult male and female runners when compared to younger runners. Further, older runners demonstrate decreased peak vertical ground reaction force. These findings suggest that older runners have a decreased ability to absorb passive forces during loading and a decreased ability to generate active eccentric forces at midstance. Based on these findings, interventions and training paradigms could be developed that focus on altering passive and active landing mechanics. The results of the current study suggest that sex is not a factor related to differences in loading or joint coupling in young or old runners. Future work should focus on loading characteristics in injured older runners and intervention studies to determine if these loading parameters can be augmented.

REFERENCES


ABSTRACT

Background: Military personnel and first responders (police and firefighters) often carry large amounts of gear. This increased load can negatively affect posture and lead to back pain. The ability to quantitatively measure muscle thickness under loading would be valuable to clinicians to assess the effectiveness of core stabilization treatment programs and could aid in return to work decisions. Ultrasound imaging (USI) has the potential to provide such a measure, but to be useful it must be reliable.

Purpose: To assess the intrarater and interrater reliability of measurements of transversus abdominis (TrA) and internal oblique (IO) muscle thickness conducted by novice examiners using USI in supine, standing, and with an axial load.

Study Design: Prospective, test-retest study

Methods: Healthy, active duty military (N = 33) personnel were examined by two physical therapy doctoral students (primary and secondary ultrasound technicians) without prior experience in USI. Thickness measurements of the TrA and IO muscles were performed at rest and during a contraction to preferentially activate the TrA in three positions (hook-lying, standing, and standing with body armor). Percent thickness changes and intraclass correlation coefficients (ICC) were calculated.

Results: Using the mean of three measurements for each of the three positions in resting and contracted muscle states, the intrarater ICC (3,3) values ranged from 0.90 to 0.98. The interrater ICC (2,1) values ranged from 0.39 to 0.79. The ICC values of percent thickness changes were lower than the individual ICC values for all positions and muscle states.

Conclusion: There is excellent intrarater reliability of novice ultrasound technicians measuring abdominal muscle thickness using USI in three positions during the resting and contracted muscle states. However, interrater reliability of two novice technicians was poor to fair, so additional training and experience may be necessary to improve reliability.

Level of Evidence: 2b

Key Words: Ultrasonography; Transversus Abdominis; Body Armor

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INTRODUCTION

Deployed military personnel often carry more than 100 pounds of gear and equipment while on foot patrols.¹ Body armor comprises a significant portion of this load, with the ballistic vest weighing over 20 pounds.² Body armor is standard military issued equipment that is vital to the safety of military personnel, however, increased pain and disability may be caused by this increased load carriage. Spinal posture changes significantly during weighted conditions and increased forces are imparted on the lumbar sacral spine.³,⁴ Postural adaptations in response to additional loading, such as increased trunk flexion and forward head posture, are contributing factors to back pain.⁵,⁶ Konitzer et al. found a positive correlation between increased musculoskeletal pain and soldiers who wore body armor for more than four hours each day.⁶ Additionally, many soldiers reported that they attributed their back pain to wearing body armor rather than specific job related tasks or physical training with their units.⁶

Back pain is a significant concern in the military due to attrition from a unit during deployment or training and increased medical costs. Back pain is notorious for being difficult to treat with poor success rates, often becoming a chronic condition.⁷ Generally, treatment interventions for low back pain are varied and often have mixed results. However, there is evidence to suggest that the recurrence of back pain can be reduced with core stabilization exercise programs targeting the multifidi and transversus abdominis (TrA) muscles.⁸-¹² Improving core strength has been shown to help prevent injury among firefighters by 42% and reduce lost time from injuries by 62%.¹³ The ability to quantitatively measure muscle thickness under loading would be valuable to clinicians to assess the effectiveness of core stabilization treatment programs and could aid in return to work decisions as abdominal muscle thickness has been shown to correlate with strength.¹⁴ Ultrasound imaging (USI) has the potential to provide such a measure, but to be useful it must be both valid and reliable.

