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TRAINING STRATEGIES AND MOVEMENT ASSESSMENTS IN ATHLETES AND NON-ATHLETES

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Matthew David Lewis, Student

Dr. Mark Abel, Major Professor

Dr. Heather Erwin, Director of Graduate Studies
TRAINING STRATEGIES AND MOVEMENT ASSESSMENTS
IN ATHLETES AND NON-ATHLETES

DISSERTATION

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Education at the University of Kentucky

BY
Matthew David Lewis
Lexington, KY

Co-Directors: Dr. Mark Abel, Associate Professor of Kinesiology and Health Promotion and Dr. J. W. Yates, Associate Professor Emeritus of Kinesiology and Health Promotion
Lexington, KY

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ABSTRACT OF DISSERTATION

TRAINING STRATEGIES AND MOVEMENT ASSESSMENTS IN ATHLETES AND NON-ATHLETES

This dissertation is composed of three manuscripts based on two studies related to training and assessment methods used to evaluate change and overall quality in measures of performance, postural control, and functional movement. Study one evaluated the effect of sand training on athletic performance and postural control. Study two investigated the effect of scoring strata of the deep squat (DS) component of the Functional Movement Screen (FMS) on the weight-bearing lunge test (WBLT), Star Excursion Balance Test (SEBT), and Lateral Flexion Test (LFT) in 101 male and female college students.

Study one results included significant overall improvements of the five repetition maximum (5RM) squat (p=0.002), and WBLT (p<0.001), indicating a positive effect of the training protocol regardless of surface. The standing long jump was the only outcome measure found to have a significant group*time interaction (p=0.047). After evaluation of the associated effect size, power, and minimum detectable change (MDC) scores it was determined that the most relevant results were related to the 5RM squat and WBLT. The change observed for these variables crossed (5RM) or closely approached (WBLT) the MDC threshold. We concluded that with generalized athletic performance training squat and WBLT performance can be improved.

Study two results indicated that limited dorsiflexion will lead to a reduction in DS performance and asymmetry of performance on the LFT may result in further movement limitations. Subjects scoring a one or two on the deep squat performed significantly lower (p<0.05) on the WBLT and anterior reach of the SEBT compared to those scoring a three. For the right side LFT there was a significant difference between a score of one and three (p=0.009) and a trend towards significance between scores of one and two (p=0.05). There was no significant difference between LFT performance on the left and right sides between scores of two and three. Results supported the previously established relationship between various measures of dorsiflexion and squat performance and establish a link between limited performance on the WBLT and poor performance on the FMS deep squat. Additionally, they suggest a link between asymmetrical LFT performance and further reductions in DS performance.
TRAINING STRATEGIES AND MOVEMENT ASSESSMENTS IN ATHLETES AND NON-ATHLETES

BY

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Dr. Mark Abel
Co-Director of Dissertation

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July 29, 2014
DEDICATION

To my parents for their prayers, support, and encouragement.

To my students past, present, and future for growing and learning with me.

To my professors all along the way for their knowledge, commitment, example, and support.

To Rachel for challenging me to test my limits, pushing me to be my best, encouraging me when I was at the end of my rope, and loving me no matter the outcome.

Thank you all.
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The following dissertation is largely an individual work, but it would not have been possible without the assistance, dedication, and hard work of a number of people. First, Dr. Mark Abel, my Dissertation Co-Chair, has provided insight, guidance, and valuable time to assist me throughout the process. In addition, Dr. Pat McKeon provided assistance throughout the duration of the project in many key areas and his knowledge and research experience were always valuable and greatly appreciated. I would also like to thank the complete Dissertation Committee, and outside reader, respectively: Dr. Mark Abel, Dr. J. W. Yates, Dr. Pat McKeon, Dr. Jody Clasey, Dr. Carl Mattacola, and Dr. Terry Malone. Each committee member has contributed to the completion of this project by providing their time and professional expertise and this project is better for their having been involved.

I would also like to express my thanks to the finest graduate assistant athletic trainers the University of Kentucky has ever produced: Tyler Schlosser, Kim Mace, Jackie Frilling, Kelley Seekins, and Catherine Beckemeyer. They have all supported my journey through higher education in countless ways and their support and flexibility were invaluable during this journey. I need to mention Brian Ray and thank him for his willingness to lend important timing equipment to me for the duration of data collection. Without his generosity, things would have been much more expensive. Finally, I would like to thank all of the subjects that volunteered to participate in this series of studies. Without you, this truly would not have been possible.

My pursuit of a PhD has truly been a journey. Early in my post-secondary education I was introduced to three mentors that have profoundly affected my academic, professional, and personal development over the past 15 years. I must say thank you to Christine and Dr. Tim Uhl, and Dr. Brian Zeller.

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CHAPTER 1
DISSERTATION INTRODUCTION

The research presented in the following chapters represents work conducted by the primary author and investigator in order to satisfy the requirements for completion of a PhD in exercise physiology from the University of Kentucky. These guidelines were set forth and reviewed by the Graduate School and members of the dissertation committee. The dissertation is presented in chapter format in an effort to present an organized research report. A thorough literature review summarizing the current evidence related to the training methods and surfaces, and assessment mechanisms utilized in the two completed studies comprises the second chapter. In addition, chapter two includes a review of relevant literature related to the reliability and validity of the outcome measures utilized as well as summary conclusions of literature related to each manuscript. Chapters three and four represent completed research manuscripts based on data collected as a part of the first study. Chapter five is the manuscript related to data collected as a part of the second study. Finally, chapter six presents a brief, integrated conclusion based on analysis of the results from both studies.

Study one evaluated the effect of training surface on athletic performance and postural control outcomes in a group of 17 female collegiate athletes representing the sports of volleyball, basketball, and soccer. The outcome measures are identified in Table 1.1. This study yielded two manuscripts, the first focusing on athletic performance and the second, on postural control. It is well established that athletic performance improves with appropriate volume, frequency, intensity, and specificity of training and research has also suggested this phenomenon occurs in regards to postural control [1-4]. Therefore, our initial hypotheses predicted improvements across all outcome measures due to the expected training effect, regardless of training surface. We further hypothesized that sand training would lead to additional improvement as a result of the unique characteristics of sand which were expected to elicit greater training adaptations. In support of this hypothesis, previously published results have cited improvements in various athletic performance measures [5-9]. Delimitations for this study included status as a collegiate varsity female athlete on one of the following teams: volleyball, basketball, or soccer. Assumptions included maximal effort for all outcome measures and compliances with request to refrain from additional lower body training outside of team sponsored off-season activities.
Table 1.1 Study One Outcome Measures

<table>
<thead>
<tr>
<th>Athletic Performance</th>
<th>Postural Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Jump (VJ)</td>
<td>Star Excursion Balance Test (SEBT)</td>
</tr>
<tr>
<td>Standing Long Jump (SLJ)</td>
<td>Weight-Bearing Lunge Test (WBLT)</td>
</tr>
<tr>
<td>T-test</td>
<td>Time to Boundary (TTB)</td>
</tr>
<tr>
<td>40 yd. Sprint</td>
<td></td>
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<tr>
<td>300 yd. Shuttle</td>
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<tr>
<td>Five Repetition Maximum Squat (5RM)</td>
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</table>

Performance of the 5RM and WBLT improved from baseline to post-test regardless of group assignment. These results demonstrate two things. First, the training protocol implemented was sufficient to induce improvement in these two outcome measures. Second, improvement in WBLT performance coincides with improvement in overall 5RM performance. This finding is supported by previous literature establishing a relationship between dorsiflexion range of motion at the ankle and correct performance of a weight-bearing squat [10-12].

The results of study one directed the design of our second research project. Utilizing the performance strata of the Functional Movement Screen (FMS) Deep Squat (DS), we evaluated their effect on measures of postural control and functional ankle range of motion in male and female college students. Outcome measures included the SEBT, WBLT, and Lateral Flexion Test (LFT). Subjects were volunteers from a general college student population ranging in age from 18-25 years. Based on our previous findings further developing the connection between functional dorsiflexion and squat performance, we hypothesized that individuals demonstrating limited WBLT performance would also fall into one of the two lower scoring strata of the FMS DS. Possible scoring strata for the FMS DS are 1) unable to perform movement task with assistance of compensatory strategy 2) able to correctly perform movement task with compensatory strategy 3) able to perform functional, symmetrical movement task without assistance of compensatory strategy [13, 14]. Delimitations for study two included status as a student officially enrolled at a participating institutions and an age between 18 and 25 years. Assumptions for this study included maximal effort where appropriate during the testing protocol and honest reporting of pain if present during FMS movements.

The results of study two supported our hypothesis. Subjects demonstrating poor performance on the WBLT were stratified in score category one or two, and were significantly
different than those performing highest on the WBLT were stratified in category three (p<0.001). This was also true for performance on the anterior (ANT) reach of the SEBT (p=0.001). These results are in agreement with previous authors whom have reported a positive relationship between WBLT and ANT reach of the SEBT [15]. These results demonstrate the effect of limited functional dorsiflexion on squat performance and the use of the FMS DS strata allow us to further evaluate these findings. The significant decrease in performance on the WBLT and SEBT ANT reach between FMS DS strata of three and two demonstrates the need for a compensatory strategy to overcome the limited functional ROM. This is provided in the form of a two inch heel lift which effectively provides additional dorsiflexion by placing the ankle into plantarflexion at the beginning of the squat. Since no significant difference was identified between functional dorsiflexion scores of subjects stratified as a two vs. one, it appears that an additional factor contributes to a further reduction in squat performance. Our results indicate that asymmetry in LFT performance may be this factor. We identified a significant difference between FMS DS strata of 1 and 3 (p=0.009), and a trend of near-significance between scores of 1 and 2 (p=0.05) indicating that decreased LFT performance contributes to further reduction in squat performance. Subjects stratified as a three demonstrated no right to left difference in LFT performance. However, those stratified as either a one or two had a minimum of an eight-second difference with the right side consistently presenting with a shorter hold time.

Our results provide further evidence to support the established connection between dorsiflexion and squat performance, as well as the relationship between the WBLT and SEBT ANT reach. Specifically, they indicate that decreased performance on the WBLT (< 10cm) and SEBT ANT reach (< 61% of leg length) result in FMS DS stratification at a score of two. Asymmetrical performance on the LFT (right/left difference greater than 8 seconds) coupled with limited WBLT performance, results in FMS DS stratification at a score of one. These results, combined with our previous findings related to WBLT and 5RM squat performance after a period of sand training indicate that WBLT performance may be improved with general athletic performance training and this may in turn result in improved squat performance as measured by the FMS DS. Further research is indicated to determine the best approach for reduction of the LFT asymmetry identified here.

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CHAPTER 2
REVIEW OF LITERATURE

Section One: Sand Training for Performance

Introduction

The use of sand as a training or competition surface is not new for athletic and recreational populations, but its use is becoming more popular [6]. Traditionally, sand has been used as an alternative training surface for distance runners and sand-based competition has been limited to portions of Iron Man events and lifesaving competitions [9, 16-19]. Among team-sports, athletes and coaches looking for a training edge have utilized sand as an adjunct surface in hopes that it may lead to positive adaptations [5, 19-21]. Today, the large increase in popularity of sand-based sports such as beach volleyball and soccer has led to increases in the use of sand as a competition surface. Increased participation in sport-specific performance training and the constant pursuit of a safe, legal, affordable, and accessible training edge is leading coaches and athletes to the use of sand as an ancillary training surface [5]. The increased participation in sand training is driving further investigation into the potential benefits and detriments it may pose [22, 23].

Traditionally, individual and team-sport training has taken place on natural grass, artificial turf, or wood surfaces. Sand has been proposed to possess unique qualities that can lead to positive neuromuscular adaptations as well as reduced risk of chronic injury often seen during or following periods of intense training. Many kinematic, neuromuscular, and physiological changes have also been reported in the literature regarding sand training [5, 7, 20, 23-26] and these adaptations may lead to positive changes in sprint speed, aerobic conditioning, jump performance, agility, and muscle hypertrophy [6-9, 18, 27]. Additionally, Impellizzeri et al. and Miyama et al. have reported a reduction in muscle soreness after completion of plyometric training on sand versus a firmer surface [8, 17]. The reported increase in energy cost during sand-based activity is also a proposed mechanism for improvement of aerobic and anaerobic conditioning [5, 9, 18, 19, 28-30]. However, additional research is necessary to further examine whether or not these adaptations are beneficial, or even transferable, to firm-surface performance.
Sand as an Absorptive Surface

Dry, non-compacted sand is a unique training surface due to its composition of individual particles that are easily displaced upon force application [8, 26, 28]. It is absorptive and inelastic, and therefore attenuates ground reaction forces (GRF) as well as alters kinematic and neuromuscular patterns in a unique way [16, 26, 27, 31-33]. Barrett et al. recorded impact forces after dropping objects of a known mass from a height designed to mimic heel strike during running on dry, non-compacted sand versus wet sand. They reported significantly less mean (467 ± 175 N vs. 1547 ± 514 N) and peak (934 ± 367 vs. 3397 ± 1015 N) impact force for the dry condition. Although not significantly different, there was a trend for the energy absorbed to be higher for the dry, non-compacted sand (24.8 ± 17.8 J vs. 18.0J ± 12.0 J). The authors describe the spectrum of surface firmness and state that the dry, non-compacted sand would be found on the very soft side of the spectrum, whereas the wet sand is similar to synthetic track surfaces often used in running competition and would be placed much farther toward the firm end of the spectrum [16]. The absorption of force evident here explains the decrease of GRF seen during sand-based activity.

Dispersal of sand particles upon force application represents force that cannot be recycled to the musculotendinous junction for re-use [28]. In order to attempt to maintain the same level of performance seen on a firm surface, the body must attempt to generate additional force, some of which would also be lost to the sand surface. This inefficient cycle can be observed by well-documented decreases in performance on sand as compared to similar tasks on firmer surfaces [5, 23, 24, 26, 32, 33]. This loss of elastic energy, which leads to a limited contribution to power production by the stretch-shortening cycle (SSC) may be overcome to some degree by increased concentric force production [23, 26, 32]. However, the question remains largely unanswered whether or not sand training has the potential to contribute positively to firm-surface performance. This and the transferability of training adaptations between surfaces will be discussed further in a later section of this review.

Plyometric training is often utilized as a training tool to improve strength and power in a broad range of athletic activities [8, 27, 34]. If not designed well, or if undertaken by inexperienced individuals, a plyometric training regimen can result in intense muscle soreness due to the eccentric loading of the involved muscles and overuse injuries caused by high impact training on a firm surface [8, 17]. A training modification that has been proposed in the literature is to conduct plyometric training on a sand surface in an attempt to reduce muscle
soreness and other overuse injuries [8, 17]. However, at this time the training effect of this surface change is not fully understood in terms of the potential alterations to neuromuscular function, especially as they relate to the SSC. The reduced GRF and subsequent changes to propulsive force and impact on the body must be examined further.

The Stretch-Shortening Cycle

The SSC involves elongation of a skeletal muscle immediately prior to quick, forceful concentric action [35-37]. Previous research has demonstrated that the optimal length for force production in a given sarcomere is slightly longer than resting length [35]. Optimal sarcomere length allows for maximum cross-bridge interaction between the actin and myosin filaments, and greater force production. This explains why an appropriate rapid stretch, that positions the sarcomere at optimal length and not longer, results in increased force production compared to concentric action from a resting position [35]. Power production is equally reliant on force produced and speed of movement. Powerful movements occur at higher speeds and this limits the cross-bridge interaction due to limited time for attachment/detachment of myosin heads. Therefore, optimal power production relies heavily on proper positioning of the muscle at optimal length in order to maximize surface contact for potential cross-bridge interaction [35].

There are a number of proposed mechanisms that could be responsible for effectiveness of the SSC as compared to concentric action occurring from a resting position [35, 36]. Increased time and greater range of motion for force development, storage and reutilization of elastic energy, interaction of the series elastic component (SEC: fiber, cross-bridges, aponeurosis, tendon) and contractile machinery of the muscle, potentiation of contractile machinery, and contribution of stretch reflexes have all been suggested as possible explanations [35-37]. Beginning a movement with a rapid eccentric action lengthens the muscle and allows greater range of motion over which force development can occur once concentric movement begins. This precursory motion prior to concentric action also allows greater time for force production compared to concentric action alone [35]. The series elastic component (SEC; fiber cross-bridges, aponeurosis, tendon) stores a portion of the mechanical work applied as elastic energy. This energy is released upon recoil of the SEC during amortization and concentric muscle action and is believed to enhance power production [35]. The mechanism of the SSC involves a rapid shortening of the musculotendinous unit (MTU). The MTU is made up of the SEC and contractile units of a skeletal muscle. The SEC shortens at a faster rate than the
contractile units and as it recoils, stored elastic energy is released. Contractile units of the muscle do not recoil as fast and this allows greater time for force production and cross-bridge interaction according to the force-velocity relationship [35]. Previous research into the in vivo function of skeletal muscle has demonstrated that the force-producing capabilities of myosin cross-bridges are increased when they are placed on a mild stretch prior to action [35]. Lengthening of the MTU and resulting mechanical deformation, triggers a stretch reflex that increases muscle activation and tone via increased alpha-motoneuron activity [35].

As is evident by the number of mechanisms listed above, further research is warranted into SSC function to truly understand power production in skeletal muscle and how it is affected by interaction with an external surface. Regardless of the mechanism, the SSC has been shown to contribute strongly to performance of powerful tasks such as running and jumping as compared to concentric muscle action alone or prolonged static lengthening prior to concentric action [35]. Firm surfaces allow for a faster transition from eccentric to concentric action, or amortization phase. This results in greater production of muscular power. In order for muscle action to result in efficient movement of the body as a whole, there must be a high force-return from the surface, or larger GRF. Decreased GRF, increased contact time, posterior slippage of the foot and the subsequent loss of energy as heat that occurs with a lengthened amortization phase all limit the contribution of the SSC during sand-based activity [23]. These factors, and the subsequent lack of specificity present with sand training have led previous authors to question the efficacy of sand as a training surface if the goal is neuromuscular adaptation related to activities that rely heavily on the SSC [8]. Additional research will provide a clearer understanding of the effect of training, and training surface, on the SSC [5].

Kinematic Changes

Kinematic changes occur as a result of the shifting surface during activity on sand. Not only does sand compress when force is applied, but depending on the angle of takeoff and the task, some degree of posterior foot slippage occurs [23, 24, 30]. This excessive, unplanned movement must be accommodated for elsewhere in the kinetic chain in order to achieve a movement goal. Pinnington et al. reported significant increases in hip and knee flexion and total hip and knee range of motion during sand running at two different speeds as compared to running at the same speeds on a firm surface [20]. Overall, these authors stated that the kinematics of running at slow speeds on sand closely mimic running on a firm surface at much
faster speeds [20]. Wise also reported an increase in knee flexion angle [33]. Alcaraz et al. reported decreases in hip angular velocity at mid-stance and decreased hip extension at push off [24]. Multiple authors have reported an increase in forward trunk lean during sand running [20, 24, 33]. An altered angle of trunk flexion has the proposed purpose of altering the horizontal GRF and compensating for the slippage of the foot during the push-off phase of running.

In addition to joint kinematics, gait characteristics appear to change when activity on a sand surface is initiated. Posterior slippage of the foot during the propulsive phase of sand running results in a shortened stride length and decreases forward and vertical propulsion forces [20, 26, 33]. Furthermore, multiple reports state that stride frequency also decreases [20, 24, 26, 28, 33]. A number of previous studies have reported that sprint speed in sand is decreased as compared to sprinting on a firm surface [20, 24, 33]. Pinnington et al. reported a longer stance phase of gait on sand [20] and this is supported by findings of an increased contact time during running and jumping activities on a sand surface [24, 27, 30, 32]. The kinematic changes observed have been labeled as negative adaptations [24], but they likely represent the body’s neuromuscular accommodation to surface change.

Alcaraz et al. reported that the center of mass displaces more inferiorly on a sand surface during the stance phase of running and reaches a lower vertical height during the flight phase compared to firm surface running [24]. These findings are disputed to some degree by a report by Ferris et al. which stated lower limb stiffness increased during activity on softer surfaces in an attempt to limit the excursion of the center of mass and maintain a similar pattern seen during firm surface running [38]. The body is required to compensate for the decreased compressive forces and therefore decreases the amount of eccentric knee flexion during initial weight-bearing while running. The authors argue that efficiency is the primary goal of the body during gait and therefore the central nervous system alters neuromuscular function and joint patterns in an effort to decrease excursion of the center of mass. Electromyographic studies indicate changes in lower extremity skeletal muscle activity during sand training as well. Pinnington et al. consistently found significant increases in EMG activity in the hamstrings group throughout the gait cycle, quadriceps group at mid-stance, tensor fascia latae during the stance phase, and gastrocnemius during mid-stance [20]. Increased demands on stabilizing muscles in response to the instability of a sand surface likely result in this increase in EMG activity which indicates greater recruitment of motor units. Overall, these kinematic changes represent the
body's attempt to identify movement alterations that will allow for efficient running form in a new environment.

**Effects of Sand Training**

*Increased Energy Expenditure*

It is well established in the literature that training in sand, whether it be aerobic or anaerobic in nature, has a higher energy cost (EC) compared to activity of the same absolute intensity on a firmer surface [5, 6, 9, 18, 19, 22, 26, 28-30, 39]. Many of these authors have taken an additional step in regards to their findings and suggest that this training adaptation may result in improved performance on a firm surface [5, 9, 18, 19]. A number of mechanisms have been suggested as possible explanations for this increase in EC, including loss of elastic energy to the environment, decreased contribution of the SSC, and instability of the surface [5]. However, based on work published by Pinnington et al., it appears that the main factor in increased EC during sand-based activity is increased muscle activity in the lower extremities [5, 20]. During running on a firm surface, the surface itself provides a large measure of the stability necessary for successful movement. As the stability of the surface decreases, increased activity from accessory and stabilizing muscles is necessary to maintain proper body position and control [5, 20]. This, in turn, results in an increased energy cost. Sand is a variable surface and type of sand, water content, and depth will all affect the firmness, stability, and absorptive qualities of the surface [5]. As the firmness of a sand surface moves towards more traditional training surfaces such as grass or wood on the firmness spectrum, the difference in energy cost will be diminished. This should be considered by practitioners incorporating sand into training protocols.