USI is a quick, inexpensive tool that has been shown to be valid for measuring muscle thickness during most isometric, submaximal muscle contractions.¹⁵ It has also been established as reliable for measuring the thickness of abdominal muscles in healthy and unhealthy adults.¹⁸,²⁰ A study by Teyhen et al. that also included novice US technicians with 20 hours of training demonstrated good (ICC >0.8) or excellent (ICC >0.9) interrater and intrarater reliability with TrA, internal oblique (IO), rectus abdominis, and lumbar multifidus muscle thickness imaging and measurements.²¹ Ultrasound imaging has been used to measure thickness of the muscles in the abdomen with the subject in multiple positions²² or with the muscles under load.²³ However, no studies to the authors’ knowledge have assessed the reliability of USI with individuals standing wearing body armor or assessed the reliability of technicians with very minimal training (less than five hours). As the vast majority of physical therapists do not learn or routinely perform USI, the training described in this study is relevant to practicing physical therapists. Therefore, the primary purpose of this study was to assess the intrarater and interrater reliability of measurements of TrA and IO muscle thickness conducted by novice examiners using USI in supine, standing, and with an axial load.

METHODS

Participants

Thirty-six active duty volunteers aged 18 to 40 were enrolled in this study by responding to fliers in the U.S. Army Medical Department (AMEDD) Center and School at Fort Sam Houston, TX. Participants were included if they were asymptomatic, without history of peripheral neuropathy or any condition that affected standing balance. Exclusion criteria included inability to ambulate or use of an assistive device during ambulation and inability to perform core stability exercises. During the initial appointment, participants were screened by a physical therapist using a brief clinical examination to rule out low back pain. The examination included lumbar range of motion and bilateral quadrant test to ensure pain-free, active motion within a normal physiological range and with provocation (positioning into combination extension and rotation). Participants signed consent forms pre-approved by the Brooke Army Medical Center Institutional Review Board (protocol C.2011.170).

Examiners

Two physical therapy students attending the U.S. Army-Baylor University Doctoral Program in Physical
Therapy at the AMEDD Center and School were the ultrasound technicians for the reliability study. Neither examiner had previously utilized USI in clinical practice or in research, and both examiners performed approximately 3-4 hours of hands-on training with the help of an experienced instructor who was familiar with the specific USI machine and protocol used in this study.

**Procedures**

A prospective, test-retest study design was used as part of a larger randomized controlled trial. Testing included USI of abdominal muscle thickness in hook-lying and standing with and without body armor. Testing of the three positions was standardized in this order of increasing task difficulty to avoid confounding related to fatigue of the abdominal muscles. Images of the TrA and IO were taken with a SonoSite M-Turbo ultrasound machine (SonoSite, Inc., Bothell, WA) in B-mode (brightness mode) with a 60 mm 2-5 MHz curvilinear array. Imaging for each of the three positions (hook-lying, standing, and standing with body armor) was performed three times by each examiner. This was done in order to average the results of three consecutive trials for each condition which has been shown to optimize intrarater reliability. While one examiner positioned the transducer, the other saved the image (Figure 1). To avoid an order effect related to fatigue or learning, the order of the imaging examiner was counterbalanced.

During the imaging, the US technician cued the subject using one of three methods in order to preferentially activate the TrA: the abdominal drawing in maneuver (ADIM), cutting off the flow of urine, or closing the anal sphincter. The method that best activated the TrA in each subject was used at both sessions. Based on the US images, the US technician determined when the participant correctly performed preferential TrA muscle activation using one of the previously described methods. In order to measure the muscles consistently, the anterior and lateral fascia of the TrA was aligned with the edge of the screen for each measurement (Figure 2). The subject's left side was imaged just superior to the iliac crest in order to standardize data collection (Figure 3).

In the hook-lying position, participants were supine with their knees bent and feet flat to minimize lordosis. In standing, participants lined up the base of each of their fifth metatarsals inside a 30.48 cm tile on the floor. The body armor used was the same model worn by service members currently engaged in combat operations (Point Blank Enterprises, Inc., Pompano Beach, FL). The manufacturer modified the body armor under the direction of the research team in order to allow access to the abdomen for US imaging while maintaining the structural integrity and weight distribution caused by the Ballistic Panels, Small Arms Protective Inserts, and Enhanced Small Arms Protective Inserts. All inserts were training grade but still possessed the same weight and size as the combat-grade inserts.

All images were measured independently by the same novice examiners who had conducted the US imaging on a separate date from the date of the capture of the image. Both examiners were blinded to the subject's group, to each other's measurements,
and to their own previous measurements. ImageJ software (V1.38t, National Institutes of Health, Bethesda, MD) was utilized to measure TrA and IO thickness midway between the medial and lateral borders on the screen (Figure 2).

**Statistical Methods**

Data entry and statistical analyses were performed using IBM SPSS Statistics 20 (Chicago, IL). Data from 33 participants was obtained for three measurement conditions (hook-lying, standing, standing with body armor) with three trials for each condition in resting and contracted states. The percent change in thickness for each muscle was determined based on the average of three trials for each position according to the equation below and multiplied by 100%.

\[
\Delta t = \left[ \frac{t_{TrA \text{ contracted}}}{t_{Total \ AB \text{ contracted}}} - \frac{t_{TrA \text{ resting}}}{t_{Total \ AB \text{ resting}}} \right]
\]

This equation calculates the relative change in the proportion of the TrA relative to the total lateral abdominal muscle thickness, with higher values indicating more change in TrA thickness and lower values indicating more change in IO and external oblique thickness. ICCs with 95% confidence intervals (CI) were calculated for intrarater reliability (model 3,3) and interrater reliability (model 2,1). The standard error of measurement (SEM) was calculated using the formula: SD x √[1-ICC]. Minimal detectable change (MDC) was calculated using the formula: 1.96 x SEM x √2. To determine the minimal change in thickness that represents a true change, MDCs were calculated with 95% confidence intervals.
RESULTS
A total of 36 military service members were enrolled and 33 (17 men, 16 women; average age 28 ± 4.9 years) completed the study. All participants successfully completed TrA muscle contractions by one of the three cuing methods, and the resting and contracted images were captured and measured.

With respect to intrarater reliability, all ICC values for novice ultrasound technician 1 ranged from 0.90 to 0.98 for the resting and contracted measurements in hook-lying, standing and standing with body armor for the TrA and IO. Similar values were found for the second novice technician and are therefore not included in the tables. The standard error of measurement ranged from 0.03 to 0.07 cm. The ICC values for percent activation are predictably lower ranging from 0.59 to 0.83 as it compounds the error to calculate this value. These values are summarized in Table 1. Inter-examiner reliability ICCs ranged from 0.39 to 0.79 with SEM values from 0.07 to 0.17 cm; these values are summarized in Table 2.

DISCUSSION
This study assessed the intrarater and interrater reliability of two novice ultrasound technicians’ ability to obtain values of muscular thickness for

<table>
<thead>
<tr>
<th>Table 1. Intrarater Reliability of Ultrasound Technician 1</th>
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<tbody>
<tr>
<td>ICC&lt;sub&gt;3,1&lt;/sub&gt; (95% CI)</td>
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<tr>
<td>----------------------------</td>
</tr>
<tr>
<td><strong>TrA in Hook-lying</strong></td>
</tr>
<tr>
<td>Rest</td>
</tr>
<tr>
<td>Contracted</td>
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<tr>
<td>% Activation</td>
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<tr>
<td><strong>TrA in Standing</strong></td>
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<tr>
<td>Rest</td>
</tr>
<tr>
<td>Contracted</td>
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<tr>
<td>% Activation</td>
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<tr>
<td><strong>TrA in Body Armor</strong></td>
</tr>
<tr>
<td>Rest</td>
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<tr>
<td>Contracted</td>
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<tr>
<td>% Activation</td>
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<tr>
<td><strong>IO in Hook-lying</strong></td>
</tr>
<tr>
<td>Rest</td>
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<tr>
<td>Contracted</td>
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<tr>
<td>% Activation</td>
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<tr>
<td><strong>IO in Standing</strong></td>
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<tr>
<td>Rest</td>
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<tr>
<td>Contracted</td>
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<tr>
<td>% Activation</td>
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<tr>
<td><strong>IO in Body Armor</strong></td>
</tr>
<tr>
<td>Rest</td>
</tr>
<tr>
<td>Contracted</td>
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<tr>
<td>% Activation</td>
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</tbody>
</table>