A number of previous studies were identified what examined EC changes during sand activity. Zamparo et al. published findings related to the EC of sand running in 1992 [30]. In nine healthy adults they reported a significantly (p < 0.0001) greater EC during sand running compared to firm-surface running (5.33 ± 0.47 vs. 4.35 ± 0.33 J·kg⁻¹·min⁻¹) [30]. The authors went on to report a sharp increase in rate of perceived exertion (RPE) as velocity increased during sand running and hypothesized that this was caused by the increased EC evident during sand running [30]. Lejeune et al. reported a significant (p < 0.0005) increase in aerobic EC while running on sand of 1.6 times that seen during firm-surface running [28]. Walking on sand resulted in an even greater EC; 2.5 times that of walking on a firm surface [28]. They reported a
net EC of 4.1 J·kg⁻¹·min⁻¹ during running on a firm surface which was independent of speed and unaffected by the curves on a standard competition track. A decreased efficiency of the muscle-tendon complex during sand high-speed walking and during running on sand was also identified. This was due to a disproportionately large increase in EC compared to the increase in mechanical work [28]. Pinnington and Dawson reported similar findings in two studies published in 2001 [18, 19]. In one publication, they reported an aerobic EC during sand running that was 1.36 times greater than similar firm surface running conditions (6.18 ± 0.44 vs. 4.53 ± 0.24 J·kg⁻¹·min⁻¹) in elite surf iron men runners and 1.41 times greater in male recreational runners (6.56 ± 0.67 vs. 4.64 ± 0.35 J·kg⁻¹·min⁻¹) (p < 0.001) [18], but the results between groups of runners were not significantly different. Furthermore, Pinnington and Dawson reported a significant (p < 0.01) difference between the net EC of sand running (6.98 ± 0.75 J·kg⁻¹·min⁻¹) versus running on grass (4.38 ± 0.48 J·kg⁻¹·min⁻¹) [19].

These EC changes appear to occur during activity on sand, regardless of training mode. In a study examining EC of maximal vertical jumps on sand, Muramatsu et al. reported statistically significant (p < 0.01) differences in both energy expenditure (37.0 ± 1.64 vs. 31.2 ± 3.46 kcal) and total oxygen consumption (7.39 ± 0.33 vs. 6.24 ± 0.69 L) compared to a jump of similar height on a firm surface [29]. Oxygen consumption was measured from three minutes prior to initiation of a 30-repetition jump protocol and until oxygen consumption returned to a baseline resting level. Energy cost was calculated using a formula equating one liter of oxygen to five kcal [29]. The authors acknowledge a loss of elastic energy and decreased contribution of the SSC. However, they suggest that both of these factors result in a decreased contribution of the plantar flexors to jumping. This decrease in recycled energy requires greater contribution of other lower extremity muscles and results in the greater EC evident in their results [29]. Yigit and Tuncel compared the effect of aerobic sand training to aerobic training on asphalt on predicted VO₂max in 51 high school and college-aged males [9]. Subjects trained for six weeks and were assessed at pre and post-test sessions using the Cooper run/walk test. The authors reported a significant (p < 0.05) increase in VO₂max in the sand group (1.9 ml·kg⁻¹·min⁻¹ ± 0.85%). The authors did not report overall energy cost in J kg⁻¹·min⁻¹. The increase in VO₂max was primarily attributed to the increased muscle size also reported in this study that will be discussed later in this review.
Improved Motor Unit/Muscle Fiber Recruitment

The current evidence in the literature regarding sand training suggests that repeat exposure to this training surface results in an increased level of concentric force production [27, 34, 40]. This adaptation allows for a greater production of muscular power, assuming the productivity of the SSC is unaffected by previous sand training upon return to participation on a firm surface. Previous authors reported a link between improved force production and increased motor unit recruitment as well as an increased contact time during activity on a sand surface [27]. Additional contact time allows for greater muscle fiber recruitment and subsequently greater force production [27]. If this adaptation is transferable to firm-surface performance, it is possible that greater power production would occur compared to that produced prior to exposure to sand training.

The construction of a new movement strategy in which the benefits of sand training (i.e. improved concentric force production via increased motor unit recruitment) and those of firm-surface participation (i.e., SSC function) are combined, is likely to lead to improved performance of powerful activities such as sprinting and jumping. Additional research has been published since Markovic and Mikulic published their review in 2010. However, their assertion that the current research regarding the effect of plyometric training on non-rigid surfaces remains accurate and more research is needed prior to making any definitive statements [36].

Alterations to Sprint Performance

Opposing views exist in the literature regarding the benefits of sprint training in sand, but it has been established that maximum sprint speed on sand is significantly lower than on a firm surface [6, 24, 26, 33]. Binnie et al. examined the effect of sprint training in sand on firm-surface 20-meter sprint speed. Across an eight-week intervention they consistently reported significantly (p < 0.05) slower sprint speeds on sand in both training groups, sand (Week 0: 3.82 ± 0.27 vs. 3.57 s ± 0.23 s, Week 4: 3.73 ± 0.27 vs. 3.46 ± 0.21 s, Week 8: 3.67 ± 0.26 vs. 3.41 ± 0.22 s) and grass (Week 0: 3.67 s ± 0.21 vs 3.46 s ± 0.18, Week 4: 3.71 s ± 0.20 vs. 3.40 s ± 0.15, Week 8: 3.67 s ± 0.18 vs. 3.32 s ± 0.12) [6]. Subjects were randomized to either a dual-surface training group (sand and grass) or a grass-only group and trained for eight weeks. Results demonstrated a significant improvement in grass sprint time for both groups, whereas only the dual-surface group demonstrated an improvement in sand sprinting performance [6]. These results signify two things. First, sand training does not hinder firm-surface sprint performance.
Second, improving sprint speed on sand requires exposure to sand training. This demonstrates a unidirectional transfer of training benefits – sand appears to positively influence sprint performance on a firm surface, but the opposite does not appear to be true. Alcaraz et al. reported a 15.8% decrease in horizontal velocity while sand running in male subjects and a 12.4% decrease in females [24]. However, this study did not compare firm-surface and sand-surface running or assess the effect of sand training on firm-surface performance. The authors stated concerns regarding negative kinematic adaptations seen during sand running that may affect firm-surface sprint performance. They do not report as to whether these adaptations are in fact transferable to firm-surface sprinting, but caution should be used by coaches and athletes regarding the implementation of sand training as a part of an overall regimen designed to improve firm-surface sprint performance [24].

Sand sprinting has also been evaluated from a kinematic standpoint. Gaudino et al. identified a significant ($p < 0.001$) difference between sand ($2.28 \pm 0.09s$) and grass ($1.98 \pm 0.06s$) performance of 20-meter sprint speed in male professional soccer players [26]. This study did not examine the effect of sand training on firm-surface performance. Rather, the authors evaluated kinematic and performance changes observed on sand and concluded that sand training may be beneficial as a training surface due to its absorptive qualities as well as the increased EC evident in their subjects. The authors go on to state that sand may serve a useful function as a training surface during recovery from injury due to the reduction in GRF and as a part of a regular training protocol due to the ability to achieve maximum training intensity at slower speeds. This was a positive effect resulting in decreased stress on joints and increased overall safety of training [26]. Wise also reported a significant ($p < 0.05$) decrease in 30-meter sprint speed when running in sand in a population of physically active college men and women (n=15) [33], but he concluded that caution should be used when employing sand as a training surface. These reservations come from the decreased sprint speed recorded on sand as well as observed negative kinematic changes. The author expresses concern that these adaptations may result in decreased performance and sprint activities on a firm surface [33].

Previous research has also evaluated the crossover effect sand-based plyometric training on sprint performance. In 2011, Asadi examined the effects of a six-week, sand-based plyometric training program on 20-meter sprint speed. Twenty-seven male college students were randomly assigned to one of three groups: drop jump, counter-movement jump, or an inactive control group. All training took place on a sand surface and sprint speed was assessed.
at pre- and post-training. The results demonstrated a significant ($p < 0.05$) positive effect on 20-meter sprint performance upon completion of the six-week plyometric training program. Asadi suggests that the improvement may be attributable to alterations in stride length and/or stride frequency. Additionally, the author states that the training intensity, training volume, and sample size present in this study may account for the differences in their results compared to other authors that did not find similar results in relation to the effect of sand training on sprint performance [34]. Use of a firm-surface training group would have strengthened the results of this study by allowing for comparison between the novel surface (sand) and a more traditional training surface. Questions still exist regarding the transferability of any physiological or kinematic adaptations that occur on sand and further research is needed to conclude whether or not firm-surface performance can be improved by the inclusion of sand training in an activity regimen.

**Plyometric Adaptations**

The effect of sand training on explosive strength and plyometric performance has been the subject of a number of previous publications in the literature [8, 23, 32, 34]. It is well established that jump performance is hindered while on sand [17, 23, 32], but the question of whether or not sand training holds benefits for firm-surface plyometric performance is still largely unanswered [36]. In 2003, Bishop published findings related to a study he conducted comparing jump performance on firm ground vs. sand surface in a population of 18 (10 males, 8 females) beach volleyball players. Subjects completed four different jumping tasks (squat jump, countermovement jump, block jump, spike jump) and consistently performed significantly ($p < 0.05$) lower on sand vs. the firm surface [32]. Bishop attributes this decreased performance on sand to the absorption of force by the surface and subsequent loss of recycled force that on a firm-surface would contribute to jump performance. Finally, he concludes that jumping is a general quality and not greatly influenced by the surface. Although jump height will be decreased when performed on a sand surface, those individuals producing the highest jump scores on firm ground would be expected to also produce the best scores on a sand surface [32]. Giatsis et al. published data supporting the findings of Bishop regarding overall jump performance on sand [23]. Fifteen elite male beach volleyball players were tested and their vertical jump height was significantly ($p < 0.05$) lower on sand as compared to a firm surface (28.8 cm ± 4.5 vs. 24.8 cm ± 4.1) [23]. The authors also quantified their results in another way
stating that maximum effort jump height on sand would be 14% lower than a jump of similar intensity performed on a firm surface. The authors attribute this decrease in jump height to the instability of the sand and the resulting lack of power production due to an inefficient contribution of the SSC [23].

The effect of sand training on plyometric performance was previously investigated by Asadi, specifically relating to vertical jump capability [34]. The results indicated a significant (p < 0.05) increase in vertical jump for both the drop jump and counter-movement jump groups. The author suggests that the positive results may be explained by the type of plyometric intervention utilized, along with reported increases in motor unit functioning and recruitment, evident in the EMG data collected as a part of this study. Significant (p < 0.05) increases in EMG activity were reported for the vastus lateralis, rectus femoris, and vastus medialis from pre- to post-test [34]. Impellizzeri et al. also reported results regarding the effect of sand training on firm-surface performance [8]. They included 37 male amateur soccer players and compared effects of four weeks of firm vs. sand-surface training on jump height. Training on both surfaces resulted in a significantly increased firm surface counter-movement jump height (Grass: 37.8 ± 3.6 vs. 43.3 ± 5.9 cm [p < 0.001] and Sand: 37.2 ± 3.6 vs. 39.6 ± 5.5 cm [p < 0.01]) [8]. These results demonstrate that sand training is not a hindrance to firm surface performance. Additionally, they imply that sand training may be a positive training stimulus for firm-surface jump performance. However, the grass group did outperform the sand group in this study. This supports the prevailing line of thinking in the current literature that a firm surface is the better choice for plyometric training if the primary goal is achieving maximum height. Prieske et al. stated that a firm-surface should be considered the only viable option for plyometric training if the goal is to improve jump performance [41]. This assertion is based on results that indicate a decreased jump performance when completing jump tasks on an unstable surface. The subjects in this study were not exposed to a sand surface, but rather a foam balance pad served as the unstable surface [41]. These two surfaces would be quite different in composition and impact on kinematics and force-production related to jumping. However, this study supports the notion that jump performance decreases when the stability of the surface decreases and attenuation of impact forces occurs. Additionally, the authors urge practitioners to choose wisely when selecting a training surface so as to provide the best environment for athletes to achieve their goals [41].
Muscular Adaptations

No studies were identified at the time of this review that examined the effect of sand training on lower extremity strength. However, Yigit and Tuncel reported significantly greater muscle hypertrophy in subjects after a period of aerobic-based sand training [9]. Fifty-one male students were randomly assigned to one of three groups: road running, sand running, or control. After six weeks of endurance training, they reported a significant (p < 0.05) increase in thigh (0.86 cm ± 0.35%) and calf (0.60 cm ± 0.48%) circumference. These results indicate an increased load on these particular muscles, and suggest a positive adaptation resulting from sand training [9].

Adaptations within Agility

A single study was identified where researchers had examined the effect of sand training on agility [7]. Gortsila et al. implemented a ten-week training intervention in pre-pubescent female volleyball players with the goal of assessing the effect of sand training on agility. Their findings indicated a significant (p < 0.001) decrease in time required to perform the T-test in both groups, sand and firm surface. Pre-training, the mean firm surface t-test time was 15.3 ± 0.4 versus 13.2 s ± 0.2 s at post-training. The sand surface mean time at pre-training was 18.0 ± 0.5 versus 15.0 s ± 0.5 at post-training [7]. These results present a case for the transferability of sand-training adaptations to firm-surface performance which will be discussed further later in this review.

Transferability of Adaptations

The transferability of neuromuscular and physiological adaptations is ultimately what researchers are hoping to identify when conducting studies regarding the effectiveness of sand training. Despite the huge growth of beach volleyball and beach soccer and the popularity of life-saving and Iron-Man competitions in some parts of the world, the vast majority of athletic competition still occurs on a firm surface, whether grass, synthetic turf, synthetic track, or wood. This means that the value of sand training is largely limited to the transferability of whatever adaptations occur to firm-surface performance. Gortsila et al. reported a significant improvement in firm-surface t-test time after a ten-week period of sand training that was significantly different than the improvement in the firm-surface training group [7]. These results indicate that sand training leads to beneficial adaptations that are transferable to firm-surface performance. Binnie et al. reported an improvement in 20-meter firm-surface and sand sprint
times after completion of a training protocol that included time spent on both grass and sand. The group that trained exclusively on grass did improve their sprint time on grass, but did not improve their sprint performance on sand. The authors point out that this may indicate a one-way transferability of adaptations achieved by training in sand and that surface specificity and consideration of possible training adaptations and their transferability should play a role in deciding what type of surface athletes will train on [6].

Injury and Training Surface

No definitive research was identified in the current literature regarding injury risks of sand training. However, a number of studies include suppositions regarding injury risk, the possibility of injury reduction, and the potential of sand to be used as a rehabilitative or recovery surface [5, 8, 16, 17, 36]. It appears that the prevailing opinion in the literature links the potential for acute injury to a sand surface due to its instability and the likely unfamiliarity with the surface that would be the case with most athletes [5, 16]. On the other hand, sand training is viewed as a method to reduce chronic training injuries that often occur during intense pre-season training regimens [5, 8, 17]. Finally, some authors propose the use of sand as a recovery or rehabilitative surface [5, 26]. The instability of sand and increased energy cost that occurs when participating on that type of surface have been suggested as beneficial to athletes beginning return to play protocols after time lost to injury or to those actively recovering from some musculoskeletal or neuromuscular injuries.

Training-induced muscle soreness has been examined specifically as a part of the conversation pertaining to the benefits of sand training. Impellizzeri et al. also examined muscle soreness present in subjects after completion of their assigned plyometric workout (sand vs. firm-surface). Using a seven point Likert scale, subjects rated their muscle soreness after each week of training. There was a significant (p < 0.05) main effect for time from week one to week four (p < 0.001). Additionally, a significant (p < 0.001) between subjects effect was identified between the average Likert scores calculated over the course of the training period [8]. The sand group score was lower than the grass group. These results indicate that sand may be an appropriate surface to use when introducing plyometric training as a new training stimulus or when adding plyometrics to an already demanding training regimen in an effort to reduce training-related muscle soreness [8]. One additional study was identified involving the assessment of muscle soreness related to sand training [17]. Miyama and Nosaka utilized five
sets of ten repetitions of drop jumps and counter-movement jumps, onto either a sand or firm surface, to assess the resulting muscle soreness. Sixteen male subjects with little background in resistance training volunteered for this study [17]. Results indicate that subjective muscle soreness was lower in the sand group subjects than the firm surface. Also, chemical indicators of muscle damage (i.e. creatine kinase, CK) increased significantly in both groups after exposure to the training protocol. However, the firm-surface group increased significantly more [17]. The authors suggest that although sand training appears to result in reduced muscle damage and self-reported soreness, sand may not always be the appropriate surface for plyometric training. The needs and training state of the athletes involved should be taken into consideration prior to deciding which surface will be most beneficial [17].

Conclusion

The use of sand as a training surface may hold benefits applicable to multiple training goals including power, strength, agility, speed, and aerobic endurance. Additionally, sand may prove to be useful as a rehabilitative surface or training surface appropriate for early-stage functional exercise after an injury. It has been demonstrated that certain neuromuscular and physiological adaptations do occur during and after a period of sand training. However, inconsistencies in training intervention design, intensity, volume, and frequency as well as difference in subject populations in the available research have made it difficult to arrive at any type of consensus. Despite a growing body of literature related to this topic, additional research is required before clinicians are able to definitively understand the benefits and limitations of this training mode.

Section Two: Sand Training for Improvement of Postural Control

Introduction

Static balance may be defined as an individual’s ability to maintain the position of the body’s center of gravity over the base of support [42], or an attempt to maintain a steady base of support while initiating as little movement of body segments and center of gravity as possible [3]. Boccolini et al. and van Diest et al. added that this ability comes from neuromuscular actions as a response to feedback from visual, vestibular, and somatosensory systems [42, 43]. Balance is often referred to as postural control as well, and the terms are further qualified as either static or dynamic. Dynamic balance is defined by various authors as the ability to
establish and maintain a base of support while completing another movement task [44-46], or the ability to maintain, achieve, or restore a position of postural equilibrium during any activity [43, 47].

Various assessments of static and dynamic postural control have been set forth in the literature and many have merit as either field or laboratory tests. These include static measures such as center-of-pressure (COP) assessments, and dynamic measures such as time-to-boundary (TTB) assessment, and the Star Excursion Balance Test (SEBT), among others. Additional field tests have been developed for the assessment of functional range of motion (ROM) and have been tied to performance of various postural control assessments. An example of this is the Weight-Bearing Lunge Test (WBLT).

Quantification of postural control has garnered interest as it may add to the understanding of injury prevention, injury prediction, and impairment identification in the lower extremity. The initial area of interest in the scientific literature was static balance, specifically COP characteristics. These assessments provide important information regarding an individual’s ability to maintain a static posture and base of support, but do not provide a clear picture of one’s ability to maintain postural control during a dynamic situation. This information is vital in providing insight into the characteristics of balance and how they interact with an individual’s ability to control body position and avoid injury. They may also provide insight into the role dynamic balance may play as a predictor of injury as well as a discriminatory tool to be used in acknowledging the presence or absence of a certain pathology.

Over the past 15-20 years, a move has been made to quantify dynamic postural control in various populations in order to establish a clearer picture of the role dynamic balance plays in activities of daily living (ADLs) as well as recreational and competitive physical activity. The TTB, SEBT, and WBLT have been used frequently in the scientific literature as assessment tools designed to better quantify postural stability and factors that influence it [48-50].

**Time-to-Boundary (TTB)**

*Background*

Time-to-boundary has been defined as a spatiotemporal analysis of COP data points that quantifies the theoretical time an individual has to make postural adjustments in order to maintain postural stability [51]. Originally described by Slobounov [50] and termed virtual time to contact (VTC), this assessment has also been referred to as time to contact (TtC) [52].
Traditionally, COP data were assumed to represent the amount of instability present during either static or dynamic tasks [50]. However, this new approach goes beyond simply quantifying the movement of the COP away from the equilibrium point. Time-to-boundary measures attempt to establish the relationship between the COP and the boundary of the base of support [50, 53]. To do this, instead of using all of the COP excursion information as is done with traditional COP measures, TTB includes only minima (data points where COP is closest to the boundary of the base of support). This novel method allows for a measure of an individual's ability, and the variations within, to control the rate at which the COP moves to the base of support boundary and their ability to reverse the motion of the COP to avoid crossing that boundary and surpassing the limits of their postural control, which results in a loss of balance [50, 54-56].

Time-to-Boundary is a novel approach to assessing postural stability and has been found to assess different aspects of postural stability than traditional COP measures [53-55]. This test is unique because it considers not only the location of the COP within the base of support, but it assesses the change of position of the COP relative to time, indicating the ability/inability of the subject to maintain balance and recover from any excursion of the COP towards the boundary of the base of support [51, 57]. The velocity of the COP is more critical the closer it is to the boundary of the foot. High velocity of movement of the COP in the center of the base of support is not as detrimental to overall postural stability since there is a greater distance between the COP and the boundary of the foot, thus allowing more time for correction. High velocity movement of the COP near the boundary of the foot is harder to correct and therefore more likely to result in a loss of balance, especially in those with low standard deviation (SD) values since lower variability represents a diminished ability to adapt to sudden changes in position of the COP [58].

The time-to-boundary literature must be sub-divided into two sections, based on whether the assessment involved a bi-pedal or uni-pedal stance. The nature of athletic activity and the frequency at which athletes are in a single-limb, weight-bearing stance led to the decision to evaluate only the TTB studies conducted which placed subjects in a uni-pedal stance. In addition, the intent was to clarify the sensitivity of TTB measurement to various interventions and its ability to discriminate between differing populations in terms of injury state or presence of other neuromuscular or musculoskeletal pathology.
Reliability

Time-to-boundary assessment has been shown to demonstrate similar reliability scores as compared to more traditional COP measures [56, 59]. The inherent variability seen in postural control tasks undertaken by healthy subjects has resulted in questions about the TTB assessment’s validity. The postural control system is redundant in that there are multiple strategies that may be used to maintain contain the COP within the base of support [56]. These redundancies create a paradox within TTB assessment. The same variability that allows for multiple balance strategies and subsequently the ability to respond to a variety of perturbations and environmental changes (i.e. eyes open vs. eyes closed, CAI vs. healthy, hypoesthesia vs. unimpaired sensation) also results in lower reliability scores as calculated by intra-class correlation coefficients (ICC). Despite this contradiction, TTB reliability scores are similar to traditional COP measures, and therefore viewed as a reliable assessment. Hertel et al. reported ICCs for traditional COP measures from .35 - .80 and .40 - .74 in the medial/lateral (ML) and anterior/posterior (AP) directions respectively [56]. For TTB they reported ICCs ranging from .34 - .81 (ML) and .50 - .87 (AP) [56]. Yamanaka et al. reported ICCs for TTB ranging from .53 - .69 (ML) and .50 - .61 (AP) [59]. These values are slightly higher than previously reported, but still in agreement with earlier results published by Hertel et al. A certain degree of variability is expected in standing tasks and this may partially contribute to the inconsistency in reliability results reported by various authors [56]. Also, Yamanaka et al. used different methodology for the TTB assessment. Both Hertel et al. and Yamanaka et al. used a 10-second sample of quiet single-limb stance. However, Yamanaka et al. used 30-second standing trials and sampled the middle 10-seconds of each trial [59]. This may have allowed additional time to stabilize prior to data collection that could explain the slightly higher reliability scores reported. Overall, the authors concluded that the reliability of TTB was similar to more traditional COP measures of postural stability.