*Values in centimeters except % Activation
TrA= Transversus abdominis, IO= Internal Oblique
the TrA and IO. ICC values above 0.75 are considered excellent reliability,\textsuperscript{26} which was found with all intrarater reliability. While ICC values in this study for intrarater reliability are consistent with previous studies using USI of the abdominal muscles, the interrater reliability in this study was generally poor to fair (0.39-0.79) through all three positions in either resting or contracted states. Failure to establish quantitative guidelines for determining when the participant correctly performed preferential TrA muscle activation may be one reason for the poor to fair interrater reliability. The technicians' bias in selecting one of the three cueing methods could have introduced systematic error into measurement of TrA and IO thickness. A systematic review of the reliability of USI of lumbar trunk and abdominal muscles found excellent (ICC > 0.93) intrarater and interrater reliability for intraimage measurements.\textsuperscript{16} Interrater reliability for interimage measurements was also excellent (ICC > 0.90).\textsuperscript{16} Intrarater reliability for interimage measurements, however, were more variable (ICC 0.62-0.97).\textsuperscript{16} The authors of the

<table>
<thead>
<tr>
<th></th>
<th>ICC (_{2,1}) (95% CI)</th>
<th>Mean ± SD (cm*)</th>
<th>SEM (cm*)</th>
<th>MDC (cm*)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TrA in Hook-lying</strong></td>
<td></td>
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</tr>
<tr>
<td>Rest</td>
<td>0.39 (0.08-0.63)</td>
<td>0.30 ± 0.09</td>
<td>0.07</td>
<td>0.49</td>
</tr>
<tr>
<td>Contracted</td>
<td>0.62 (0.37-0.79)</td>
<td>0.49 ± 0.13</td>
<td>0.08</td>
<td>0.71</td>
</tr>
<tr>
<td>% Activation</td>
<td>0.25 (-0.07-0.53)</td>
<td>70.5 ± 36.2</td>
<td>31.3</td>
<td>157.4</td>
</tr>
<tr>
<td><strong>TrA in Standing</strong></td>
<td></td>
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<tr>
<td>Rest</td>
<td>0.72 (0.50-0.85)</td>
<td>0.43 ± 0.17</td>
<td>0.09</td>
<td>0.69</td>
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<tr>
<td>Contracted</td>
<td>0.46 (0.16-0.69)</td>
<td>0.60 ± 0.21</td>
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<td>1.04</td>
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<tr>
<td>% Activation</td>
<td>0.45 (0.14-0.69)</td>
<td>44.5 ± 34.0</td>
<td>25.1</td>
<td>114.0</td>
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<tr>
<td><strong>TrA in Body Armor</strong></td>
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<tr>
<td>Rest</td>
<td>0.69 (0.45-0.83)</td>
<td>0.40 ± 0.16</td>
<td>0.09</td>
<td>0.64</td>
</tr>
<tr>
<td>Contracted</td>
<td>0.66 (0.41-0.81)</td>
<td>0.61 ± 0.22</td>
<td>0.13</td>
<td>0.97</td>
</tr>
<tr>
<td>% Activation</td>
<td>0.51 (0.21-0.72)</td>
<td>57.5 ± 39.3</td>
<td>27.6</td>
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</tr>
<tr>
<td><strong>IO in Hook-lying</strong></td>
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</tr>
<tr>
<td>Rest</td>
<td>0.77 (0.59-0.88)</td>
<td>0.66 ± 0.18</td>
<td>0.08</td>
<td>0.89</td>
</tr>
<tr>
<td>Contracted</td>
<td>0.79 (0.61-0.89)</td>
<td>0.76 ± 0.21</td>
<td>0.10</td>
<td>1.03</td>
</tr>
<tr>
<td>% Activation</td>
<td>0.52 (0.22-0.73)</td>
<td>15.8 ± 13.5</td>
<td>9.4</td>
<td>41.7</td>
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<tr>
<td><strong>IO in Standing</strong></td>
<td></td>
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</tr>
<tr>
<td>Rest</td>
<td>0.78 (0.58-0.89)</td>
<td>0.76 ± 0.24</td>
<td>0.11</td>
<td>1.07</td>
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<tr>
<td>Contracted</td>
<td>0.76 (0.53-0.88)</td>
<td>0.90 ± 0.30</td>
<td>0.15</td>
<td>1.30</td>
</tr>
<tr>
<td>% Activation</td>
<td>0.53 (0.24-0.74)</td>
<td>18.1 ± 19.7</td>
<td>13.5</td>
<td>55.5</td>
</tr>
<tr>
<td><strong>IO in Body Armor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rest</td>
<td>0.64 (0.39-0.80)</td>
<td>0.76 ± 0.24</td>
<td>0.15</td>
<td>1.16</td>
</tr>
<tr>
<td>Contracted</td>
<td>0.76 (0.57-0.87)</td>
<td>0.95 ± 0.33</td>
<td>0.17</td>
<td>1.41</td>
</tr>
<tr>
<td>% Activation</td>
<td>0.61 (0.25-0.80)</td>
<td>26.2 ± 20.8</td>
<td>13.0</td>
<td>62.2</td>
</tr>
</tbody>
</table>