Methodology

Time-to-Boundary assessment involves collecting data via force plate during single-limb standing trials with eyes open and/or eyes closed conditions. The most common standing trial time is 10 seconds [55, 58, 60, 61], but some authors have used differing, lengthier trial durations [59, 62]. Subjects are instructed to stand as still as possible during data collection and are provided with a stationary visual target to focus on during the eyes open condition [56].
McKeon et al. and Pope et al. described the subject’s standing position as arms folded across chest and opposite limb held at 45 degrees of hip flexion and 30 degrees of knee flexion [58, 61]. Three trials are recorded for each condition included in a particular study and data are collected bilaterally. A failed trial is recorded if the subject touches down the opposite limb or is unable to maintain the described position for the duration of a 10-second trial [58].

The mean and standard deviation (SD) of the minima are the most important variables to consider when analyzing time-to-boundary (TTB) data [63, 64]. These variables should be considered for both the mediolateral (ML) and anteroposterior (AP) directions for both eyes open and eyes closed conditions. The mean of the minima represents the average minimum time a subject has before reaching the boundary of their base of support in a given direction (ML or AP). This is calculated using an instantaneous velocity and the relative distance to the boundary when the instantaneous velocity is measured [54, 55]. The SD of the minima represents the variance in the mean of the minima [56]. This is important because it represents the number of different adjustments a subject can make in an effort to maintain balance. Lower means and SD of the minima represent a potential decrease in postural stability resulting from decreased time to make postural adjustments and move the COP back towards the center of the base of support. Lower minima represent less time to make a postural adjustment and a likely inability to maintain balance. A lower SD represents an inability to adapt to the dynamic situation in regards to postural stability and a likelihood of allowing the center of pressure (COP) to move outside of the base of support. A lower SD of the minima represents a neuromuscular system operating under more constraints. This means that a subject has fewer options in terms of strategies to maintain balance due to the decreased TTB [60].

Prior to data collection, the shoes are removed and the length and width of the test foot are measured. These measurements are used to model the foot as a rectangle, the center of which runs through the center of the force plate, bisecting the ML and AP center lines [58, 62]. This method of identifying the boundaries of the foot is potentially flawed since it is not representative of the anatomical foot. However, its use is widely accepted as a part of the standard methods for TTB. Cobb et al. reported that either a trapezoidal or multisegment polygon shape may be more accurate in terms of defining the boundaries of the foot. They reported significant differences in ML TTB scores during eyes open and eyes closed conditions between the rectangle and trapezoid, and rectangle and multisegment polygon designs [62]. There were no significant differences between the trapezoid and multisegment polygon designs,
or between any of the boundary shapes in the AP direction [62]. There are greater variations in
the shape of the foot in the ML direction as compared to the AP direction, which may explain
the results presented by Cobb et al. As the COP approaches the boundary of the base of
support, TTB is more critical as there is less time for adjustment before balance is lost. The COP
is likely located more posterior than the widest point of the foot at the metatarsal heads. Since
the foot is narrower and shorter at points than the rectangle set up to define its boundaries, the
resulting calculated TTB values may not be totally accurate. A narrower foot compared to the
boundaries of the x,y rectangle would result in arrival at the boundary of the base of support
sooner than calculated [62]. Additional research is needed to determine the overall best
boundary shape to use for TTB. These results are important as they demonstrate a flaw in the
use of a rectangular boundary for the foot. However, no evidence is available in the literature at
this point demonstrating that the rectangular boundary is inadequate in terms of defining the
boundaries of the foot for the purposes of TTB. The relative ease of setup it will result in the
continued use of this method as the standard until new evidence is presented.

**Discriminatory Capabilities and Susceptibility to Intervention**

An investigation into the literature was undertaken to determine the effectiveness of
TTB in discriminating between differing injury states, postural characteristics, or other
musculoskeletal or neuromuscular conditions, along with whether or not TTB can be
manipulated by therapeutic intervention. Additionally, evidence stating differences between
TTB and traditional COP measures was noted. Hertel and Olmsted-Kramer reported that TTB
and traditional COP measures were not as closely correlated as the various measures within
each method (TTB vs. traditional COP). This led them to conclude that TTB assesses different
aspects of postural control than traditional COP and represented a novel approach to
quantifying postural control and stability during single limb stance [56].

Hertel and Olmsted-Kramer reported two general findings that establish TTB as a unique
test with the ability to identify postural control deficits that traditional COP measures could not
[55]. They reported COP was only able to identify a significant difference between subjects with
chronic ankle instability (CAI) and age-matched healthy, active female controls for one variable
(group main effect for COP velocity in the AP direction p = .05). Center of pressure data from
the involved and uninvolved sides were pooled since no significant differences were identified
between the two sides. Time to boundary was able to identify significant differences in AP
absolute minimum (p = .03), ML mean of the minima (p = .05), AP mean of the minima (p = .004), ML SD of the minima ((p = .05), and AP SD of the minima (p = .001) between the subjects with CAI and the control group [55]. These results demonstrate the ability of the TTB to discriminate between individuals with CAI and those without in the population tested. Furthermore, they demonstrate a clear difference between traditional COP measures and TTB in regards to ability to differentiate between those with and without CAI.

Wikstrom et al. examined the differences in postural control between those with and without CAI [64]. They examined 16 copers (previous history of ankle sprain with little to no lasting effect), 16 young adults with CAI and 16 age-matched healthy individuals. Each subject completed two, 30-second trials of single-limb stance on a force plate in the eyes open condition. Copers and subjects with CAI stood shod on the involved limb and the healthy controls stood on the matched limb. Center of pressure and TTB data were analyzed. The authors reported the CAI (1.67 ± 0.24s) and Coper (1.61 ± 0.09s) groups demonstrated significantly (p < 0.01) lower TTB ML mean minima compared to the control group. The CAI group also had a lower TTB AP mean minima as compared to the control group (4.26 ± 0.61s vs 4.96 ± 0.63s). Despite the significant findings, Wikstrom et al. concluded that certain COP measures were more sensitive to postural control differences between the populations tested. Limitations related to the calculation and interpretation of the TTB data collected in this study led to this conclusion. The methods utilized in this study differed from other TTB studies in that the subjects remained shod during data collection and completed 30-second trials in only one visual condition [64].

In contrast, Knapp et al. reported that no force plate measure was effective in predicting the presence of CAI [53]. They did report that the SD of COP ML eyes closed (p = .04), range of COP utilized ML eyes closed (p = .01), and TTB absolute minimum ML eyes closed (p = .03) presented with significant differences between the control and CAI group means. Despite finding individual significant differences, the authors stated that overall, these force plate measures are not clinically valuable for the identification of those with and without CAI [53]. Overall, these findings are not in agreement with the previously mentioned study by Hertel and Olmsted-Kramer. The two studies had similar methodology, but differing test populations. Hertel and Olmsted-Kramer had 24 female volunteers and Knapp examined 63 total subjects (30 males, 33 females). The difference in test population may account for the lack of agreement in their results.
In addition to differences between COP and TTB assessments, it is important to examine internal differences between the TTB variables such as vision condition, or ML and AP direction. In a study involving 20 subjects with self-reported CAI, Hoch and McKeon reported two important findings related to TTB [60]. First, they reported a significant treatment by vision interaction for TTB AP minima \((p = 0.001)\), SD of TTB AP minima \((p = 0.001)\), and the TTB ML minima \((p = 0.03)\). The eyes closed condition had significantly lower values for all of these variables indicating decreased postural stability. The removal of visual input narrows the strategies available for maintenance of postural stability and this may draw out existing differences between two groups that may not be evident when the postural control task does not present sufficient challenge. Second, Hoch and McKeon reported that after a single treatment with grade III joint mobilization at the ankle TTB AP minima and SD of the minima with eyes open were significantly different than the pre-mobilization values. Subjects were randomly assigned to one of two groups. On the first treatment day, one group received the joint mobilization and the other received a control treatment consisting of a 5-minute rest period. On the second treatment day, the groups received the opposite treatment. The joint mobilization treatment was found to increase TTB values in the AP direction and therefore led to the conclusion that a single session of joint mobilization may have a positive effect on certain components of postural control as measured by TTB [60]. It is important to note that TTB was assessed on the same day as the joint mobilization treatment.

As a follow-up, Hoch et al. completed a study on the effect of a 2-week joint-mobilization intervention on single-limb balance in a group of 12 volunteers with CAI [65]. This study involved a period of time greater than 24 hours between completion of the joint-mobilization protocol and assessment of TTB. No significant findings were reported for any measures. The authors cited the delay between the end of the treatment protocol and the TTB assessment as the primary reason for the lack of significant results. They hypothesized that the effects of joint-mobilization shown in their previous study may be transient and depend more heavily on the time frame between application of the intervention and TTB assessment, rather than length of the overall intervention [65].

Time to boundary assessment is one of many methods available to help identify those with CAI. Linens et al. reported that one portion of the TTB assessment, ML TTB SD, may be used to identify those with CAI [66]. In a study involving 17 individuals with CAI and 17 age-matched controls, they reported that a ML TTB SD \(\leq 1.56\) seconds may be used as a cutoff in
identifying those with CAI. This study provided a list of 10 (some lab/some field) specific balance assessments that may be capable of predicting CAI in this population. Based on their results, TTB may not be the most time/cost-effective measure for the classification of those with CAI.

Previous studies have also examined the effect of training interventions on TTB performance. McKeon et al. investigated the effect of a 4-week supervised balance training program on postural control in a group of 31 young adults with self-reported CAI [51]. Subjects were randomly assigned to the intervention or control groups and postural control was assessed via TTB and traditional COP performance pre- and post-intervention. The amount of time that passed between the conclusion of the intervention and TTB assessment was not reported. No significant interactions or main effects were reported in the eyes open condition [51]. The eyes closed condition for the balance group demonstrated significantly (p < .05) higher TTB measures for the absolute minimum TTB ML, TTB AP mean of the minima, and SD of the TTB AP minima [51]. The balance group also demonstrated a significant (p < .05) decrease in COP velocity in the ML direction. Both groups demonstrated a significant (p < .05) decrease in COP velocity in the AP direction at post-test. These results agree with earlier studies recognizing the ability of TTB to assess different aspects of postural control than traditional COP measures [55, 56] and go on to provide evidence that TTB may be positively impacted by initiation of a supervised balance training program. The authors suggest that training of the sensorimotor system over a 4-week period resulted in improved ability to overcome constraints on the sensorimotor system seen in people with CAI [51]. It should be noted that the eyes open condition did not present a challenge to the sensorimotor system sufficient to demonstrate differences between the control and balance training groups. Removal of visual input seems to allow for differentiation between subjects involved in the balance training and those in the control group.

In a similar study, McKeon and Hertel reported evidence in support of the ability of TTB to differentiate between those with and without CAI in the absence of a training intervention [57]. Thirty-two subjects with self-reported CAI and 32 age-matched controls were included in this study. Subjects performed three trials of TTB on both legs and in both conditions (eyes open/eyes closed). No significant group by gender interactions or main effects for gender were identified for either visual condition [57]. For the eyes closed condition, the CAI group demonstrated significantly lower values for TTB AP mean of the minima (p = .03), TTB AP SD of the minima (p = .03), TTB AP absolute minimum (p = .03), and TTB ML absolute minimum (p = .03) [57]. These findings support the earlier results published by McKeon et al. that identified
significant differences between individuals with CAI and control subjects in the eyes closed condition of TTB [51]. These results indicate that the subjects with CAI not only had less time to recover their balance prior to their COP moving outside the base of support, but also that their postural control strategies were more predictable and limited in their ability to recover postural control once it begins to move towards the boundary of the base of support. This is evidenced by the decreased SD of the minima [57].

These results are contrasted by an investigation by McKeon and Hertel that reported gender differences between male and female subjects with CAI [67]. Fourteen males and 10 females with self-reported CAI were compared to 20 healthy controls. All subjects completed three trials of TTB on each leg and in both eyes open and eyes closed conditions. Males did not demonstrate any significant differences as compared to their control counterparts. However, the female subjects had significantly decreased values compared to their control counterparts in the TTB mean of the minima (p = .013), TTB SD of the minima (p = .019), and TTB absolute minimum (p = .013) in the AP direction. There were no significant differences in the ML direction[67]. A possible explanation for the differing findings related to gender differences in TTB is the approach to classifying CAI subjects in these studies. Subjects self-classified themselves in all of the above mentioned studies based on previous history of at least one ankle sprain and self-perception of resulting disability. An attempt was made to identify subjects using the Foot and Ankle Disability Index (FADI), but it is possible that a broad range of ankle disability was represented and this may explain the varying results regarding gender differences in TTB [57, 67].

Further evidence that TTB can be manipulated was presented by McKeon and Hertel examining the effects of plantar hypoesthesia on postural control as measured by TTB [63]. Thirty-two healthy subjects (16 males and 16 females) volunteered for postural control assessment via TTB. The goal of the study was to assess changes in postural control after creation of a condition of hypoesthesia induced by a 10-minute immersion in an ice bath [63]. The most important results of this study demonstrated an increase in TTB AP absolute minimum, TTB AP mean of the minima, and TTB AP SD of the minima [63]. These changes in postural control contradict conventional expectations in that a decrease in sensation resulted in an increase in variability of postural control strategy and increased TTB. Intuitively, loss of sensation would lead to an overall decrease in postural control. However, the authors suggest that the change in plantar sensation resulted in a reorganization of postural control strategies.
that led to an increase in variability as the somatosensory system attempted to limit excursion of the COP and maintain postural control [63]. An important limitation to note is that single-limb TTB was always assessed second during this study (after double-limb stance TTB). This may have resulted in a reduced hypoesthesia condition as a result of time elapsed between removal of the foot from the ice bath and assessment of single-limb TTB [63].

In 2010, McKeon et al. also examined the effects of hypoesthesia in a lateral ankle ligament [61]. Investigators used lidocaine to induce the condition of impaired sensation. Twenty-two healthy adults (13 males and 9 females) participated in this study. Each subject participated in a control day (TTB without lidocaine injection) and a test day (TTB after lidocaine injection). The injection was intended to affect the lateral ankle ligaments, capsule, and peroneal tendons. The anesthesia resulted in significantly decreased values in the AP direction for TTB absolute minima \( (p = .008) \) and TTB SD \( (p = .044) \) [61]. These results were in line with the author’s hypothesis that reduced sensory capability at the lateral ankle would have negative effects on postural control. However, they are in contrast with the reported outcome of the hypoesthesia study conducted by McKeon and Hertel that affected the plantar surface of the foot. The method and location of sensory alteration may explain the differences in outcomes between the two studies.

In addition to examining effects of balance interventions and sensory alterations, the effect of altered plantar-receptor stimulation has also been examined in terms of its effect on TTB [68]. Twenty physically active individuals (12 males, 8 females) with self-reported CAI volunteered for this study, and the sensory alteration was induced with the use of a textured insole placed in the subject’s shoe prior to data collection. Each subject was tested under three conditions: textured insole, sham (smooth) insole, and no insole. They were also provided with a standard pair of nylon socks in order to standardize the interaction between the plantar surface of the foot and the various insole conditions. Each subject completed 3 10-second trials in single-limb stance in both eyes open and eyes closed conditions. Significant reductions in TTB values were found for the TTB ML absolute minimum \( (p = .04) \) and SD \( (p < .05) \) [68].

**Conclusion**

Previous research has demonstrated the ability of TTB to identify postural control deficits in individuals with specific pathologies or injury histories [55, 57, 58, 64, 66, 69]. TTB outcomes may also be manipulated by a change in visual input [57, 60, 61, 63, 68], completion...
of postural control or manual therapy interventions [51, 60] or alterations in sensory function in the ankle and foot [61, 63, 68]. Gender has also been identified as a characteristic that TTB may be able to differentiate [67]. However, contradictory evidence exists in the literature. McKeon and Hertel published a systematic review in 2006 examining the ability of TTB to differentiate between those with and without CAI and reported that the evidence was inconsistent and further research was needed to support this claim [70]. McKeon and Hertel reported no group by gender interactions or main effects for gender in a 2008 study [57]. Hoch and McKeon reported that a 2-week joint-mobilization intervention was not effective in improving postural control as measured by TTB in those with CAI [65]. In the studies reviewed, visual condition appears to be the only constant in terms of factors affecting TTB. Published results are consistent in stating that the eyes closed TTB condition results in lower TTB values as compared to eyes open. Continued research will provide a more thorough understanding of the diagnostic and discriminatory capabilities of TTB.

**Weight-Bearing Lunge Test**

*Background*

Adequate dorsiflexion range of motion (ROM) is necessary for performance of functional activities such as squatting, standing from a seated position, stair climbing, walking, running, and jumping [48, 71, 72]. It has been reported that limited weight-bearing dorsiflexion may result from ankle sprain [73, 74], ankle fracture and subsequent immobilization [75], and may also predispose individuals to injuries including ankle sprain, plantar fasciitis, navicular stress fractures, and patellar and Achilles tendonopathies [71, 76]. The clinical importance of maintaining or restoring functional dorsiflexion ROM has led to published research attempting to establish the best methods for its assessment.

The weight-bearing lunge test (WBLT), as described by Bennell et al. is a simple field test for assessment of weight-bearing dorsiflexion ROM [48]. However, it should be noted that the WBLT is viewed as an assessment tool for global ankle mobility and not specifically dorsiflexion at the talocrural joint. The WBLT may be influenced by movement occurring at other joints in the foot and ankle [77]. Traditionally, dorsiflexion has been assessed in a non-weight-bearing position by using a goniometer [71]. This measure has been shown to be less reliable [71, 72, 78] and the limited ability of the dorsiflexion musculature to overcome tight posterior musculature and joint capsular tissue may result in underestimation of functional dorsiflexion in
a weight-bearing position [74]. Weight-bearing dorsiflexion assessments allow for the use of the individual’s body weight to further stress tissue and identify the true ROM limits and better represent an individual’s functional ROM available for task completion [74]. The smallest real difference (SRD) between raters was calculated to be 13.8mm [75]. Same rater SRD ranged from 8.3mm – 7.3mm [75]. A review of the literature was undertaken to identify the most common methods for this assessment, determine the reliability of the measure, and summarize the findings of previous studies that have utilized this assessment tool.

**Methodology**

Prior to assessment, a tape measure is secured to a firm flooring surface, perpendicular to a wall. The test as described by Bennell et al. [48] involves the rater marking the tibia 15cm below the tibial tuberosity. This is the point of application for an inclinometer for a measure of maximum tibial tilt at the end of the subject’s dorsiflexion ROM. Next, a line is drawn bisecting the calcaneus to ensure consistent placement of the foot. The subject is positioned facing the wall with both hands on the wall, the feet staggered with the foot to be tested closest to the wall, and positioned along the measuring tape previously applied to the floor. Subjects are told to lunge forward, attempting to touch their knee to the wall without lifting the heel of the involved foot. The rear foot must stay perpendicular to the wall, but it is not necessary to keep the rear heel in contact with the floor and the subject can place it in a position of comfort. The foot is moved progressively farther from the wall in an attempt to identify the maximum dorsiflexion angle. When the maximum distance from the wall is identified, the distance from the great toe to the base of the wall is measured. In order to properly identify this maximum reach distance, the rater lightly palpates the heel during reach attempts in order to identify when/if it lifts from the ground. Additionally, while holding their knee to the wall at their maximum reach distance, the angle of the tibia is measured using an inclinometer at the point previously marked [48].

More recently published studies have suggested alterations to the methods published by Bennell et al. and some studies have proposed new weight-bearing test positions that may better, or more completely, capture weight-bearing dorsiflexion ability. O’Shea and Grafton modified the WBLT to involve a moveable object instead of a wall for the target [72]. Instead of progressively moving the subject’s foot away from the wall as they moved towards their maximum distance, they positioned a lightweight table leg directly in front of the subject’s knee,
with the base of the leg initially positioned at zero in a tape measure secured to the floor. As the subject lunged forward, the table leg was pushed farther away from the great toe. At the point of maximum reach, where the heel was palpated to be lifting from the ground, the distance between the great toe and table leg was measured [72]. The authors suggest that this method may be easier to assess since the subject’s foot does not need to be repeatedly moved and repositioned. A problem that arises with this method, as well as the one previously described, is that some individuals with severe dorsiflexion limitations will not be able to achieve a distance of zero where the knee meets the target with the great toe in contact with its base, either the wall or the moveable table leg. In this case, O’Shea and Grafton recommend measuring the distance between the table leg and patella and noting it as a negative reach distance [72]. Intra-class correlation coefficients (ICC) for intra-rater reliability were high (rater 1 = 0.98, rater 2 = 0.99) [72].

An alternative assessment of weight-bearing dorsiflexion ROM has been suggested by Munteanu et al. that involves a knee extended test position as opposed to the knee flexed position described by Bennell et al. [48] and others [71]. They point out that the WBLT assesses primarily the ROM of the soleus and joint capsule structure at the ankle and does not accurately determine ROM of the gastrocnemius. The assessment involves similar methods to those proposed by Bennell et al. [48]. The primary difference is that the rear leg is now the one being assessed and the front leg is positioned perpendicular to the wall in a position of comfort. The subject is instructed to reach their rear leg as far back as possible, keeping the knee extended, and attempting to keep the heel of that foot in contact with the ground [71]. In this position, the angle of inclination of the tibia of the rear leg is measured. For a more thorough assessment of weight-bearing dorsiflexion ROM, it may be appropriate to include both measures so that all structures potentially affecting this measure may be included. The authors reported high intra-rater reliability for the experienced raters for both a digital inclinometer (ICC = 0.88) and a clear acrylic plate apparatus (ICC = 0.89) previously described by Menz et al. [71]. For the inexperienced raters, intra-rater reliability was 0.77 and 0.99 for the digital inclinometer and clear acrylic plate apparatus respectively. Inter-rater reliability was high for both apparatuses (0.95, 0.97) [71].


Reliability

Previous studies have reported that the WBLT is a reliable test for the assessment of weight-bearing dorsiflexion ROM [48, 75, 78, 79]. In a study involving 13 healthy subjects Bennell et al. reported inter-rater reliability scores (ICCs) for distance of 0.99 and angle of 0.97. Their intra-rater reliability scores were also high at 0.98 for distance and 0.98 for angle [48]. Hoch and McKeon reported high (ICC = 0.99) scores for intra-trial reliability of the WBLT in a study involving 35 healthy adults [76]. Konor et al. reported reliability scores for three different methods of assessing dorsiflexion angles during the WBLT [78]. The within session intra-rater reliability (ICC) scores for the tape measure (right = 0.98, left = 0.99) inclinometer (right = 0.96, left = 0.97), and goniometer (right = 0.85, left = 0.96) were high [78]. In a study involving weight-bearing dorsiflexion ROM assessment in individuals at the time of cast removal post ankle fracture, Simondson et al. reported an ICC of 0.97 [75].

The expense of digital inclinometers, $150 or more according to Williams et al, led to the development of a free app available for the iphone™ has been suggested as a reliable alternative for measurement of the tibial inclination angle during the WBLT [80]. Williams et al. reported intra-rater ICCs ranging from 0.65 – 0.85 for novice and expert raters assessing weight-bearing dorsiflexion in both a knee flexed and knee extended position for both the TiltMeter app and digital inclinometer [80]. Inter-rater reliability scores ranged from 0.80 – 0.96 between novice and experienced raters for the TiltMeter app and digital inclinometer in both test positions [80]. These results potentially greatly decrease the expense necessary to digitally assess angle of inclination of the tibia during assessment of the WBLT. The authors caution readers that these results apply only to the iphone™ and have not been replicated on other smart phone devices [80].

Dorsiflexion and Postural Control

The question of whether or not dorsiflexion affects postural stability has been addressed in the literature, but the results are not in total agreement. Bradic et al. reported that dorsiflexion was not correlated to the performance of a balancing task on a Biodex Stability System [81]. Dorsiflexion was assessed using the WBLT as described by Bennell et al. and single-limb postural stability was assessed during single-limb, eyes open standing on an unstable Biodex platform [81]. No significant correlations were identified between the WBLT and any of the three Biodex assessments [Overall Stability Index (p = 0.18), Anterior-Posterior Stability
Index \( p = 0.33 \), Medio-Lateral Stability Index \( p = 0.71 \) \] \] [81]. This study differs from others that have established a correlation between postural stability and the WBLT [73]. Bradic et al. used the Biodex system whereas Hoch and McKeon utilized the Star Excursion Balance Test (SEBT) to evaluate dynamic balance [73]. The differing demands placed on subjects’ balance abilities may explain the contradictory results. However, Gribble and Hertel published results in 2003 stating that they found no significant \( p > 0.05 \) correlation between performance on the SEBT and weight-bearing dorsiflexion as measured by the WBLT [46].

Additional studies have investigated the relationship between dorsiflexion ROM as measured by the WBLT and dynamic balance assessed by the SEBT. Hoch et al. completed a study in 2010 involving 35 healthy adults [73] requiring all subjects to complete the WBLT and modified SEBT (anterior, mediolateral, posterolateral reach directions) assessments during a single testing session. Their results demonstrated a significant \( p < 0.05 \) correlation between the WBLT and anterior reach of the SEBT \( p = 0.001 \) [73]. The posteromedial and posterolateral SEBT directions were not significantly correlated to the WBLT results [73]. These results contradict the findings reported by Gribble and Hertel in 2003 [46]. Kang et al. reported similar findings and went on to suggest that individuals exhibiting poor dynamic balance as measured by the SEBT should be evaluated for weight-bearing dorsiflexion deficits utilizing the WBLT [82]. Thirty physically active subjects had their performance on the WBLT evaluated and compared to their performance on the Y-Balance Test [83], a commercially available tool for the assessment of dynamic balance based on the SEBT. Their findings included significant \( p < 0.05 \) correlations between the WBLT and all three reach directions of the Y-Balance Test (Anterior, Anteromedial, Anterolateral) [82]. These results support those of Hoch et al, but go on to suggest a relationship between all Y-Balance Test reach directions as opposed to only the anterior reach of the SEBT.

**Discriminatory Capability**

As with any assessment tool, the ability of the test to discriminate between groups and its susceptibility to manipulation by therapeutic intervention must be examined. Meakins and Watson evaluated the ability of conductive heating (hot water bottle) and long wave ultrasound on functional ankle mobility [77]. Eighteen asymptomatic subjects (11 female, 7 male) volunteered for the study and were treated on two separate occasions at least one week apart. Preceding and following treatment, subjects were evaluated using the WBLT to assess the
change in weight-bearing dorsiflexion ROM. Both treatments were found to result in significant
(p < 0.0005) changes to WBLT results as compared to the control group. However, the two
treatments were not found to be significantly different at the p < 0.0005 level (p = 0.125) [77].
The post-treatment measure of the WBLT was taken immediately after termination of the
thermal modality to limit the effects of temperature decay on the outcome. The results
reported here may not be replicated if too much time lapses post-treatment prior to ankle
mobility assessment and this should be noted by practitioners [77].

There is limited evidence available in the literature related to the discriminatory
capability of the WBLT. However, a study by Williams et al. was identified that employed the
WBLT to assess ankle mobility in a group of 60 children separated into either idiopathic toe
walking (ITW) or non-toe walking (NTW) groups. They reported a “highly” significant difference
between the two groups with the ITW group demonstrating limited ankle mobility as compared
to the NTW group. The level of significance and resultant p-values were not reported in the
published manuscript of the presentation. The authors concluded that an ITW gait has a direct
and significant impact on the amount of dorsiflexion available at the ankle [84].

Conclusion

The WBLT is a simple, inexpensive field test that can be utilized to assess functional,
weight-bearing dorsiflexion ROM. However, it is not without limitations. The dual roles of the
musculature comprising the calf complex may necessitate the use of both the WBLT as
described by Bennell et al. and the knee extended method described by Munteanu et al. [48, 71]
in order to develop a clearer picture of the overall dorsiflexion available during weight-bearing
activity. The literature has made a strong case for these weight-bearing methods replacing
traditional non-weight-bearing methods for assessing passive dorsiflexion. Functional activity
does not take place in a non-weight-bearing position, so it is only logical to assess ROM in the
same manner that it will be utilized.

These weight-bearing measures have demonstrated better reliability than the non-
weight-bearing methods previously used, and are even reliable in novice raters which allows for
broad application of this assessment by clinicians of any experience level. This is due in large
part to the limitation on weight-bearing ROM being more absolute in nature as it is controlled
by true limits of connective tissue and bony structure as opposed to the non-weight-bearing
assessment which is controlled by the relationship between dorsiflexor strength and plantarflexor tightness/stiffness.

**Star Excursion Balance Test (SEBT)**

*Background*

The TTB assessment represents a valid and reliable test for the assessment of static single-limb postural control and balance. However, the ability to maintain balance during still standing may not be representative of an individual’s ability to maintain postural control during more complicated movement tasks [85]. The Star Excursion Balance Test (SEBT) is a widely used field test for the assessment of dynamic postural control and can be conducted with minimal expense and inconvenience to the practitioner or patient. In addition to straightforward postural stability assessment, previous literature has suggested the SEBT may be used as a predictor of lower extremity injury [86] and athletic participation [87], may have discriminatory capabilities to differentiate between those with and without ankle sprain or CAI [15, 88-91] and those who are ACL deficient, and is sensitive to the effects of various therapeutic [1-4, 92-96] and prophylactic interventions [97-99]. Evidence also exists in the literature demonstrating the negative effects of fatigue on performance of the SEBT in uninjured, healthy subjects, as well as those with CAI [90, 91, 100].

**SEBT Evolution**

The original SEBT was described by Gray and combined single-leg squat tasks with maximum reach by the non-stance limb in eight different directions [49]. Each reach distance was marked by lines on the floor in a star pattern with the rays laid out in 45-degree increments. Successful completion of the task required maintenance of postural control while completing each maximum reach. If the heel of the stance foot lifted, the stance foot shifted at all, or weight was transferred from the stance limb to the reach limb the trial was not accepted and repeated. After each reach, subjects were required to return to tall standing with the feet side-by-side prior to reaching in the next direction. The distance is measured along the line of reach from the great toe of the stance limb to the most distal point touched with the reach foot. A greater distance implies greater postural control [85]. Kinzey and Armstrong reported that a survey of clinicians regularly utilizing the SEBT found that more clinicians conducted the assessment with their subjects wearing shoes [101]. Furthermore, there was no consistency amongst those surveyed regarding the length of the reach limb. The authors stated that they
did not control for either of these factors since it did not appear at the time that there was any consistency in the clinical protocol being used [101].

Recommendations have since been made to simplify the SEBT due to redundancy found in the eight reach directions [102]. In a 2006 study, Hertel et al. reported that subjects' reach distance in any one direction was highly correlated with the seven other reach distances. Therefore, the authors recommended reducing the number of reach directions from eight to three [anterior (ANT), posterolateral (PL), posteromedial (PM)] [102]. The reach directions are defined by position of the stance foot. Reduction in the number of reach distances greatly reduces the amount of time taken to complete the test. In 2010 Demura and Yamada recommended a modified SEBT model consisting of four reach directions (anterior, medial, posterior, lateral) based on results that indicated the same level of validity and overall assessment of postural stability may be achieved with the assessment of these four directions and as few as three reaches in each direction [103]. No practice trials were utilized in this study and the authors reported that after the second reach in a given direction the values were not significantly different [103].

The number of practice trials required prior to data collection has also come into question regarding the SEBT. In 2000, Hertel et al. reported that subjects continued to improve their reach score with each additional attempt in a given direction until the seventh trial. Based on these results, they concluded that six practice trials should be concluded for each reach direction in order to ensure capture of true maximum reach directions during data collection [104]. However, Robinson and Gribble suggested reducing the number of practice trials to four based on their results in a 2008 study [105]. Based on maximum reach distance and kinematic data, they reported that SEBT performance stabilized after four practice trials and subsequently recommended a reduction in practice trials from six to four [105]. Munro and Herrington reported findings in support of this reduction [44] and this change in methodology has led to further reduction in the time required for completion of the SEBT and has therefore made it easier to use both clinical and research settings without sacrificing the integrity of the results. Once the practice trials are completed, three test trials are completed and the mean reach distances are calculated [45, 73, 105, 106]. If no significant differences exist between the right and left sides, the means are then pooled and analyzed as one.

Based on the recommendations of Hertel et al, Fullam et al. compared the SEBT and a newly developed and commercially available assessment tool based on this test, called the Y
Balance Test (YBT) [107]. The YBT utilizes the same three reach directions proposed by Hertel et al. for their modified SEBT. However, instead of a simplistic set-up involving properly laid out lines of tape and visual assessment of maximum reach distance by a rater, the YBT requires subjects to slide a block along a calibrated bar while standing in a single-limb stance on a raised platform [107]. The authors hypothesized that since the assessments were so similar, their results should be similar as well. Fifteen healthy male and 14 healthy female subjects were assessed using both the SEBT and YBT and the results in terms of maximum reach distances were compared. Leg length was used to normalize the data and the measurement method previously described by Gribble et al. and Bastien et al. was utilized [46, 88]. The authors reported subjects reached significantly (p < 0.05) farther in the anterior direction on the SEBT as compared to the YBT. This was further supported by the fact that 28 of the 29 participants demonstrated greater maximum reach distances in the anterior direction on the SEBT [107].

The authors suggest that these consistent significant differences were caused by kinematic differences observed during the two tests. A negative, non-significant correlation was observed between sagittal hip flexion angle and anterior reach distance on the SEBT (r = -0.06, R² = 0.36, P > 0.01) and a positive, non-significant correlation was identified between the same hip variable and the YBT (r = .43, R² = .18, P > 0.01). Based on these results, the authors hypothesized that the decreased hip flexion seen during the SEBT results in less anterior translation of the center of mass, which in turn allows subjects to use this as a counterbalance and subsequently achieve a greater maximum reach distance in the anterior direction [107].

Robinson and Gribble established a somewhat conflicting relationship between hip flexion and SEBT anterior reach distance compared to the findings of Fullam et al. [105]. They reported that hip and knee flexion angles accounted for 78% of the variance (p < .001) for anterior reach. These results indicate that greater hip flexion, or a combination of increased hip and knee flexion, are primarily responsible for determining anterior reach distance [105]. Further research is necessary to determine the efficacy and clinical relevance of the YBT and how it compares to the SEBT.

SEBT Reliability and Validity

The reliability of the SEBT has been reported in multiple previous studies. In a study examining 16 healthy, recreationally active adults Hertel et al. reported on the intratester and intertester reliability of the SEBT as originally described [104]. They recommended a minimum
of six practice trials be completed prior to data collection to allow for attenuation of the familiarization effect. Intratester reliability (ICC) was .78-.96 on day one and .81-.93 on day two. For intertester reliability (ICC), day one ranged from .35-.84 and day two ranged from .81-.93 [104]. Demura and Yamada reported intertester reliability as represented by ICCs > 0.99 in all four reach directions assessed (anterior, medial, posterior, lateral) [103]. Additionally, they reported overall test re-test reliability scores between 0.92 and 0.99, which included an evaluation of dominant and non-dominant stance limbs, and an evaluation of various groupings of reach trials. Trials, 2-9, 2-4, and 2-3 were assessed and all resulted in high reliability scores [103]. Munro and Herrington reported test re-test reliability ranging from 0.84 – 0.92 in a study involving modified (anterior, lateral, posterior) SEBT assessment in 22 healthy recreational athletes in 2010 [44]. Gribble et al. reported additional findings that support use of the modified (anterior, posteromedial, posterolateral) SEBT as a reliable assessment of postural control [108]. In their 2013 study, they found that intrarater reliability of normalized scores was high, ranging from 0.86 – 0.92. for non-normalized values, the ICCs were even higher, ranging from 0.89 to 0.94 [108]. Finally, Bastien et al. reported ICCs ranging from 0.986 – 0.992 for test re-test reliability using a modified (anteromedial, medial, posteromedial) SEBT [88]. The current literature has established that the SEBT is a reliable tool for the measure of postural control.

Gribble et al. reported on the validity of the SEBT, and stated that evidence exists in the literature to confirm the SEBT as a valid test for the prediction of lower extremity injury, and identify dynamic balance deficits. They also stated that the SEBT has been found to be influenced by training programs in healthy individuals and those with injuries in the lower extremity [85]. Most recently, Bastien et al. reported that the SEBT had high concurrent validity between visual estimation of reach distance and the gold-standard of 3D motion analysis [88]. They also discussed the discriminant validity of the SEBT and found that it was able to differentiate between healthy subjects and those in the lateral ankle sprain group. Normalization by height was found to have a stronger effect size (0.96 – 1.40) and ability to differentiate than the more widely used method of normalization by leg length (0.81 – 1.30) [88]. This was true for comparison of each reach direction (anteromedial, medial, posteromedial) individually, as well as comparison of the overall score.
SEBT Normalization Methods

In order to compare reach distances between subjects, a normalization procedure becomes necessary to account for anthropometric differences. Two methods have been proposed, one focusing on leg length (LL) and the other focusing on overall height [1, 46, 85, 88]. Gribble et al. and Bastien et al. described the LL measurement as follows: subject lying supine, LL measured from anterior superior iliac spine (ASIS) to the center of the ipsilateral medial malleolus [46, 88]. Hoch et al. and Plisky et al. described a very similar method to Gribble et al. However, they stated the measurement was taken to the distal end of the medial malleolus [73, 86]. Plisky et al. reported an ICC of 0.99 for their LL assessment method [86]. Filipa et al. described a similar method in 2010, but described the bony landmarks used as the most inferior portion of the ASIS and the most distal aspect of the lateral malleolus [1]. Despite differing methods, the LL measurement has been widely used to normalize reach distances between subjects to allow for comparison. At this point, no method has been established as the gold-standard in the literature and all methods appear to be reasonably effective. Bastien et al. reported that the LL measurement displayed good discriminant validity, but not as strong as that associated with body height [73]. Therefore, the authors recommended using body height as the variable for normalization in order to maximize the discriminatory capabilities of the SEBT between those with and without lateral ankle sprain [73].

Gribble and Hertel reported that height and LL were strongly correlated to each other (R² = .77) in recreationally active adults. Additionally, they reported significant (p < 0.05) correlations between height and excursion distances (R² range: 0.10 to 0.19), and LL and excursion (R² range: 0.10 to 0.23) [46]. Therefore, they concluded that LL should be utilized as the normalization method of choice.

Bastien et al. reported conflicting results [88]. They presented R² values in their healthy subjects of 0.60 and 0.52 for the height-adjusted and LL-adjusted groups respectively. For the lateral ankle sprain subjects, R² values were 0.24 and 0.17 respectively [88]. This led the authors to conclude that the height adjustment method was the more effective normalization tool [81]. Considering the conflicting results and the presence of both methods in the literature, a gold-standard for SEBT reach distance normalization has yet to be established. For whatever method is chosen a normalization formula must be utilized. As an example, Filipa et al. published one for their method of assessing LL and normalizing SEBT composite scores: [(ANT + PM + PL)/(LL x 3)] x 100 [1].
SEBT Predictive Capabilities

Plisky et al. determined the effectiveness of the SEBT as a predictor of lower extremity injuries in a group of 235 male and female high school basketball players [86]. All subjects were evaluated using the SEBT during pre-season and then had their time lost due to injury over the course of the season monitored. The results demonstrated that players with a side-to-side reach distance difference larger than 4cm were two and a half times more likely to suffer an injury to the lower extremity (p < 0.05) [86]. They also identified 94% of LL as the cutoff point for an increased risk of injury to the lower extremity in female high school basketball players. Girls with a composite reach distance below 94% were 6.5 times more likely to suffer injury than those whose composite score was above the cutoff point [86].

SEBT Discriminatory Capabilities (Sensitivity to Internal Factors)

Bastien et al. reported that SEBT maximum reach distance, normalized by height or LL, had the ability to discriminate between men in the Canadian military with and without history of lateral ankle sprain [88]. Both normalization methods resulted in statistically significant differences between the two groups. Expressed as a percentage of LL, significance values for anteromedial, medial, posterolateral, and overall score were ≤ .04 [88]. For height, the values were ≤ .006 [88]. The authors suggest that normalization by height may be the more insightful method despite the common use of normalization by LL. They state that the height normalization method considers the subject’s torso and the role it plays in maintenance of postural stability [88]. This study represented a specific population and tested only a small sample, but adds to the mounting evidence that the SEBT is discriminatory and that normalization using either method allows for comparison of reach distances across subjects.

In a study involving 38 subjects (17 men, 21 women) Nakagawa and Hoffman reported that SEBT performance was significantly different between subjects with and without a history of recurrent ankle sprains [89]. Based on injury history, subjects were placed in either the control (n=19) or recurrent-ankle-sprain (n=19) groups. All subjects had their postural stability assessed via SEBT. It was concluded that there were no significant differences between the two groups for the composite score calculated from their SEBT performance [89]. In the authors’ comments, they suggest that the SEBT may not be sensitive enough to identify proprioceptive and postural control deficits caused by recurrent ankle sprains [89].
An individual’s performance on the SEBT provides important insight into their postural control. Deficiencies in postural control may lead to an increased likelihood of injury, and poor performance in the SEBT may be linked to specific injury histories. Herrington et al. compared SEBT performance between a group of 25 subjects (17 male, 8 female) with a current ACL injury [ACL deficient (ACLD)] adults and 25 matched controls [106]. The ACLD subjects were found to have significantly lower reach distances in four of the eight directions tested (anterior, p = 0.003; lateral, p = 0.005; posteromedial, p = 0.002; medial, p = 0.001) [106]. Additional significant differences were identified in the medial (p = 0.001) and lateral (p = 0.001) reach directions between the uninjured limbs of the ACLD subjects and the control group [106]. These results indicate two important findings. First, ACLD individuals have postural control deficits compared to those without this condition. Second, ACLD individuals may have a neuromuscular deficiency that contributes to the occurrence of the ACL injury. The authors recommend further inquiry into whether or not the deficiency they identified is predictive of future ACL injury [106].

Anterior reach distance has the unique characteristic of relying more heavily on ankle ROM than any of the other reach directions in the SEBT, or any of its modifications. This means that a potential limitation in ankle dorsiflexion ROM may limit anterior reach capability even if no other neuromuscular deficiencies exist in an individual. Hoch et al. assessed the relationship between the SEBT and WBLT and whether or not either was limited in subjects with CAI [15]. Thirty subjects with CAI volunteered for the study and were matched with 30 healthy subjects. All of the subjects were assessed using the WBLT and SEBT. Significant differences were identified between the two groups for performance on the WBLT (CAI: 10.73 ± 3.44cm, Healthy: 12.47 ± 2.51 cm; p = 0.03) and the anterior reach of the SEBT (CAI: 76.05 ± 6.25%, Healthy: 80.12 ± 5.88%; p = 0.01) [15]. The relationship between the WBLT and anterior reach of the SEBT demonstrates that this reach direction is affected by ankle ROM. These results also indicate that the SEBT is capable of identifying those with dorsiflexion ROM insufficiency and CAI [15].

**SEBT Discriminatory Capabilities (Sensitivity to External Factors)**

The effectiveness of orthotics, prophylactic braces and taping techniques on postural control and SEBT performance have been the topic of previously published studies [97-99, 109]. Orthotics are commonly used to improve patient outcomes for individuals with lateral ankle sprain, medial tibial stress syndrome, and patellofemoral pain [99]. Olmsted and Hertel [99] and
Hadadi et al. [98] examined the effects of orthotics on postural control. Olmsted and Hertel [99] recruited and randomly assigned 30 healthy subjects to groups based on foot type and then assessed all subjects via the SEBT. All subjects were fitted for and instructed to wear custom semi-rigid orthotics designed for their foot-type four hours per day for two weeks. At the conclusion of the treatment interval, subjects were re-assessed to determine the effect of the orthotic on their postural stability. Subjects with cavus feet performed significantly ($p = 0.03$) better on the SEBT in the anterolateral, lateral, and posterolateral directions [99]. Additionally, the pes cavus subjects had improved their reach distances in all directions as compared to the pes rectus or pes planus groups after completion of the orthotic intervention [99]. The authors suggested that the use of orthotics in subjects with pes cavus feet may improve the coupling of the foot and balance surface and therefore allow improved neuromuscular function and greater postural control. However, it is still unknown what clinical implications these results may have [99].

Hadadi et al. went a step further in investigating the effects of orthotics and compared SEBT performance between subjects with functional ankle instability and healthy controls [98]. All subjects were tested in three conditions: no orthosis, soft orthosis, and semi-rigid orthosis. In the FAI group, reach distances were significantly greater in the anteromedial and medial reach directions for the semirigid (10%, 9%, $p = 0.01$) and soft (13%, 14%, $p = 0.01$) orthoses groups compared with the no-orthosis condition [98]. There were no significant differences between the soft and semi-rigid treatments in these two directions. For the posteromedial reach, significant differences were identified between all conditions. The soft orthosis condition resulted in a 14% difference ($p < 0.01$), semi-rigid outperformed the no orthosis group (8%, $p < 0.01$), and soft outperformed the semi-rigid group (5%, $p < 0.05$) [98]. In summary, the authors concluded that soft and semi-rigid orthoses were effective in improving reach distances in the SEBT for individuals with functional ankle instability. More specifically, their results indicated that the soft orthosis was the most effective in the posteromedial reach direction [98].

The results published by Hadadi partially support those by Olmsted and Hertel. Both found that semi-rigid orthoses positively affected one or more SEBT reach distances. However, the test populations were different and the study goals were dissimilar. Olmsted and Hertel attempted to match foot-types to the proper orthosis in healthy subjects to determine if a period of repeat exposure would result in improved postural control [99]. Hadadi compared those with functional ankle stability to those without and each subject was exposed to various
orthoses conditions [98]. Continued research is necessary to determine the full effects of orthotic use on postural control in individuals with varying foot types and ankle pathologies such as functional ankle instability.

Prophylactic ankle braces are often used for prevention or stabilization purposes in relation to ankle injury. However, their effect on postural stability has not been fully elucidated in the scientific literature. Hardy et al. concluded that prophylactic ankle bracing had no significant effects on any of the eight originally described SEBT reach directions [109]. They examined 36 healthy, physically active, college-aged volunteers (18 male, 18 female) by assessing their SEBT maximum reach distance in three different bracing conditions including unbraced (UB), semi-rigid (SR), or lace-up (LU). The authors reported that bracing condition had no statistically significant effects on any of the SEBT reach distances [109]. The authors reported that their results concurred with previously published results regarding the effect of prophylactic bracing on functional performance.