*Values in centimeters except % Activation

TrA= Transversus abdominis, IO= Internal oblique
systematic review also noted that greater measurement error was reported in measures obtained by novice examiners.\(^{16}\)

To the authors’ knowledge, this study was the first using novice raters with limited (less than five hours) ultrasound training and experience. A previous study conducted by Teyhen et al.\(^{21}\) used novice technicians consisting of two physical therapists and four physical therapy doctoral students who were instructed in 20 hours of US training and were evaluated for proficiency prior to data collection. Novice technicians with minimal training may still have good intrarater reliability to capture abdominal muscle measurements using USI with a TrA-cuing technique but are less likely to be standardized with more experienced technicians or therapists. Based on the results from this study, a standardized method with formal training for abdominal US measurement may be necessary to have interrater reliability values approaching those of experienced technicians.

Few studies have assessed the reliability of percent thickness from resting to contracted states of the abdominal muscles.\(^{20,23,24}\) Understandably, the ICC for percent thickness is considerably lower (.59-.83) due to the multiplied effect of error to calculate percent thickness. Consequently, it is important to note that determining the patient's percent thickness change may have less clinical benefit due to its decreased reliability for a novice US technician.

Only one previous study assessed the percent thickness change for a subject under a load.\(^{23}\) Reliability under a load may have been affected by the ability to maintain the same contact pressure of the transducer on the abdomen as used in the hook-lying and standing positions. This contact pressure could have affected how flattened the acquired image of the abdominal muscles was. Our novice examiners found it easier to maintain constant contact pressure in hook-lying than in standing conditions. Acquiring measurements in standing was also more difficult because the technician had to physically maneuver around the body armor to access the abdomen just above the iliac crest. Although the body armor had been modified to allow access, it was difficult to maintain the transducer in a position perpendicular to the skin because of the limited space afforded between the body armor and the subject’s body depending on their shape.

Study Limitations
All study participants were within healthy body mass index (BMI) range and a relatively narrow age range since all were active duty military. Increased superficial soft tissue (i.e., adipose) would require greater US depth resulting in a decrease in the scale of the muscles which could potentially cause decreased accuracy and reliability. This study is also limited since it did not evaluate the reliability of symptomatic individuals. Therefore, the results cannot be generalized to the injured or diseased population, especially as it relates to measuring the ability to preferentially contract the TrA. Future studies should validate these findings in similar healthy, as well as patient, populations. Lastly, the use of only two examiners is a limitation to the study. Future studies with more examiners should be encouraged, to validate these findings with other examiners and in other settings.

CONCLUSIONS
TrA and IO thickness measurements using USI in asymptomatic individuals using the average of three measurements is highly reliable within a single technician. Reliability between multiple technicians with minimal USI experience is low, so additional training and experience may be necessary to improve interrater reliability.

REFERENCES


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• The Kevin Wilk Traveling Fellowship Presentations
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