In addition to prophylactic bracing, corrective taping such as McConnell taping for PFPS is a commonly used intervention to decrease pain and increase functional capacity. Aminaka and Gribble published findings related to the effect of patellar taping on dynamic postural control in 2008 [97]. They reported that corrective taping led to reduced pain (p = 0.005) as measured by a visual analog scale and increased reach distances in the PFPS subjects. The PFPS subjects increased their reach distance (62.8 ± 1.2% vs. 63.5 ± 1.3%) when completing the SEBT in the taped condition [97]. Additionally, the control subjects demonstrated a decrease in reach distance with the application of the corrective taping (65.6 ± 1.2% vs. 64.8 ± 1.3%) [97]. These are important findings that provide insight into the effect of patellar taping. The control subjects actually experienced a decrease in postural control performance in the corrective taping condition. Applying corrective taping to a normally functioning patella resulted in a decreased performance [97]. This demonstrates that patellar taping actually results in altered function and only appears to be beneficial in those individuals with altered patellar function.

Lastly, Sabin et al. published findings related to the effect of testing surface on SEBT performance [87]. The study compared SEBT performance on a firm surface to that on an unstable (foam pad) surface in healthy collegiate athletes and age-matched controls (non-athletes). Each subject completed two SEBT assessments, one on each surface. Analysis of the anterior reach demonstrated a significant between-group effect (p < 0.01), indicating that the overall reach was 7% greater in the control group compared to the athlete group [87]. For the
medial direction, the control group reached significantly (6%, p < 0.01) further than the athlete group overall and a significant (4.5%, p < 0.01) difference was found between the two testing surfaces, with the firm surface out-performing the unstable surface [87]. Finally for the posterior reach, overall distance was 9% (p < 0.01) greater on the firm surface compared to the unstable surface, men reached significantly farther than women overall (5%, p < 0.01), and the control group reached farther than the athlete group (7%, p < 0.01) [87]. These results raise questions regarding the interpretation of SEBT results and the effect of athletic skill and participation on postural control. In this study, athletes performed consistently lower on the SEBT as compared to non-athlete controls. Neither group was known to have any type of lower-extremity injury that may have affected their postural control. Training methods, available ROM, and limited sample size may have led to these unexpected results. However, it is important as comparing different populations using the same assessment tool may not be an affective assessment strategy.

**SEBT Influence of Training Interventions on Performance**

Balance training is not standardized and many tools are available that purportedly enhance balance over time. Often, a progression is made from uniaxial to multiaxial unstable surfaces in an attempt to progressively challenge individuals participating in rehabilitation. However, the effects of these different modes of instability affect dynamic postural control. Eisen et al. reported no significant differences between a uniaxial (rocker board) and multiaxial (air-filled disc) training intervention [47]. Thirty-six subjects including male soccer players and female soccer and volleyball players were assigned to one of three groups (control, rocker board, air-filled disc) and completed a simple training protocol which included a task of single-limb balance while catching a ball and standing on their assigned rehabilitation implement. This was done three times per week for four weeks. Postural control was assessed using the SEBT pre- and post-intervention. The absence of significant results is attributed to the small test population and the possibility that the training intervention was not challenging enough for the subjects to result in identifiable changes in their postural control as assessed by the SEBT [47].

Lower extremity injury is often unilateral in nature and rehabilitation for these injuries is often focused on the injured extremity, with little attention paid to the uninjured side. However, if neuromuscular control is centrally mediated, it may be possible to begin neuromuscular training earlier in the rehabilitation process by beginning training with the
uninvolved side. Hale et al. investigated this possibility involving 34 volunteers (26 women, 8 men) with CAI [94]. The exercise group completed two 30-minute exercise sessions for four weeks and the control group simply continued normal activity. All exercises for the exercise group were completed unilaterally on the uninvolved limb and postural control was assessed bilaterally using the SEBT. The training protocol for the exercise group was targeted towards the improvement of static and dynamic postural control. For data analysis, the limb scores were combined and analyzed as one. Both groups demonstrated significant ($p < 0.05$) improvement over time in the posterolateral reach direction, but the exercise group had a greater improvement. The exercise group also improved significantly ($p < 0.05$) in the anterior and posteromedial directions. These results indicate the potential for earlier neuromuscular improvements if training is conducted on the uninvolved side until the involved lower extremity is capable of safely completing this type of activity [94].

Training surface has not been extensively analyzed in terms of its effect on SEBT performance. However, one study was identified that involved a comparison of training surfaces and their effects on postural control. Latour et al. examined the effect of sand training on SEBT performance by comparing the effects of a nine-session training intervention conducted on either sand or hard ground [95]. The authors reported an overall positive effect of sand training on ankle stability [95], but further detail was not available since this was a foreign-language manuscript.

In addition to training surface alterations, new methods of training have been introduced in an effort to improve patient enjoyment during training, as well as achieve more traditional rehabilitation goals. “Exergaming” systems, such as the Wii Fit have been utilized to achieve this purpose. Two studies were identified using this technology and both reported that exergaming resulted in similar improvements compared to more traditional rehabilitation protocols [87, 92, 93]. Fitzgerald et al. recruited 22 healthy adults and randomly assigned them to either the exergaming or control group. The SEBT was used to assess dynamic postural control prior to initiation of the training protocol and again once it had been completed. Training included 12, 15-minute sessions of a highly specific postural stability training program. They reported that both groups demonstrated significant ($p < 0.01$) improvements in posteromedial and posterolateral reach distances after completion of their respective interventions. There were no significant differences between the two groups. The authors also report that the exergaming subjects had higher interest and enjoyment scores on the Intrinsic
Motivation Inventory compared to the control group. Based on these results they recommend the use of exergaming for the improvement of postural control since there is evidence that it leads to improvements in SEBT performance and appears to result in higher patient interest and adherence [93].

In 2013, Baltaci et al. published a study related to the use of exergaming for the improvement of postural control [92]. Their results were similar to those of Fitzgerald et al. discussed earlier. Thirty male subjects who underwent unilateral ACL reconstruction were recruited and assigned to either an exergaming group or a conventional rehabilitation group for the first 12 weeks of their rehabilitation. They reported similar significant (p < 0.05) improvements in the anterior and posteromedial reach directions for both groups at the completion of the 12 week period [92].

Approaches to improving postural control vary in the literature and include core strengthening, static and dynamic balance training, lower extremity strength training and various combinations thereof. Hale et al. developed a 4-week rehabilitation program to improve postural control and applied it to a group of individuals with CAI [2]. The rehabilitation intervention involved ROM and strengthening exercises along with balance training and functional tasks. Workout sessions were completed primarily at home, but subjects did visit the lab and at various times throughout the intervention and were asked to keep a workout log to track compliance. Nineteen healthy subjects without CAI were assigned to a healthy group, 13 subjects with CAI were assigned to the control group, and 16 subjects were assigned to the CAI-rehab group. The healthy and CAI control groups were asked to continue with their normal activities over a four-week period while the CAI rehab group completed the intervention. Postural stability was assessed using the SEBT at pre- and post-test intervals. Subjects with CAI were found to have postural control deficits as compared to the healthy subjects. They also demonstrated significant (p < 0.05) differences between the involved and uninvolved limbs. Upon completion of the rehabilitation protocol, CAI-rehab patients demonstrated greater improvements than their counterparts that did not participate in the rehab program in the posteromedial, posterolateral, and lateral reach directions [2]. The authors suggested use of the SEBT as an assessment tool to determine the effects of postural control training interventions [2].

Leavey et al. published their findings after completing three different six-week training programs with the goal of improving postural control [110]. Thirteen subjects in the gluteus
medius strength training group, 12 in the proprioceptive training and combination groups, and 11 in the control group completed the study. All subjects completed a pre- and post-test of their dominant limb using the SEBT and all training exercises were completed on the dominant limb. The training interventions were supervised and included three, 20-minute sessions for six weeks. The results indicated no significant differences between the three treatment groups from pre- to post-test, but all three groups improved significantly compared to their baseline measures. The combination training group demonstrated the most improvement, but it was not significantly different from the other two treatment groups [110]. The posteromedial, posterior, and posterolateral reach directions improved significantly for all groups except the control from pre- to post-test. Ultimately, the authors concluded that the SEBT was sensitive to the effect of a six-week training protocol including proprioceptive training, gluteus medius strength training, or a combination of both [110].

Kahle et al. also conducted a six-week intervention and examined its effect on postural control [3]. Their study centered-around core stability training and was conducted using thirty healthy subjects randomly assigned to either a control (8 male, 7 female) or exercise (9 male, 6 female) group. Postural control was assessed pre- and post-intervention using the SEBT. The core stability training protocol involved completion of a steadily progressed program three times per week for six weeks. The core-strengthening group demonstrated significant (p < 0.001) increases from pre- to post-test that were not seen in the control group for the anteromedial, medial, and posteromedial reach directions [3]. The results presented by Kahle et al. indicate that core-strengthening leads to an improvement in dynamic postural control as measured by the SEBT and since there were no significant effects for gender identified, these results may be applied to individuals of both genders in their training and rehabilitation protocols [3].

Neuromuscular training is a broad term implying time spent training balance, functional movement, core stability, etc. with the goal of improving joint stability and possibly preventing injury [4]. A number of studies have been published examining the effect of various neuromuscular training protocols on SEBT performance. Valovich-McLeod et al. and O’Driscoll et al. both reported the effects of a six-week neuromuscular training program on SEBT performance [4, 96] (REFs). Valovich-McLeod et al. recruited 62 female high-school players and assigned them to either an intervention (n = 37) or control (n = 25) group. All subjects performed the SEBT pre- and post-intervention. The intervention group participated in a six-
week neuromuscular training program involving plyometric, balance, functional strength, and stability ball exercises. The intervention group demonstrated significantly (p < 0.05) increased reach distances in the lateral, anteromedial, medial, and posterior directions compared to the control group. This study provided two substantive points related to the SEBT. First, their intervention was specific enough to dynamic postural control that it resulted in improvements in a number of reach directions. Second, the SEBT is sensitive enough to recognize the effects of the training intervention utilized [4]. These results are in agreement with previously published studies reporting the positive effects of various core strengthening and balance training protocols on SEBT performance [2, 3, 110]. They also provide additional evidence supporting a certain degree of duration, intensity, and specificity required to achieve notable change in SEBT performance, which is accentuated by the lack of significant improvement reported by Eisen et al. after completion of their single-task treatment intervention [47].

A case study utilizing a neuromuscular training program with components similar to those published by Valovich-McLeod et al. [4] was published by O’Driscoll et al [96]. They tracked the progress of a 19-year old male rugby player following an acute, unilateral lateral ankle sprain through the six-week intervention. The authors reported increased reach distances in all directions (anterior, posteromedial, posterolateral) compared to the baseline test [96]. Care must be taken in order to not over-emphasize the results of a case study with a single subject. A number of factors could help explain the improvement over time, separate from the effectiveness of the intervention. For example, healing will naturally occur over time and would be expected to be accompanied by improved reach distances. However, the authors cite at least one previously published study with similar findings in support of their results [96]. Filipa et al. provided additional evidence regarding the efficacy of neuromuscular training for improving postural control as measured by the SEBT [1]. They utilized an evidence-based training protocol and implemented it in a group of 20 uninjured female soccer players (13 experimental, 7 control). All subjects were assessed using the SEBT and then either participated in the training intervention two times per week for eight weeks (experimental group) or to simply continue their previous level of activity (control group). After eight weeks, all subjects completed a second round of SEBT assessment and the experimental group significantly (p = .024) improved their composite (overall representative score) score on both limbs. Specifically, the right (p = 0.008) and left (p = 0.04) limbs significantly improved in the posterolateral direction as well as the left limb in the posteromedial direction (p = 0.028). No training effect
was observed in the control group [1]. These results support the previous publications that have reported the positive effects of neuromuscular training on SEBT performance.

Despite these findings, not all studies examining the effects of neuromuscular training on SEBT performance reported positive effects. Two recent studies were identified that reported no significant improvement in postural control after participation in a neuromuscular training protocol. Zech et al. assessed changes in SEBT performance in a group of 30 youth field hockey athletes after participation in either a 20-minute, two times per week for 10 weeks training intervention and reported similar increases between the control and intervention group [111]. The authors speculated that the training protocol was not specific enough to effect a change in SEBT performance despite it leading to significant changes in static balance capability (p < 0.001) [111]. Lindblom et al. also reported a lack of significant findings after examining the effect of a neuromuscular warm-up program in 41 youth female soccer players [112]. Subjects in the intervention group participated in 15-minute warm-up program completed two times per week for 11 weeks which included plyometric, agility, and sprint training. The authors reported that poor subject compliance and a lack of training specificity led to the absence of significant findings [112].

In a review published in 2011, O’Driscoll and Delahunt acknowledged that there is evidence in the current literature to support the use of neuromuscular training to improve postural control. However, their review of the current literature exposed many of the existing studies as underpowered and potentially biased. Therefore, further randomized controlled trials (RCT) research is indicated in order to strengthen the body of knowledge related to this topic [113].

**SEBT Effect of Fatigue on Performance**

Fatigue is an inevitable result of intense or long duration physical activity and can increase the risk of injury due to its effect on neuromuscular control [90, 91]. Gribble et al. reported in two different studies that previous research has established that fatigue has a negative effect on static balance, but its effects on dynamic balance were less well-understood [90, 91]. A 2004 study by Gribble et al. concluded that the combination of CAI and fatigue led to decreased postural control. Thirty physically active subjects volunteered and were placed in one of two groups: CAI (8 males, 8 females) or healthy (7 males, 7 females). All subjects completed five fatiguing protocols and had dynamic postural control assessed before and after each one by
completion of the SEBT. Fatigue protocols included three different protocols (sagittal motion at ankle, knee, and hip) as well as a weight-bearing lunge to fatigue and a control treatment that involved sitting quietly for five minutes. Subjects in the CAI group demonstrated significantly ($p < 0.05$) less maximum reach distance in all three test directions (anterior, medial, posterior) compared to their uninjured limb as well as the limb-matched controls [91]. Additionally, they reported that fatigue resulted in significant ($p < 0.05$) reductions in knee and hip flexion angles in both the CAI and uninjured groups, but not the control group. The injured limb in the CAI group consistently demonstrated the greatest reductions of ROM at these two joints [91].

The authors highlight the previously established relationship between CAI and decreased postural control as well as attempt to explain the mechanism behind the deficits seen after completion of the fatigue protocols. Performance of the SEBT declined in both the healthy and CAI groups, but to a greater degree in the subjects with a history of ankle injury. This particular finding demonstrates the disadvantage of CAI in predisposing people to further injury – they appear to be less resistant to the negative effects of fatigue than individuals with healthy, stable ankles. They went on to say that CAI subjects appeared to rely more heavily on proximal joints for postural control since the ankle has been compromised to some degree. This may allow them to function at a high level prior to the onset of fatigue, but results in a greater decline in postural control once fatigue sets in [91].

Gribble et al. continued to investigate the effects of fatigue on SEBT performance in a 2007 paper involving similar subject populations and fatigue protocols to their 2004 study [90]. The primary goal of this study was to establish the predictive values of CAI and the various fatigue protocols related to SEBT performance. The primary finding was that for the lunge fatigue group the presence of CAI predicted 18% of the variance in maximum reach distance in the anterior direction and 20% in the medial direction. For the posterior direction, CAI was not predictive (1%) of the variance in maximum reach distance. The results demonstrate the effect of a fatigue-inducing lunge task on dynamic postural control. This evidence should prompt clinicians to not only target dynamic balance recovery, but also to train patients with the goal of building endurance in the lower extremity to delay the decline in postural control accompanied with the onset of fatigue [90].

Hosseinimehr et al. compared the effect of fatigue on postural stability in a group of healthy physical education students to those with CAI [114]. Each group had 15 subjects and both genders were equally represented (14 males, 16 females). Subjects underwent postural
control assessment utilizing the SEBT before and after completion of a 15-minute fatigue protocol. Both groups demonstrated significantly (p < 0.001) lower reach scores in all eight directions measured after completion of the fatigue protocol. Also, the CAI group was significantly lower (P = 0.01) than the controls for the lateral reach and higher (p = 0.001) for the anterolateral direction. These results indicate that fatigue does have a negative effect on postural control and that it may be exacerbated in certain individuals with CAI. The specific finding of greater anterolateral reach distance in the CAI group after completion of the fatigue protocol does not logically fit with the other reported findings of this study, but the authors do not provide any insight in their discussion of the study [114].

A final study identified examining the effects of fatigue on SEBT performance involved 40 untrained healthy subjects [100]. Subjects performed the SEBT prior to completion of a seven-station fatiguing protocol and then repeated the SEBT. The authors reported that their fatiguing protocol resulted in a decline of dynamic postural control as assessed by the SEBT and was also closely related to the rate of perceived exertion reported by the subjects [100]. Specifics of the results were not identified in the summary of this unpublished poster presentation.

The SEBT is an established, valid, reliable field test for the assessment of postural control. The overall body of research suggests that it is sensitive to changes induced by postural training protocols with adequate specificity, musculoskeletal pathologies such as ACL tear and CAI, and fatigue. Additionally, it has been suggested to have predictive capabilities related to lower extremity injuries such as lateral ankle sprain and ACL tear. This evidence supports the use of the SEBT as a diagnostic as well as a preventative screening tool in a variety of populations, but especially in young, healthy, active individuals.

**Conclusion**

Postural control is an important neuromuscular function which is the foundation for not only the completion of activities of daily living, but also more complex movements such as involvement in sport. The use of evidence-based medicine to better understand proposed evaluation tools and their ability to assist with the prevention, diagnosis, and treatment of various injuries and conditions is paramount to the improvement of patient care. The goal of this review was to summarize the current evidence available in the scholarly literature related to the TTB, WBLT, and SEBT and provide a current assessment of their utility and efficacy.
The WBLT and SEBT are straightforward assessment tools that require minimal time and expense and may be conducted in the field or laboratory setting. Despite requiring a higher level of technology and equipment, the TTB may also be administered in the field and does not require a great deal of time to complete. Together, these tests provide a thorough assessment of postural control including factors such as static and dynamic balance, proprioceptive ability under various conditions, functional strength and range of motion, and knowledge of previous injury history. Current evidence has established that these are reliable and valid tests, but further research will continue to provide understanding of their additional potential, as well as any unidentified limitations.

Section Three: Lateral Flexion Test and the Functional Movement Screen

Introduction

The following review of literature is an attempt at summarizing the current literature related to the Functional Movement Screen (FMS) in an attempt to summarize current thinking and identify areas requiring further research. The FMS is a relatively new movement assessment screening tool that has become widely used for the identification of movement asymmetries and deficiencies, potential for increased injury risk, and prediction of athletic performance. However, questions remain as to what the full capability and best applications are for the FMS.

The Lateral Flexion Test (LFT) is briefly addressed at the start of this review. This was utilized as a performance variable to assess lateral core muscle capability in our most recent study. Performance on this test was recorded in an effort to determine whether or not a relationship existed between the FMS Deep Squat and core muscle capability, along with measures of postural control and ankle range of motion (ROM) discussed in previous sections of this project.

Lateral Flexion Test Methodology

The Lateral Flexion Test (LFT) is commonly used to assess the functional capacity of the lateral core musculature, primarily the quadratus lumborum [115-119]. Also known as the side bridge test, it was originally described by McGill et al [118]. To complete the test, a subject begins by lying on their side (usually assessed bilaterally) with the bottom foot placed behind the top foot and hips and knees in zero degrees of flexion. Next, they are asked to lift their hips
off of the floor until they are in line with the shoulders and feet, using only their feet and elbow on the side they are lying on. The top arm is held across the chest, resting on the opposite shoulder. The test is timed and terminated when the subject is unable to maintain proper form. McGill reported no significant difference between the left and right sides and recommended using the right side only for ease of data collection [118]. However, it is still routinely assessed bilaterally for research purposes [119-121] and utilized bilaterally as a rehabilitation exercise [122].

**Lateral Flexion Test Reliability**

Evans et al. reported intra-rater reliability (ICC) coefficients ranging from 0.81 to 0.85 [116]. Inter-rater reliability was reported to range from 0.82 to 0.91 (ICC) [116]. Subjects completed the side bridge test on two different occasions and were assessed by two different raters at both sessions. Testing sessions were separated by two weeks and the raters included one inexperienced (graduate student) and one experienced observer (experienced manipulative therapist). The subject pool for the reliability study included 24 healthy adults (16 male, 8 female).

**Lateral Flexion Test Normative Data**

As a part of the same study, Evans et al. measured performance of the side bridge test in a larger group of 79 young (21.2 ± 2.3 yr), healthy elite athletes (32 male, 47 female) from six different sports [116]. Mean hold times were 104.8 ± 44.1s for the right side and 103.0 ± 41.3s for the left. The right and left side bridge tests were highly correlated ($r = 0.86$, $p = 0.01$). Additionally, male athletes exhibited significantly longer hold times for the right ($p = 0.001$) and left ($p = 0.002$) side bridge test than their female counterparts. The authors recommend use of the LFT in assessing lateral trunk muscle endurance, but warn that relatively large changes must occur in order for true change to be identified due to large variances in hold times [116].

Leetun et al. published data in agreement with Evans et al. regarding the significantly greater hold times with the LFT in males (84.3 ± 32.5 s) than females (58.9 ± 26.0 s) in a group of 80 female and 60 male intercollegiate basketball and track athletes prior to the beginning of their season [117]. Lateral Flexion Test hold times were not significantly different between athletes suffering injuries during the season (64.7 ± 28.8 s) versus those that were not injured (72.0 ± 32.4 s) [117]. For the purposes of this study, all back and lower extremity injuries were recorded by the athletic training staff. Injury was defined as any event resulting in at least one
missed day of athletic participation and an event that required medical attention from the athletic trainer [117].

**Lateral Flexion Test and Core Muscle Capability**

Nesser et al. examined the relationship between core stability and athletic performance in 29 male strength and power athletes from a NCAA Division I institution [119]. They utilized the LFT to assess lateral core musculature capacity and reported significant correlations between it and the following performance variables: 20m sprint (right = -0.410, left = -0.376), 40m-sprint (right = -0.435, left = -0.397), pro-agility (left = -0.374), vertical jump (right = 0.403), power clean of body weight (right = 0.519, left = 0.460), and bench press of body weight (right = 0.372) [119]. All tests were completed prior to the beginning of off-season training. These results indicate that the LFT is weakly to moderately correlated, either positively or negatively, to a number of athletic performance variables. The authors suggest that these relationships are not stronger due to a lack of specificity in the LFT for strength and power athletes. Some of the negative correlations may be explained by the endurance nature of the lateral flexion test and anaerobic/power demands of the performance measures utilized. Use of the LFT may need to be limited to endurance athletes if it is to be used with the goal of predicting athletic performance.

Keogh utilized the LFT as part of a larger core stability test battery to determine whether they could predict shoulder press performance on a stable and unstable surface [120]. A comparison was made between three groups with varying instability strength levels (ISL), which represented a ratio between shoulder press performance on a firm surface and performance of the same task on an unstable surface. A ratio closer to one represents greater similarity in the performance of the two tasks. There were no significant (p < 0.001) relationships identified between LFT performance and any of the three ISL groups (ISL > 0.90, 0.85 ≤ ISL ≤ 0.90, ISL ≤ 0.85) [120]. These results are in agreement with the Nesser et al. [119] study suggesting that the LFT is not specific enough to evaluate performance in a strength-based task.

Schilling et al. included the LFT in a battery of tests used to assess the effectiveness of two strengthening protocols (core isotonic strength (n = 5) and core isometric strength (n = 5)) completed two times per week for six weeks [123]. Training programs consisted of three core stability exercises each with a progressive increase in repetitions per set over the course of the
six-week period. The results demonstrated a significant ($p < 0.05$) increase in right LFT hold time from baseline ($65.40 \pm 12.27$s) to post-test ($104.60 \pm 15.42$s) in the isometric training group [123]. The left LFT demonstrated a similar gain from baseline to post-test, but had larger variance which may explain the lack of a significant finding. This study utilized a very small sample size per group ($n = 5$) and exposed them to limited training volume, intensity, and duration. Additionally, the training protocol was not specific to a number of the performance variables tested. The practical importance of a significant finding for the increase in right LFT hold time must be questioned as a result of these limitations.

Barati et al. reported much lower hold times ($30.60 \pm 10.38$ s) utilizing the LFT than what has been reported in previous studies [115]. Despite the lower level of performance, the authors reported that LFT performance predicted 38% of the variability of the static balance test (measured by single-leg stance test hold time) in 50 healthy male university students. These results demonstrate that lateral core muscle capacity plays a key role in determining single-limb stance capability, but similar results have not been reported by separate authors.

**Conclusion**

The LFT is a commonly used assessment for the evaluation of lateral core muscle capacity. However, its application should be limited to questions regarding muscle endurance, as evidence in the literature demonstrates only minimal relationship between this measure and strength and power assessments. The static nature of the test and endurance-minded outcome are not specific to powerful performance measures, but are appropriate for use in assessment of static balance or other endurance-oriented assessments. This is a simple, inexpensive field test that can be completed in a short amount of time with minimal equipment, but demonstrates high variance which means a relatively large change must occur in order for true clinical change to be identified.

**The Functional Movement Screen**

**Background**

Rehabilitation professionals are increasingly using a kinetic chain model of the body as a way to diagnose orthopedic dysfunction. This has led to the need for, and subsequent development of, a clinical diagnostic tool with the purpose of assessing overall movement quality. According to Gray Cook, the screening and proactive searching for impairment or dysfunction are logical approaches to assessment currently used by specialists in other allied
health fields [124]. However, it has only recently been applied to musculoskeletal evaluation. Cook goes on to encourage an approach that allows symptom resolution and restoration of functional movement to complement, instead of replace, each other as treatment strategies [124].

Assessment of movement quality may lead to recognition of dysfunctional or asymmetrical movement which provides clinicians with a starting point in the effort to restore or improve an individual’s movement patterns. These tools may serve a preventive or rehabilitative purpose as well. When used as a pre-participation screening tool, the FMS may provide information regarding an individual’s predisposition to injury that could be useful in developing a corrective strategy aimed at reducing risk of future injury [13]. Functional movement assessment and associated interventions are growing areas within the research literature and a great deal of the current evidence has focused on the Functional Movement Screen (FMS) developed by Cook et al. [13, 14].

The FMS is an evaluation tool commonly utilized by coaches, clinicians, and strength and conditioning professionals to assess the ability of an individual to perform functional movement tasks and possibly predict injury occurrence [13, 125]. It was designed to serve as a bridge between pre-participation exams and performance tests by evaluating individuals in a dynamic and functional capacity [13]. The FMS was intended to be employed as part of a battery of tests which share the goal of achieving a complete evaluation of an individual’s physical health and ability, including prediction of injury likelihood and athletic ability [13].

The FMS involves seven basic movement patterns and three additional clearing exams and is intended to assess an individual’s mobility and stability and allow for observation of the quality of movement produced [13, 126]. Ultimately, the goal is to identify healthy individuals currently functioning at a less than optimal level due to movement restrictions or asymmetries. Once identified, the creators of the FMS believe that corrective exercises may be prescribed in order to make corrections resulting in restoration of full function, allowing for movement without restriction, and correct any imbalances that may predispose an individual to injury [124, 126].

Scoring is done using a 0-3 scale [126]. Pain has the potential to alter movement patterns, and as a result a score of zero is given if pain is experienced during any portion of the screen [124]. A report of pain should result in cessation of the screening and referral to a clinician with the capabilities of assessing and correcting the underlying issue [13]. Scores of 1-3
are given based on the quality of movement and scoring is conducted via specific criteria for each movement and up to three repetitions of each component may be completed. Components of the FMS include the deep squat (DS), hurdle step (HS), in-line lunge (ILL), shoulder mobility test (SMT), active straight-leg raise (ASLR), trunk stability push-up (PU), and rotary stability test (RST). Clearing tests include the shoulder clearing test (SCT), spinal extension clearing test (SECT), and spinal flexion clearing test (SFCT) and represent additional tasks assigned to identify painful movements [13, 14]. The FMS creators intended for each movement to be scored and reviewed independently, thus maximizing the specificity of the assessment and allowing for implementation of the most appropriate intervention [127]. Since the various components of the FMS are not directly related, the sum score may weaken the ability of the FMS to identify impaired movement patterns or specific asymmetries [127].

The original design of this study included the three lower extremity components of the FMS: DS, HS, ILL. However, the final study centered on the DS for reasons addressed in the manuscript to follow. The DS begins with a subject with feet approximately shoulder width apart and facing straight ahead. The subject then positions their hands on a dowel with a wide grip, holding it above their head with palms facing forward. The arms are then fully extended in an effort to raise the dowel as high overhead as possible. Then, while holding the dowel in position, the subject is instructed to descend into a squat position. Correct squat position includes the heels remaining on the floor, head and chest facing forward, and the dowel remaining fully pressed overhead. If the subject cannot perform the squat properly, a 2” in height block is placed under their heels and the movement is repeated. This serves as a compensatory tool and if the subject is subsequently able to perform the movement correctly with the compensation, a score of two is given. If they remain pain free, but unable to complete the squat with the compensation, a score of one is given [13].

The HS begins with the subject standing facing the FMS hurdle with their feet together and toes touching the base of the hurdle. The hurdle height is set at the level of the tibial tuberosity. The dowel is rested on the shoulder below the neck and held in place by the subject and they are instructed to hold it as level as possible during execution of the movement. Next, the subject is directed to step over the hurdle and touch their heel to the ground while keeping the stance leg in an extended position. The moving limb is then returned to the starting position. This movement should be completed slowly and may be done up to three times bilaterally. A score of two is awarded if they are able to complete the movement, but do so with
a loss of alignment between the hips, knees, and ankles; if the dowel does not remain parallel to the hurdle; or movement is noted in the lumbar spine. A score of one is given if they are unable to complete the movement by exhibiting a loss of balance or there is contact between the moving foot and hurdle, but have no pain [13].

The ILL begins with the subject standing on the FMS board in a split stance position with the great toe of one foot at the “zero” marking on the board and the heel of the other foot placed out in front at a distance equal to the height of their tibial tuberosity. The dowel is held behind the back in a vertical position in such a way that it touches the back of the head, thoracic spine, and sacrum simultaneously. The top hand on the dowel should be the hand opposite the front foot. Next, the subject lowers the back knee into a lunge position far enough to allow the knee to touch the board behind the heel of the front foot. A score of two is awarded if the dowel does not remain in contact with the three points described, anterior or lateral movement is noted in the torso, the dowel and feet do not remain in the sagittal plane, or the knee does not touch the board behind the heel of the front foot. A score of one is given is a loss of balance is noted [13].

Scoring System

The FMS scoring system is intentionally basic since the purpose is simply to identify people with general movement abnormalities. However, this simplicity is also a limiting factor. A score of three or one provides a good deal of information regarding an individual’s movement capabilities; their functional movements are either close to perfect or grossly dysfunctional. A score of two provides less useful information as it simply implies that a given movement may be completed, but not without the presence of one or more abnormalities or asymmetries, or use of a compensatory strategy. A score of a two on any individual component of the FMS should result in clearance to participate and an effort to improve the quality of movement with an intervention including technique instruction, corrective exercise, and/or tissue mobilization. Additional research is necessary to provide further insight into the causes of dysfunctional movement on components of the FMS.

Noda and Verscheure utilized a modified scoring system that broke the DS movement down into a mechanical checklist (Figure 1-1.) [12]. Analysis involved reviewing video of completed DS trials in order to more thoroughly grade the movement. Video was taken from a front, side, and rear view and certain aspects of the DS form were assessed from each angle.
Instead of grading using a one, two, or three; assessment was based on joint and limb position and each trait was marked as either “yes” or “no” [12]. The results of this study are discussed in another section of this review. The scoring scale used by the authors in this study appears to provide additional information regarding the cause of movement dysfunction within the DS. If developed and implemented, similar dysfunction checklists may prove to be useful in the assessment of other components of the FMS.

**Figure 2.1** Checklist of items observed during execution of the deep overhead squat [12].

Recently, the emphasis in scoring of the FMS has shifted in the literature from that of individual components to the use of a composite score. This was not the original intent of the FMS creators, but it has become a part of its interpretation and is often used as a predictive tool for future injury potential [127-129]. Kazman et al. published a study examining the efficacy of the cumulative FMS score and reported that a disproportionately number of subjects scored a two on a number of the components and that evidence was lacking to support the validity of the cumulative score [127]. A population of 934 marine officer candidates was assessed using the FMS. The RST (87%, 0.4%), HS (84%, 1%), and DS (63%, 2%) had a disproportionately high number of subjects scoring a two and subsequently a very low number scoring ones or threes. This trend held true for the remaining variables, but to a lesser degree. This evidence, coupled with the finding that the FMS components are not similar enough to be grouped together and assigned a single score led the authors to raise questions regarding the efficacy of the cumulative FMS score. They caution practitioners regarding the use of it and recommend assessing, scoring, and correcting each component on an individual basis [127].

Another question that remains related to the scoring of the FMS involves the possible learning effect that may occur between testing sessions or the influence knowledge of the testing criteria may have on an individual’s performance. The first question will be discussed further in a later section regarding the reliability of the FMS. Regarding advanced knowledge of the scoring criteria, Frost et al. conducted a study involving 21 firefighters in an attempt to
answer this question [130]. Each subject completed the FMS twice, once prior to receiving instruction regarding the scoring criteria and once immediately after. A standardized script was used for both assessments and no coaching or feedback was provided. The subjects demonstrated a significant (p < 0.001) improvement in FMS composite score (14.1 ± 1.8 to 16.7 ± 1.9) after receiving instruction [130]. Additionally, there were significant (p < 0.05) improvements in the deep squat (1.4 ± 0.7 to 2.0 ± 0.6), hurdle step (2.1 ± 0.4 to 2.4 ± 0.5), in-line lunge (2.1 ± 0.4 to 2.7 ± 0.5), and shoulder mobility (1.8 ± 0.8 to 2.4 ± 0.7) movements individually [130]. The authors express concern regarding the apparent effect knowledge of the scoring criteria has on the reproducibility of the FMS and its individual components. Furthermore, they question whether or not the FMS is fully capable of identifying dysfunction since scores were significantly affected by other factors in this study [130].

Hickey et al. developed a 100-point modified FMS scoring system aimed at providing practitioners more information and possibly improving the screen’s predictive value [131]. In this model, each component of the FMS is subdivided into specific movement characteristics and each one is assigned a score. For example, instead of the deep squat being scored on the 0-3 scale, it is broken down into a possible 18 points: six points for upper torso position, eight points for knee alignment, and four points for dowel position [131]. If a subject is unable to complete all test criteria, the two inch board is placed under the heels and they are scored using the following criteria: two points for femur below horizontal, two points for upper torso position, two points for knee alignment, and two points for dowel aligned over feet. If pain is reported at any time throughout the movement, a score of zero is given and the painful movement task is discontinued. The clearing tests are still scored (+) or (-) based on the presence of pain with the movement. The authors’ intent is for this system to be used in the rehabilitation and research settings to more specifically identify limiting factors, which would in turn allow for more targeted interventions to be developed [132]. The authors do not claim to have developed this in an effort to replace the current FMS scoring system. The original system is simple and fast and allows practitioners in the field to quickly assess an individual’s movement quality. The newly developed modified scoring systems appear to be best implemented by trained professionals within movement assessment-related fields, and not sport coaches or similar lay people, due to the increased need for background in movement analysis in order to correctly complete the assessment. Reliability and normative data will be reported in later sections of this paper.
An et al. reported the use of a different modification to the traditional FMS scoring system (Figure 1-2.) [133]. In a study involving only assessment of the DS, ILL, and HS they broke each component down into 5 sub-components worth 0.2 points each. Using the traditional 0-3 scoring system, they used the modification to more precisely award points based on ability to complete each sub-component. For example, instead of simply awarding a score of two to an individual who was able to complete the DS with the aid of the two-inch lift, they may have awarded additional points in 0.2 increments based on specific movement criteria [133].

<table>
<thead>
<tr>
<th>Test</th>
<th>Criteria</th>
<th>Left</th>
<th>Right</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep Squat</td>
<td>Heels stay down</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feet do not slide or rotate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips are below knees</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knees are aligned over feet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Upper extremities stay straight</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-line Lunge</td>
<td>Minimal to no upper body movement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feet remain on the tape</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Back knee touches tape</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dowel touches head, thoracic spine, sacrum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Balance is maintained</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hurdle Step</td>
<td>Dowel does not dip right or left</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hips do not dip right or left</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knees stay aligned over feet</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Ankles stay under knees</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Balance is maintained</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2.2** Functional Movement Screen Test Description [133].

**Normative Data**

As with any new screening or diagnostic tool, the establishment of normative data provides a benchmark for comparison of new subjects to a larger population of their peers. The current literature provides FMS norms for various age groups and activity levels, but there is room for further study in this area. Perry and Koehle published normative FMS values for middle-aged adults (N = 622) with various backgrounds in athletic activity [134]. Age range of
the subjects was 21-82 with a mean of 50.91 years and a standard deviation of 10.80. Once individuals completed the FMS, their cumulative score was calculated and used for the purposes of this study.

For all subjects combined, the mean FMS score was 14.15 ± 2.85. The results were further broken down by gender and age demonstrating that the younger (20-39 yr) averaged the highest FMS score (15.08) and the subjects 65 and older had the lowest (12.68). Further analysis revealed that women between 20-39 years of age had the highest mean score (15.43). Relationships were also reported between body mass index (BMI) and FMS score, showing subjects with a BMI > 30 had significantly lower FMS scores than those identified as having a lower BMI. Finally, physical activity was found to be related to FMS performance. Subjects with higher physical activity scores as measured by the Health Physical Activity Participation Questionnaire (HPAP) also had higher mean FMS scores. The authors concluded that age, BMI, and physical activity all had an effect on FMS performance. However, these three variables only accounted for 24% of the total variance [127]. This indicates that there are potentially many other factors affecting the FMS score of a given individual.

A 2011 study published by Schneiders et al. provided normative FMS data for a tighter age distribution of active adults [135]. Two hundred and nine subjects (101 males, 108 females) volunteered and their FMS performance was assessed. The mean FMS composite score was 15.7 with a 95% confidence interval (CI) between 15.4 and 15.9. No significant differences were found between males and females or those that reported previous musculoskeletal injury and those that did not [135].

A third set of normative data was provided by Fox et al. in 2013 [136]. This particular study involved a unique population, but may have broader implications to the general population. Sixty-two elite and sub-elite Gaelic football and hurling players were assessed using the FMS. The FMS scores of the elite (n = 30) and sub-elite (n = 32) were compared and no significant differences were identified [136]. These results are in agreement with those published previously by Schneiders et al. [135] and Perry and Koehle [134], providing additional evidence to demonstrate that FMS performance appears to decrease with age. However, Fox et al. did present evidence contradictory to the results published by Perry and Koehle regarding the relationship between BMI and FMS performance, reporting no significant relationship between the two [136]. Despite a higher level of athletic training and competition than active adults, the Gaelic athletes included in this study did not perform significantly higher on the FMS.
The authors suggest that the movements included in the FMS may not be representative of those necessary for the success of a Gaelic player. Therefore, the athletes in this study did not appear to have superior movement capabilities compared to the average, active young adult. This may have implications regarding the use of the FMS in that these results suggest that this screening tool may not be appropriate for individuals participating in highly specialized activities.

Webster et al. reported a significant main effect for gender (male: $14.5 \pm 2.34$, female: $15.5 \pm 2.23$, $p = 0.039$), but no significant effect for sport-level ($p = 0.28$) and no significant interaction between gender and sport-level ($p = 0.14$) [137]. Eighty-eight high school and college-level basketball players volunteered for this study and were evaluated using the FMS as part of their pre-season physicals. The authors’ state that even in the presence of a statistically significant difference, there may not be a clinically significant difference between genders in the population tested as a result of a small effect size ($d=0.43$). They concluded that the FMS does not appear to be biased regarding gender or competition level and may subsequently be used to evaluate functional movement capability in both genders at varying levels of sport participation [137].

The potential of the FMS to predict injury and possibly provide valuable information for creation of more effective corrective exercise protocols, has led to its application to an ever-expanding population of athletes, including participants in youth sports. Butler et al. reported a composite score of $57.2 \pm 1.9$ using their newly-developed 100-point modified FMS scoring system in a group of 30 healthy middle school students [132]. Each student completed the FMS one time and their performance was recorded on video. This is the only study that has been identified reporting reliability for this new scoring system.

Finally, a pediatric population was assessed by Duncan and Stanley and they reported mean FMS scores of $13.5 \pm 3.4$ in boys ($n = 29$) and $14.5 \pm 2.8$ in girls ($n = 29$) ten to eleven years old [138]. Results for 39 normal weight ($15.5 \pm 2.2$) and 19 overweight/obese ($10.6 \pm 2.1$) children were also included. These results draw an interesting parallel between the linemen ($11.8 \pm 1.8$) and non-linemen ($13.3 \pm 2.4$) assessed in the study by Kiesel et al. [139] suggesting that regardless of population, excess body weight may have a negative impact on FMS performance.
Longitudinal Change

Functional movement deficiencies have been associated with an increased likelihood of injury. Chapman et al. published results indicating that FMS performance is also related to an individual's ability to improve what they refer to as longitudinal competitive outcomes [140]. One hundred and twenty one elite track and field athletes completed the FMS prior to the start of their competitive season. In addition to the FMS data, the authors also gathered data regarding each subject’s top performance during the previous and current competitive seasons. Subjects were compared in the following ways: <14 and >14 FMS scores, presence of FMS asymmetry vs. no asymmetry, and a score of one on the DS vs. a score of either two or three. The >14 FMS group had a significant increase in performance from the previous year to the current year (0.41% ± 2.5%) compared to the <14 FMS group (-0.51% ± 2.30%) (p = 0.03). A significant change was also present between the asymmetry (-0.26% ± 2.10%) group and the group without any asymmetries (0.60% ± 2.86%) (p = 0.03), and for subjects who scored a two (0.13% ± 2.28%, p = 0.03) or three (1.98% ± 3.31%, p = 0.001), compared to those scoring a one (-1.07% ± 2.08%) [140]. These results indicate that longitudinal performance is related to functional movement capability.

Kinematics

Imbalance in the kinetic chain can lead to movement pattern irregularities and possibly increase the likelihood of injury. A change in mobility at one joint will likely result in altered joint function in neighboring links, in order to preserve overall normal function. Long-term, these kinematic changes may lead to the alteration of tissue flexibility as well as neuromuscular changes [141]. Functional movements are the result of multiple local movements occurring in an organized manner throughout the body. Injury evaluation should include an assessment of the entire kinetic chain in order to properly assess whether or not any abnormal movement strategies exist. Pathologic movement at one joint may result in injury at another joint within the kinetic chain. Sexton and Chambers are in full agreement with the creators of the FMS when they recommend use of the FMS as one tool in a clinician’s tool box. The screen will provide useful qualitative information regarding movement patterns that should be paired with quantitative assessments in order to fully identify the cause of symptoms [141].

The DS has been the subject of multiple studies regarding different kinematic aspects of the movement [10-12]. Noda and Verscheure collected goniometric ROM data related to the DS.
in a group of collegiate athletes (N = 71) [12]. One primary investigator assessed DS performance of each subject with a modified scoring system and the second primary investigator collected goniometric measurements that included ankle dorsiflexion. All data were collected as part of the pre-participation physicals for the athletes, but the DS and goniometric assessments were not collected simultaneously. Dorsiflexion was measured passively in a non-weight-bearing position. The authors reported that dorsiflexion was significantly correlated to the occurrence of a heel lift during performance of the DS (p = 0.04) [12]. These results indicate a close relationship between the occurrence of a heel lift during performance of the DS and limited passive dorsiflexion. The authors conclude a movement restriction such as limited dorsiflexion will require a compensatory strategy to allow for completion of a task. In this case, the heel lift is the resulting compensation [12]. Ultimately, this study indicates that an observed heel lift during DS performance indicates limited passive dorsiflexion. Future research is needed to examine the relationship between weight-bearing measures of dorsiflexion and the occurrence of a heel lift during the DS.

In an effort to better understand the relationship between dorsiflexion and the different scoring clarifications of the DS, Butler et al. published a 2010 paper involving 28 subjects recruited based on their DS performance [10]. Potential subjects were pre-screened and assigned to one of three scoring groups based on their performance. Once the groups were set, subjects performed the DS again, but this time they were marked for three-dimensional motion analysis of the lower extremity. The results demonstrated that peak dorsiflexion excursion was significantly greater (p < 0.03) in subjects that scored a three compared to those that scored a one [10]. Additionally, significant kinematic differences were present at the hip and knee between the three groups. These results indicate that there are specific differences in joint kinematics between the three scoring groups as applied to the DS. This study provided some of the first data quantifying these differences and further research is necessary to strengthen this area of FMS research.

The effect of limited ankle dorsiflexion on DS performance was also examined by Marcum et al. in a 2012 publication [11]. The authors assessed DS performance in 30 healthy, recreationally active adults under two conditions: 1) no wedge, foot flat on the floor (NW) and 2) 12-degree wedge under the forefoot (W). Subjects completed seven repetitions under each condition while instrumented for three-dimensional motion analysis. The W group demonstrated significantly (p < 0.05) altered joint kinematics at the knee and ankle, but not the
These changes included: decreased knee flexion, increased knee valgus, increased medial knee displacement, and reduced ankle dorsiflexion [11]. These findings support the results published by Noda and Verscheure [12] suggesting poor DS performance was related to limited dorsiflexion. The W group, in a forefoot-elevated position demonstrated less dorsiflexion excursion compared to the NW group, indicating that heel lift is likely to occur during DS if dorsiflexion is impaired.

The use of a wedge to simulate limited ROM may not accurately reflect kinematic alterations that would occur in an individual with a real ROM limitation. However, this study provides additional insight into the relationship between altered motion at one joint and the subsequent adjustments made at neighboring joints. The authors did not include scoring of the DS utilizing the FMS scoring criteria. Therefore, the effect of limited dorsiflexion on the FMS DS score was not reported. This would have been a useful piece of information to report in an attempt to add to the understanding and body of knowledge related to joint kinematics and their effect on various components of the FMS.

Reliability

A number of studies have been published over the past few years regarding various aspects of reliability related to the FMS. This tool is becoming widely used, but since it is relatively new it is important for investigators to publish findings related to the reproducibility of the FMS in order to confirm its use as an effective tool for functional movement analysis. Interrater (two testers, same measure), intra-rater (one tester, two measures), and intra-subject (same subject, two measures) will be discussed in the following section. Intra-class correlation coefficients (ICC) are used to describe reliability related to the FMS composite score since it is an interval value and Kappa scores are used to describe reliability related to the individual components since they are categorical values. One study discussed here utilized Krippendorff’s Alpha, a statistical measure of agreement in situations involving more than two raters and a combination of interval and ordinal data [142].

Gribble et al. reported intra-rater reliability for the FMS utilizing raters of three different experience levels: 16 athletic training students (ATS), 15 certified athletic trainers (AT), and 7 athletic trainers with at least six months experience using the FMS (ATExp) [143]. When all raters were grouped together, moderate reliability (ICC: 0.754) was reported. Experience
appeared to be strongly related to the intra-rater reliability scores as the ATExp group (0.946) demonstrated the highest ICC, followed by the AT (ICC: 0.758) and ATS (0.372) groups [143].

In a similar study, Smith et al. utilized one rater from each of the following groups: physical therapy students with FMS experience, but not FMS certified (PTFMS); certified FMS raters (FMS); athletic training faculty members with no FMS certification or previous experience (AT); and physical therapy students with no FMS certification or previous experience (PT) [144]. Intra-rater reliability ranged from 0.91 to 0.81 as measured by the ICC. Interestingly, the AT rater had the highest reliability score and the FMS rater had the lowest. This was partially attributed to the AT raters extensive experience in movement analysis despite no specific experience with the FMS [144].

Parenteau-G et al. utilized three Master’s level physiotherapy students and one physiotherapist, all with their FMS certification, as raters to assess inter- and intra-rater reliability of the FMS [145]. Thirty male hockey players volunteered to serve as subjects for FMS evaluation. The first test session paired two raters to each subject and they scored their FMS assessment, blinded to the other rater’s score. Inter-rater reliability for the composite FMS score was 0.96 (ICC). Video was recorded during the second test session and was utilized six weeks later for the follow-up intra-rater assessment. Intra-rater reliability was reported to be high (ICC = 0.96). The authors also reported strong agreement between all four examiners for the clearing tests (96.4 – 100%) and for five of the seven FMS components. The hurdle step (67.9%) and in-line lunge (67.9%) had the lowest agreement scores. The authors also reported kappa values for each FMS component and they ranged from 0.65 to 1.00 for intra-rater session one and 0.76 to 1.00 for session two [145].

Eight novice physical therapy students underwent 20 hours of FMS training led by four physical therapists and one research assistant in preparation for an investigation into inter- and intra-rater reliability published by Teyhen et al [146]. For intra-rater reliability, each of the 64 active-duty military members tested completed two FMS assessments 48-72 hours apart. For the composite score, intra-rater reliability was reported to be 0.76 (ICC). A pair of examiners watched subjects simultaneously as they completed a second FMS for the inter-rater reliability assessment. The ICC for the composite score was 0.74. For all seven individual components of the FMS the inter-rater percent agreement ranged from good to excellent (68-92%). Intra-rater agreement scores were lower, ranging from 68-88%. Kappa values ranged from 0.45-0.82 for inter-rater and 0.29-0.76 for intra-rater reliability [146].
Smith et al. also reported inter-rater reliability and found it to be good for both session one (ICC = 0.89) and session two (ICC = 0.87) [144]. The authors reported 100% agreement between the raters for the three clearing exams. The least reliable FMS component was the hurdle step (ICC: 0.30 – 0.35) and highest for the shoulder mobility test (ICC: 0.96 – 0.98). In contrast, Chorba et al. published inter-rater reliability scores for the composite FMS of 0.976 (ICC) and component scores ranging from 0.774 to 1.0 with the HS and ILL scoring the lowest and SMT and ASLR scoring the highest. These results represent the scores of eight subjects and both raters were physical therapists with only minimal formal experience with the FMS.

Dewey et al. used two assessors, both graduate students and Certified Strength and Conditioning Specialists (CSCS) and one held additional certifications as an athletic trainer and FMS Certified Specialist, to determine both the inter-session and inter-rater reliability of the FMS [147]. Inter-session reliability was reported to be high (ICC = .92) for the FMS composite score and ranged widely from .17 to .89 for the individual components with the HS being scored the lowest and shoulder mobility test scoring the highest. Intra-session reliability for the composite score was .98 and the ICC values for the individual components ranged from .38 to 1.0 with the HS again scoring the lowest [147].

The inter-rater and subject reliability of the FMS was examined by Shultz et al [148]. They assessed 21 female collegiate athletes using the FMS and six raters whose experience with the FMS was not reported. The primary rater scored two FMS screens one week apart for each subject. The first session for each subject was also captured on video. The five additional raters scored the FMS video trials and their scores were compared to that given by the primary rater. Inter-rater (0.38), test-retest (0.61), and live vs. video (0.91) reliability were reported as Krippendorff’s Alpha values. Based on these results, the authors do not recommend comparison across multiple raters until adequate training has been completed so as to ensure stronger reliability than was reported here. The test-retest reliability scores were strong enough that the authors suggest any change in a subject’s FMS score should be credited to the subject and not error of the rater. Individual component inter-rater reliability scores ranged from 0.10 (ILL) to 0.95 (HS), as scored using Krippendorff’s alpha. These wide-ranging results support the author’s recommendation to avoid the use of multiple raters. Finally, video appears to be an appropriate method for multiple raters to assess an individual’s performance on the FMS [148]. The nature of video with options such as playback and varying speeds may allow for a more thorough and accurate scoring of the FMS across examiners.
Shultz et al. published further results regarding test-retest and inter-rater reliability related to the FMS and using Krippendorff’s alpha scores using methods similar to their previous reliability study [142]. Thirty-nine NCAA Division I athletes from multiple sports volunteered for the study. The authors reported an ICC of 0.92 for live vs. video. Inter-rater reliability was poor with a Krippendorff’s Alpha value of 0.38. These results are almost identical to their previous findings. The authors stated that it is unclear as to whether the poor inter-rater reliability is due to the ambiguity of the FMS testing criteria and scoring system or inexperience on the part of the raters [142].

Minick et al. examined and compared the reliability of two novice raters (completed an FMS training course) and two experienced raters (instructors of FMS certification courses) using video trials of the FMS [149]. Forty healthy college students were recruited for this study. The weighted kappa statistic was used to determine inter-rater reliability. For 14 of the 17 tests within the FMS, the novice raters demonstrated either excellent or substantial agreement. The expert raters had similar agreement for 13 of the 17 tests. The seven FMS components, including their right and left assessments as well as an overall score for each component involving individual assessments for right and left made up the 17 tests referenced here. The authors concluded that the FMS can be utilized effectively by trained individuals and is capable of assessing movement patterns in an effort to direct therapeutic interventions and performance enhancement [149].

Real-time inter-session and inter-rater reliability was assessed by Onate et al [150]. The primary rater was a Certified Athletic Trainer, CSCS, and an FMS Certified Specialist. The additional rater involved in the study was a CSCS, but had no prior FMS experience with the FMS outside reading the assessment manual. Nineteen physically active subjects were assessed twice, one week apart. The ICC for inter-session reliability was 0.92 for the composite score. Kappa values for the individual components ranged from 0.16 to 0.84. The intra-session inter-rater reliability was 0.98 and the kappa values ranged from 0.31 to 1.00 with the HS again receiving the lowest score [150].

Elias conducted a reliability study aimed at determining the inter-rater reliability between physiotherapists with no prior FMS experience [151]. Twenty physiotherapists were recruited to score video trials of five healthy elite athletes completing the FMS. The video allowed them to review each movement as many times as desired prior to assigning a score. Inter-rater reliability was high (ICC = 0.906) [151]. This may be an indicator that overall
experience and education in a field related to movement science may be more important in
determining an individual’s ability to implement the FMS than whether or not they hold an FMS
certification.

Another report regarding inter-rater reliability of the FMS between raters of differing
experience levels was published by Gulgin and Hoogenboom [152]. Twenty healthy college
students were recorded completing the FMS and four raters (three novice, one experienced)
scored the video trials. Inter-rater reliability was reported to be 0.882 (ICC) for the FMS
composite score. Inter-rater agreement as calculated by Fisher’s Exact was 100% for the right
HS, L in-line lunge, right SMT, right and left ASLR, and RST. The remaining components ranged
from 33-66% inter-rater agreement. The authors suggest that experienced raters may be more
critical in their assessment of individual FMS components, resulting in some level of
disagreement between novice and experienced raters. The composite score ICC was good, but
more information may be gained from the score of each individual component. Therefore, it is
important to have well-trained raters that demonstrate a high level of agreement.

Butler et al. reported inter-rater reliability between two experienced raters trained in
the traditional 21-point FMS scoring system and briefed on the methods of the new 100-point
system [132]. Video trials were collected of 30 healthy middle school students and scored.
Raters had the ability to watch each trial as many times as needed to ensure accurate and
complete scoring. The results demonstrated an ICC of 0.99 for the inter-rater composite score
reliability [132]. For individual components, the scores ranged from 0.91 – 1.00 with the left ILL
scoring the lowest [132]. The authors reported that use of the 100-point system improved
agreement between raters for the scoring of individual components, but did not include data
related to this claim. However, they provided rationale for the idea stating that the further
breakdown of each movement allowed for increased consistency of scoring [132]. The added
detail of the 100-point scoring system may allow practitioners to be more precise in scoring
since each movement component of a given FMS task is evaluated and scored individually.

Letafatkar et al. reported an excellent inter-rater reliability score of 0.92 (ICC) for the
FMS composite score [153]. Percent agreement was high across all components ranging from
88-100% and Kappa values ranged from 0.85-1.00. These scores are high, but the components
scoring the lowest were the HS (right = 88% agreement, 0.85 Kappa) and ILL (right = 90%
agreement, 0.86 Kappa) which are consistent with results discussed previously. This may
Data have been presented stating a case for high intra-rater and inter-rater reliability, along with strong subject intra-subject reliability. However, some data exists displaying a wide range of agreement scores within and between raters and within subjects. Experience with the FMS and in a movement science-related field may be at odds with each other in terms of allowing for scoring consistency. Practitioners with years of experience evaluating movement that are new to the FMS may be overly critical, resulting in a lower score, compared with inexperienced raters or those more experienced with rating the FMS. When using the FMS, it is important to consider the experience and potential biases of the rater(s) prior to beginning assessment.

Effect of Therapeutic Intervention on FMS Performance

A number of studies were identified in the literature relating to various interventions and their effect on FMS performance. Therapeutic exercise, taping techniques, and sport-specific and core training have all been utilized in an effort to improve an individual's FMS performance and subsequently their overall movement capability. Evidence demonstrating that the FMS is subject to the influence of various interventions will strengthen the case for its use as an evaluation tool to assess the efficacy of rehabilitation, off-season training, and sport/movement-specific protocols. Kiesel et al. suggested a score of 14 on the FMS as a cutoff point in an attempt to identify an increased likelihood of musculoskeletal injury in professional football players [129]. This cutoff score will be referenced throughout this section as an additional measure assessing the effectiveness of the interventions discussed.

Cowen published results related to the effect of a yoga-based worksite program on FMS performance in a group of 108 on-duty firefighters [154]. Baseline scores were established for the FMS prior to the beginning of the yoga initiative and measured again at the conclusion of the six-week program. Results demonstrated a significant (p < 0.001) improvement from pre-yoga (13.25 ± 2.255) to post-yoga (16.55 ± 2.131) in the composite FMS score. Individual component scores were not reported in this study. The mean FMS scores crossed the threshold suggested by Kiesel et al. and this may strengthen the case for the use of yoga as an injury prevention tool in this population. Further investigation into the effects of yoga on the
individual movement components is needed to determine the areas yoga is most likely to have a positive effect.

Interventions directed at improving or correcting specific movement restrictions or asymmetries may be developed after assessing an individual’s FMS performance. These may prove to be more effective than a general movement-based intervention, but require additional work by the practitioner as each individual will require their own intervention program. Kiesel et al. assessed FMS performance in 62 healthy professional football players and then prescribed a seven-week intervention designed specifically for each subject to address their specific movement deficiencies [139]. The programs included stretching, strengthening, and balance exercises along with self-massage and foam roller techniques aimed at improving tissue mobility and elasticity. After completion of the program, each subject completed a second FMS. At pre-test, 31 subjects recorded asymmetries somewhere in their FMS. Post-test revealed only 20 subjects with asymmetries indicating a significant (p = 0.01) decrease due to the intervention. Subjects were divided into linemen and non-linemen for the sake of data analysis. A significant (p < 0.01) main effect for time was identified. Linemen significantly improved their FMS composite score from pre-test (11.8 ± 1.8) to post-test (14.8 ± 2.4) and non-linemen improved from 13.3 ± 1.9 to 16.3 ± 2.4 [139]. Mean scores for all individual components improved after the intervention compared to pre-test, but not all of the changes were significant. Post-intervention 42 players scored > 14 compared to only seven at baseline. The authors also reported that a pre-test DS score of one made an individual five times more likely to fail (not achieve a score of > 14) at post-test. They suggest that this particular result indicates more intense or specific intervention may be required in order to achieve the desired improvement in these subjects [139]. Finally, these results indicate that an off-season program designed specifically to address an individual’s movement asymmetries or deficiencies may be effective in improving overall FMS performance.

Bodden et al. examined the effects of an exercise intervention on FMS performance in a group of mixed martial arts (MMA) athletes [155]. Twenty-five subjects volunteered and were randomly assigned to either an intervention or control group. Both groups continued their normal MMA training activities, but the intervention group also participated in a corrective exercise program four times per week for a total of eight weeks. Functional Movement Screens were completed by both groups at baseline, four weeks, and eight weeks. Results indicated a significant (p = 0.006) difference between the two groups post-intervention. Further analysis
revealed that the intervention group had improved significantly ($p < 0.01$) by week four and did not demonstrate further significant improvement between weeks four and eight ($p = 1.00$) compared to their baseline performance. The authors also reported that subjects in the intervention group were more likely to score > 14 on the FMS as compared to the control subjects ($p < 0.05$) and a greater number of intervention subjects were asymmetry-free at both four and eight weeks [155]. These results indicate that four weeks of participation in a corrective exercise program may be adequate time to result in correction of movement deficiencies and/or asymmetries in MMA athletes [155].

The effectiveness of two different strength training protocols at improving FMS scores in older (54.75 ± 8.84 years) adults was investigated by Pacheco et al [156]. One hundred and one subjects were assigned to either a conventional strength training group ($n = 50$) or a functional training group ($n = 51$). All subjects completed two sessions per week over 12 weeks. Prior to beginning the study, all subjects had two months of no formal exercises (minimal exercise participation) and one month of what the authors referred to as a “conventional general training protocol” in an attempt to establish a similar baseline fitness level among the subjects. Functional Movement Screen scores were collected at baseline and post-test. Both groups improved significantly ($p < 0.001$) after completion of their respective training protocols and there was no difference between the groups ($p = 0.234$). Further analysis revealed that men in the functional group demonstrated significantly ($p = 0.010$) greater improvement than their female counterparts. It was also reported that the women in the conventional group outperformed the women in the functional group ($p = 0.007$) [156]. Overall, these results indicate that for the population tested increased specificity of intervention does not lead to greater FMS performance [156]. Further research is needed to determine whether or not there is a relationship between age and the importance of training specificity. It may be that as people age and see a decline in movement capability that any exposure to regular, supervised physical activity may be enough to improve functional movement.

Peate et al. collected FMS composite score data in a population of 433 urban firefighters and evaluated the effect of a supervised intervention aimed at improving flexibility and core strength on FMS performance [157]. Once the FMS scores had been adjusted for age, results indicated those with prior history of injury scored 0.24 lower on the composite FMS compared to those with no injury history. However, this difference was not significant. Using the age-adjusted data, the authors set a cutoff at 16 for the FMS composite score and reported that
subjects with prior history of injury were 1.68 times more likely to fail (score < 16) the FMS. Also, it was noted that for every yearly increase in age a decrease of 0.1 was seen in composite FMS score [157]. A review of injuries occurring before and after the intervention revealed a reduction of lost time injuries by 62% and total injuries by 44%. Significant (p < 0.05) reductions in back and upper extremities injuries were noted, but this was not the case for lower extremity injuries. Ultimately, the authors concluded that a functional movement intervention may help reduce injury risk in this population.

Frost et al. [158] published the second paper identified during this review utilizing the 100-point FMS scoring system presented by Hickey et al [131] in 2010 and published by Butler et al in 2012 [132]. Sixty professional urban firefighters volunteered for this study and were assigned to one of three groups (control, movement-focused, or fitness focused) after completion of a baseline FMS preceded by no verbal feedback or instruction on how to complete the tasks outside of the standard guidelines provided by the assessor. Interventions lasted 12 weeks and the control group was asked to refrain from making any changes to their current physical activity regimen. Video was utilized to allow for repeat scoring of each subject’s baseline and post-test FMS. Each trial was scored three times using the following scoring matrices: standard FMS (STD), research standard 100-point FMS (RES), and a modified research standard (MOD). Ultimately, the results of this study indicated greater identification of change from baseline to post-test using the RES and MOD scoring systems as opposed to the STD method. Sixty RES and 59 MOD subjects had differing scores between baseline and post-test compared to only 43 for the STD system. This indicates a greater sensitivity to change in the RES and MOD scoring systems. From baseline to post-test, 17 subjects received the same score, 26 improved, and 17 recorded a decreased score. Notably, 85% of the control subjects recorded a change in score and there were no significant post-training differences between any of the groups (p > 0.176).

The lack of significant findings between groups coupled with the presence of two interventions, one based on fitness and the other based on improving movement quality, leads to some skepticism and concern about the ability of the FMS to assess change. Such a high percentage of change in a group of control subjects combined with mixed results (improved and decreased FMS performance) within the intervention groups leads to a lack of clarity in the findings. The RES and MOD scoring systems were developed with the intent of providing additional clarity and specific information regarding movement abnormalities that may be
present. However, these results do not indicate a great deal of improvement from the STD method in terms of ability to discriminate between subjects undergoing an intervention and those in a control group. This demonstrates the importance of assessing each FMS component individually and not focusing on a composite score that may ultimately mask important findings.

Klusemann et al. combined an investigation into the effectiveness of a training intervention and the differences in effectiveness between supervised and unsupervised, video-based implementation of that intervention [159]. Thirty-eight 14-17 year old junior basketball athletes were assessed via FMS before and after completion of the training program. The FMS utilized in this study was modified with the addition of a landing task. The task was not described in the article and it was unclear what the maximum possible score was for the modified FMS. Subjects were assigned to one of three groups with an effort made to keep the groups as similar as possible in terms of age, gender, and baseline strength scores. The intervention consisted of two training sessions per week for six weeks with at least two days of recovery between sessions. The intervention was identical for the two groups, but the supervised group was monitored by one of the primary investigators who provided verbal, visual, and kinesthetic feedback regarding proper form and encouragement during the sessions. The supervised group demonstrated what the authors describe as “substantial” change, but a level of significance was not reported. This group improved their modified FMS composite score from 14 ± 1 to 16 ± 2 from baseline to post-test. This represents a 14% increase in modified FMS score. Since the unsupervised and control groups did not improve their FMS scores, the authors conclude that completion of the intervention in the presence of trained FMS instructors will lead to greater improvement over time compared to completion of an identical training intervention in an unsupervised setting [159].

Bracing and taping interventions are often utilized in an attempt to reduce pain or improve function in a variety of populations. Only one study was identified that examined the use of such equipment in terms of how it may affect FMS performance. An et al. published findings related to the effect of Kinesio Tape® on FMS performance [133]. Thirty-two subjects (16 female collegiate basketball players and 16 non-varsity female students) completed a baseline partial FMS assessment (DS, ILL, HS) and were then randomized into either a treatment (KT) or control (CG) groups. After a washout period of 2-4 days, subjects were tested a second time either with (KT) or without (CG) the taping intervention. The principal investigator utilized a modified scoring system that included addition of 0.2 points for each specific criteria assessed
per FMS component. This method was discussed previously in this review. Kinesio Tape® was applied by the second investigator to the Sartorius, Rectus Femoris, Hamstrings, Patella, Tibialis Anterior, and Peroneus Brevis muscles. No significant differences were identified between groups for the DS (p = 0.667) or either side of the ILL (right, p = 0.530 and left, p = 0.291). The KT group did improve significantly compared to the CG in both the right (p < 0.001) and left (p < 0.001) sides of the HS. The authors suggest that these results indicate that Kinesio Tape® may alter motion in the non-weight bearing portion of the HS in such a way as to allow for notable improvement in a single repetition. The reported results do not indicate an effect of Kinesio Tape® on the weight-bearing components of the FMS included in this study.

Predictive Capabilities of the Functional Movement Screen

Injury Prediction

The ability of the FMS to predict injury in various populations has been examined by multiple authors and continues to be a key point of interest and topic of research. A simple, inexpensive screening tool that can be completed in a short amount of time with the ability to accurately identify those with an increased risk of injury would be invaluable. Further research is necessary to support the use of the FMS as such an assessment tool.

Kiesel et al. published the first paper identified for this review related to the predictive value of the FMS [129]. They reported that a score of 14 or less predicted serious injury with sensitivity (true positive rate) of 0.54 and specificity (true negative rate) of 0.91. Serious injury was defined as any that resulted in a minimum of three weeks spent on the injured reserve list. Forty-six professional football players completed the FMS as part of their pre-season physical process. Mean FMS composite score was 16.9 ± 3.0 for all subjects tested. Subjects that ended up suffering a serious injury (14.3 ± 2.3) scored significantly (p < 0.05) lower than those that did not (17.4 ± 3.1). A score of fourteen was the point where specificity and sensitivity were maximized [129]

The authors discuss numerous and important limitations of this study including collecting all data from a single team, the definition of injury used, the use of the same data set to both determine and evaluate the cut-off scores, and limited access to subject demographic and injury history due to privacy concerns of the professional football organization. However, this paper began the conversation related to the utilization of the FMS as an injury predictor.
What becomes problematic is the blind use of the FMS in this capacity prior to a full understanding of whether or not it is truly effective.

Chorba et al. conducted a similar study in a population (N = 38) of female collegiate athletes prior to the start of their competitive seasons [128]. All subjects completed a FMS and were subsequently monitored for injury over the course of the season. Injury was defined as being musculoskeletal in nature and met the following criteria: 1) result of participation in organized activity related to their collegiate sport and 2) injury required medical attention or athlete sought help from a certified athletic trainer, athletic training student, or physician.

The cut-off score established by Kiesel et al. [129] was utilized for the purposes of this study. The mean FMS score for all subjects was 14.3 ± 1.29, those that ultimately suffered an injury scored 13.9 ± 2.12, and those not suffering an injury scored 14.7 ± 1.29. Of those scoring at or below 14, 68.75% suffered an injury. Additionally, of those scoring at or below 13, 81.82% suffered injury and 48.28% of subjects scoring at or below 15 suffered injury. The authors reported sensitivity (0.579) and specificity (0.737) for the cut-off score of 14, which are similar to the results published by Kiesel et al [128, 129].

In a group of military officer candidates (N = 874) that completed the FMS as a part of their medical in-processing at the beginning of training, the mean FMS score was 16.6 ± 1.7 [125]. Interestingly, the FMS component with the highest frequency (84.5%) of a score of three was the push-up test, which may be a unique result to a population of military subjects. The SMT (7.6%) had the highest frequency of a score of one and the DS, HS, and RST had the highest occurrence of a score of two [125].

Risk of injury was reported to be 1.5 times greater for subjects scoring at or below 14 (p = 0.003). FMS scores did not turn out to be related to the occurrence of over-use injuries (p = 0.06). The authors also examined injury risk in those scoring 18 or greater compared to those scoring 15-17 and 14 or lower and reported a bi-modal distribution. Those scoring 18 or higher, like those scoring 14 or lower had a significantly (p < 0.02) greater risk of injury than those scoring between 15 and 17, but the authors provided little insight into this particular finding and suggested further research was necessary. This subject population was highly specific for this study, which further limits application to larger or different populations and there was a substantial subject pool. Unlike previous studies discussed, O’Connor et al. reported very low sensitivity for serious injury (0.12) at the cut-off point of 14 [125]. Further research is necessary.
to determine where, and if, a cut-off point for injury prediction utilizing the FMS should be established.

Lisman et al. published additional results related to the military cohort described above [160]. For the purposes of this study, “any injury” was defined as an event that caused physical damage to the body and resulted in the subject seeking medical attention at least once during the course of the study. Injuries were further broken down into overuse and acute injuries [160]. The primary findings of the study indicated that a score of 14 or lower was predictive of increased likelihood of any injury (p < 0.001) and traumatic injury (p < 0.005). This predictive ability was strengthened by combining a low FMS score and a slower running time on a standardized aerobic test (3-mile run > 20.5 minutes). Subjects suffering any injury, traumatic injury, and overuse injury were 4.19, 3.77, and 1.85 times more likely to suffer injury, respectively, than those who did not score low in both categories [160]. These results establish a relationship between poor aerobic fitness and poor functional movement in terms of an individual’s likelihood of suffering injury during marine officer training. An examination of 108 firefighters FMS performance was completed upon their entrance into the training academy as a part of a study published by Butler et al [161]. The composite and individual component scores were analyzed. A cut-off score of 14 or less was discriminatory between subjects with a higher and lower risk of injury. The DS and PUT were also identified as statistically significant injury status predictors [161].

Letafatkar deviated from the previously established use of 14 as the cut-off score for FMS injury prediction and set it at 17 in a study recently conducted involving 100 physically active university students competing in a variety of sports with no history of injury in the six weeks leading up to the study [153]. Students were assessed using the FMS at the beginning of the year and then had their injury status tracked by their specific athletic training staff members. Only one injury per athlete was recorded and an injury was defined as an occurrence that resulted in their missing one or more practices or games and resulted in them seeking medical treatment [153]. Mean composite score for the FMS was 16.7 ± 1.8 [153]. A cut-off score of 17 was used since it maximized sensitivity (0.645) and specificity (0.780). Subjects scoring lower than 17 had a 4.70 times greater chance of suffering injury than those scoring 17 or above. Those that ended up suffering an injury had a significantly (p = 0.005) lower FMS composite score than those that did not suffer injury. Also, there was no significant difference between those that suffered contact vs. non-contact injuries (p = 0.217), but both injury groups
had significantly lower scores (non-contact: $p = 0.032$, contact: $p = 0.013$) than those of the non-injured subjects [153]. Kiesel et al. reported relative risk of injury of 1.87 (athletes scoring at or below 14 on the FMS) and 1.80 (athletes displaying at least one asymmetry during FMS completion) [162]. Their study included 238 professional American football players and the FMS was included as a part of their screening process at the beginning of training camp. The main outcome of this study was time lost due to injury and was defined as any time lost from game or practice participation due to musculoskeletal injury [162]. The authors suggest that their results establish FMS scores and the presence of movement asymmetries as identifiable risk factors for injuries resulting in lost playing/practice time in American football players [162].

Bradley and Esformes examined the effect of breathing pattern disorders (BPD) on FMS score and cited BPD as a possible secondary cause of dysfunctional movement and possibly injury since they are known to cause pain and motor control deficits [163]. Thirty-four healthy individuals underwent breathing and FMS assessments and it was discovered that subjects utilizing diaphragmatic breathing scored significantly ($p = 0.006$) higher than those using thoracic breathing techniques. Seventy-five percent of subjects failing ($\leq 14$) the FMS were thoracic breathers and 66.6% of those passing ($\geq 15$) were classified as diaphragmatic breathers. The authors cite these results as evidence that diaphragmatic breathing is essential for proper functional movement [163].

In an effort to establish a relationship between ergonomics and the FMS, Beach et al. utilized the cut-off score of 14 to examine the relationship between peak low-back loading magnitudes while lifting in an effort to establish a relationship between FMS score and lifting mechanics [164]. Thirty men (15 $\geq 14$ FMS and 15 $\leq 14$ FMS) completed symmetrical and asymmetrical lifting tasks while being monitored via three-dimensional motion analysis and no significant differences were found between the two groups for any of the motion analysis variables measured. Despite the known importance of proper lifting mechanics for overall safety and low-back health, these results do not indicate a relationship between lifting technique and functional movement capability.

Performance Prediction

Similar to likelihood of injury, athletic performance is a trait that coaches, clinicians, and others try to evaluate, track, and predict. The availability of an inexpensive, straightforward field test that requires minimal time with the ability to accurately predict athletic performance
capability would be used extensively at all levels of competition. The FMS has been proposed as such an assessment and this section of the review will summarize the evidence related to this topic.

Klusemann et al. measured performance via a number of standardized fitness tests (20m-sprint, step-in vertical jump, agility, sit and reach, line drill, yo-yo intermittent recovery) and functional movement ability via FMS assessment in a group of junior (age 14-17) basketball athletes (N = 39) [165]. All subjects completed a battery of performance tests on a single test day and one week later completed the FMS. The primary goal of the study was to determine the relationship between FMS performance and athletic ability. No substantial correlations were identified when data from both genders were analyzed together and the FMS composite score was used [165]. However, a large \( r = 0.50 \pm 0.32\% \) relationship was identified in male subjects between the sit-and-reach test and ASLR component of the FMS. Additionally, with both genders combined, moderate correlations were identified between the sit-and-reach test and ASLR \( r = 0.43 \pm 0.23 \) as well as the push-up strength test and PUT of the FMS \( r = 0.30 \pm 0.26 \) [165]. Finally, moderate correlations were reported between the FMS composite score in female subjects and both agility \( r = -0.41 \pm 0.32 \) and intermittent recovery \( r = 0.39 \pm 0.34 \) [165]. The presence of large variability and only moderate correlations do not indicate strong relationships between athletic performance variables and FMS performance. Further research is necessary to better understand these relationships.

Parchmann and McBride also examined the relationship between FMS performance and measures of athletic ability and reported an absence of meaningful relationship between the two in a group of 25 collegiate golfers (15 male, 10 female) [166]. Subjects completed a battery of athletic performance tests (1 repetition maximum squat, 10m-sprint, 20m-sprint, vertical jump, T-test) as well as the FMS. No significant correlations were identified between FMS performance and any of the measures of athletic performance [166]. The authors suggest that the FMS should not be used to determine athletic performance or ability in a population of collegiate golfers. They suggest that since the FMS does not assess strength, which has been determined to have a strong relationship to athletic performance, it does not challenge the subject’s athletic ability enough to provide useful information about their performance capability [166].

In contrast to the findings of Parchmann and McBride [166], Okada et al. reported some significant relationships between athletic performance tests and FMS performance [167].
However, they did not identify any significant relationships between core stability and FMS performance, which the authors themselves described as odd due to the expected importance of core stability for the completion of many of the FMS movement tasks [167]. The FMS composite score was not found to be strongly correlated to any performance measure, but some relationships were identified for individual FMS components. The left ILL was moderately correlated to performance of the T-test (r = -0.462) which is partially in support of Kluseman et al. [165] report of a similar relationship between the FMS composite score and agility in female subjects [167]. The right SMT was moderately correlated to the T-test (r = 0.392) and single-leg squat test (SLS) (r = -0.446) and the left SMT demonstrated a trivial correlation to the SLS (r = -0.246) [167]. Finally, the right RST was moderately correlated with the backwards overhead medicine ball throw (r = 0.391) [167].

Despite identifying some meaningful correlations between athletic ability and FMS performance, the authors conclude that the FMS should not be utilized to predict performance. They cite specificity as a reason that the two do not correlate strongly. Athletic performance relies heavily on strength and speed of movement and the FMS is not sensitive to these characteristics. Functional movement capability may indeed be a foundational requirement for safe performance of more advanced physical tasks, but assessment of functional movement may not be appropriate to use as a predictor of more advanced physical ability. Furthermore, since it has been established that athletes at the highest levels of athletic competition perform with movement asymmetries and rely on compensatory strategies, it may not be appropriate to use the FMS to predict performance.

Performance can also be measured by metrics of sport-specific productivity. McGill et al. reported no significant relationships between any of the FMS components and statistical measures of sport-specific performance in a single team (N = 14) from a major American university men's basketball team [168]. All subjects completed the FMS as part of a pre-season test battery. Statistical categories included games played as well as minutes, points, assists, rebounds, steals, and blocks per game [168].

*Relationship of FMS to anthropometric and fitness characteristics*

Childhood obesity is a growing concern and its relationship to FMS performance, along with physical activity levels was evaluated by Duncan and Stanley [138]. Fifty-eight, ten and eleven year-old children volunteered for participation in this study and had their body mass...
index (BMI), physical activity and FMS performance measured. Physical activity data were collected using pedometers worn for a four-day period. The primary finding of this study was a significant ($p = 0.0001$) negative correlation ($r = -0.806$) between BMI and FMS score and a significant ($r = 0.301$) moderate positive relationship between physical activity and FMS score [138]. The authors also reported that BMI (52.9%) and physical activity (7.3%), defined by average steps per day, combine to predict 60.2% of the variability in FMS score in this population [138].

Duncan et al. published further results related to the effects of overweight and obesity status on FMS score involving a group of 90, seven to ten year-old British primary school children [169]. In support of their previous findings, they reported a significant ($p = 0.0001$), strong negative correlation ($r = -0.572$) between BMI and FMS score. Additionally, FMS scores were significantly higher in normal weight children compared to overweight and obese children as well as being higher in overweight children compared to obese [169]. No significant difference was identified between boys and girls for the FMS composite score. Percent fat ($r = -0.26$) and waist circumference ($r = -0.21$), were found to be mildly correlated with FMS performance in a population of 690 (569 male, 121 female) active duty military personnel over the age of 40 [170]. These results expand the findings of Duncan et al. [169] and Duncan and Stanley [138] related to the negative effect of excess body weight on FMS score. The authors also reported that upper extremity static strength ($r = 0.193$), flexibility ($r = 0.34$), and time spent sitting ($r = -0.098$) were all mildly correlated to FMS performance [170]. These findings all support participation in physical activity as a method to improve FMS score.

Pubertal maturation was determined to separate 66 adolescents from ages eight to 14 into three groups: prepubescent, early-pubescent, and post-pubescent, in order to determine whether or not physical maturation effected FMS performance [171]. Paszkewicz et al. reported a significant main effect for time for the FMS composite score related to pubescence ($p = 0.032$) [171]. Further analysis revealed significant differences between post-pubertal and pre-pubescent ($p = 0.008$) and early-pubescent ($p = 0.039$) subjects [171]. The authors discuss the possible effectiveness of FMS use to determine levels of pubescence, possibly identify musculoskeletal changes, and identify individuals with movement deficiencies that may benefit from a corrective exercise intervention.

Clifton et al. determined that no exercise-related changes occurred to FMS score after completion of a 36-minute exercise protocol involving walking and explosive jumping activities
in a population (N = 25) of young, recreationally active adults (8 male, 17 female) [172]. Subjects underwent FMS assessment pre- and post-exercise and no significant changes to FMS composite or individual component scores were discovered. Based on these results, the authors did not recommend use of the FMS in identifying individuals that may display balance deficits after exercise. However, they did report that the PUT, HS, and ASLR may be useful in identifying individuals with postural control deficits based on moderate to strong correlations (r values) between these components and various measures of center of pressure data [172].

**Conclusion**

The current literature portrays the FMS as a straightforward, well-organized, total-body functional movement assessment tool that requires minimal time and equipment. Reliability studies have established that only minimal training and advanced familiarity is necessary to become a reliable rater of FMS performance and the scoring system, as described by the creators, appears on paper to be simple and easy to implement. Additionally, some evidence exists in the literature supporting the use of the FMS as a tool to predict non-contact musculoskeletal injuries, various components of athletic performance, and balance. Finally, relationships have been established between the FMS and various measures of health and physical fitness such as BMI, waist circumference, and time spent sitting.

However, as with any newly developed assessment tool, the FMS continues to undergo investigation and subsequent change. Three modifications to the scoring system were identified in this review that have been developed in an effort to provide additional, more specific information related to the presence of movement capabilities and impairments. Creators of the FMS intended for each component to be scored individually, with no suggestion regarding the use or analysis of a composite score and it appears that the most useful information regarding the FMS is still derived in this manner. The modified scoring systems currently being examined in the literature may provide additional information that will assist with the development of targeted corrective exercise interventions, but further research in this area is needed. In order for the FMS to be fully acknowledged as an assessment tool able to detect real change over time and distinguish between effective and ineffective interventions, it must be established that more is required to improve performance than simply practice and feedback. Current research is not conclusive in distinguishing the point where these methods of correction cease to be effective and long-term neuromuscular corrective intervention is required.
The predictive value of the FMS is not something the original creators suggested. It was simply to be used as a part of a larger assessment to determine an individual’s readiness for more advanced and intense physical activity. Some intriguing information has been presented in the literature about the predictive capability of the FMS composite score, but as it stands currently, additional research is necessary to determine if and how it can be best utilized. An evaluation tool that assesses multi-joint movement patterns and provides a snapshot of the kinetic chain’s ability to produce sound, symmetrical functional movement patterns like the FMS may prove to be predictive of performance and injury risk. However, irrefutable evidence establishing these capabilities within the FMS has not been presented. This basic movement screen involving only body weight resistance and slow, controlled movements may not be specific enough to predict performance of tasks requiring strength and speed.

From an injury prediction standpoint, it is still not known how change in an upper extremity component will affect injury risk in the lower extremity and vice versa. Use of the composite score allows change in the various movement components to go undetected. For example, an individual may improve their score on one component while displaying a similar decline in another and the result would be no change in the composite score. This does not appear to be a sensitive enough system to monitor or detect real change. Furthermore, improvement of one aspect of movement may go undetected if the overall performance of that component is not improved enough to merit an increase in score from one to two, or two to three.

Future research should address the reliability and predictive nature of the modified scoring systems presented in the literature to determine whether or not they provide adequate information to allow for prediction of injury or design of corrective exercise interventions. Also, investigation into the relationship between individual FMS components and other important standardized measures of performance assessment involving body weight resistance and controlled speed of movement such as postural stability, range of motion, and core muscle capability should be undertaken. This will provide important information regarding the underlying cause of movement dysfunction or asymmetry.
CHAPTER 3
THE EFFECT OF TRAINING SURFACE ON PERFORMANCE OUTCOMES IN FEMALE ATHLETES

INTRODUCTION

Sand continues to be a popular alternative to the firmer surfaces traditionally used for training and competition. Competitive beach soccer, volleyball, ironman triathlons, and lifesaving competitions are some of the most common sand-based sports [16, 17, 23, 32]. Recreational and competitive runners are using sand as an alternative to higher impact road running [9, 20] and it has also served as an alternative training surface for athletes involved in basketball, soccer, volleyball, and football. The use of a more compliant surface has been employed as a potential mechanism for increasing performance as well as reducing training injuries [8, 9, 17]. Despite the increased popularity of sand training for various populations there is some concern that training on sand may be detrimental to anaerobic performance on a more traditional hard surface.

Many of the concerns over the potential for sand training to inhibit anaerobic performance are derived from the physical characteristics of sand. Dry, non-compacted sand produces lower mean and peak ground reaction forces (GRF) compared to wet, compacted sand [16] or presumably an even harder surface, such as a gymnasium floor. Research suggests that the force required for walking and running in sand must increase to accommodate for the posterior slippage of the foot when horizontal force is applied to the surface [9, 30]. This results in a reduced ability to transform elastic energy to kinetic energy during the gait cycle and jumping tasks. This negatively impacts the force and power production capabilities of the stretch-shortening cycle (SSC). Several investigators have stated that movement in sand requires biomechanical adjustments and thus the legs must perform more mechanical work to make up for the elastic energy that is lost to the displacement of sand [28, 29, 40]. Posterior slippage of the foot causes force application to occur over a longer period of time. Also, elastic energy cannot be stored and transferred to the same extent, and overall ground-reaction forces (GRF) are decreased [16, 28, 40].

Sand training leads to a greater reliance on, and consequently production of, concentric force in order to make up for the loss of elastic energy. Pinnington et al. consistently found significant (p < 0.05) increases in EMG activity in the hamstrings group throughout the gait cycle, quadriceps group at mid-stance, tensor fascia latae during the stance phase, and gastrocnemius
during mid-stance [20]. This increase in EMG points to a greater recruitment of motor units during activity on sand as a result of an increased demand on stabilizing muscles in response to the instability of a sand surface. If transferable, this neuromuscular adaptation, in conjunction with the contribution of the SSC, may lead to greater power production on a hard court surface.

The successful completion of a movement is less dependent on the ability to replicate a particular motor pattern and more reliant on the body’s ability to find a movement solution that achieves the goal while working within the constraints of the surrounding environment [173]. When the environment changes and different movement constraints are placed on the body, new motor patterns emerge [174]. This occurs with the introduction of sand as a training surface as the body attempts to compensate for reduced GRF, level of friction, and surface stability while maintaining the ability to achieve the movement goal.

There is limited research evaluating the chronic effects of sand training on hard court surface performance, especially among female collegiate athletes. Given the dichotomy of concerns and excitement over this training modality, more research is necessary to support its use. A thorough evaluation of the potential beneficial or detrimental effects of sand training will guide the exercise programming for these athletes. Therefore, the purpose of this study was to evaluate the anaerobic adaptations in female collegiate athletes as a result of training on sand versus a hard court surface. Anaerobic outcome measures included: strength, speed, agility, power, and anaerobic endurance.

We hypothesized that training on either sand or hard court surfaces would improve anaerobic outcome measures in response to the effects of the training protocol. Although the performance assessments involve differing amounts of strength, speed, agility, power, and anaerobic endurance, all would benefit from an increase in concentric force production. Since it has been proposed that this adaptation will occur to a greater extent in sand, we hypothesized that repeated exposure to training in sand would produce greater improvements in all performance outcomes compared to hard court training.

Delimitations

1) Collegiate varsity female athletes.
2) Participation in volleyball, basketball, or soccer.

Assumptions
1) Assumed maximal effort for performance measures.

2) Assumed compliance with request to refrain from additional lower body training outside of team sponsored off-season activities.

**METHODS**

**Experimental Approach to the Problem**

A longitudinal design was used to determine the effect of training surface on lower body strength, speed, agility, power, and anaerobic endurance. The independent variable for this study was training surface; sand vs. hard court. The dependent variables were the vertical jump, long jump, 300yd shuttle, 40yd sprint, 5 repetition maximum (RM) squat and t-test. Subjects were asked to attend 13 sessions (2 d·wk\(^{-1}\)) over a seven week period as participants in this study. This included one session each for familiarization, baseline, and post-test, as well as a series of ten 50-minute training sessions.

Training occurred either on a hardwood competition surface or in an outdoor sandpit, depending on group assignment. Group assignment was randomized within each team to make sure that subjects from each sport were evenly stratified between the two training groups. Every effort was made to ensure equity between the two groups in terms of their training volume and exercise selection in order to isolate training surface as the primary variable between the two groups. Both groups were trained by the same individual throughout the study and given similar verbal instruction and encouragement throughout each workout. All subjects were encouraged to work at a maximum effort. A true control group was not used in this study as it was considered detrimental to the subjects for them to abstain from training during the off-season. Therefore, the hard court group represented the standard treatment group and the sand group represented the experimental treatment group. Testing for all subjects took place on a hardwood competition surface in a climate-controlled gymnasium.

**Subjects**

A convenience sample of volunteers was composed of seventeen female athletes representing the sports of volleyball, soccer and basketball from a National Association of Intercollegiate Athletics (NAIA) institution. Their mean age, height, and body mass were (mean ± SD) 19.53 ± 0.78 yrs., 168.05 ± 4.45 cm, and 66.89 ± 11.79 kg, respectively. All subjects provided written informed consent after a detailed explanation of the aims, benefits, and risks associated with the study. All testing and training was completed during the subjects’ off-
season with prior approval of the respective coaching staffs. Subjects were randomly assigned to either the sand group (SG) (n = 8) or the standard treatment hard court group (HG) (n = 9) with equal representation of each sport in the two groups. There was no differentiation by position within a given sport. All subjects were tested individually, but completed all training sessions in a group setting.

Exclusion criteria for this study included: prior history of ACL reconstruction within the past year and/or current enrollment in a rehabilitation program for any lower extremity injury. All participants were required to be members of their respective varsity athletic teams and have a current sports pre-participation physical on file with the coaching staff per athletic department guidelines. Subjects were asked to abstain from additional lower body resistance training and running while participating in this study. Subjects were permitted to participate in any team-sponsored, sport-specific workouts. During the course of the study, the average time spent participating in team-sponsored workouts was reportedly less than three hours per week for all subjects. This was equal between groups since each group was made up of athletes from all three athletic teams represented in the study. However, this activity was not monitored and may have varied by team. Approval from the University’s Institutional Review Board was obtained prior to the initiation of the study.

**Procedures**

The HG completed all training sessions on the test surface. The SG completed all training sessions in an outdoor sand pit that was 24.38m x 15.24m (length x width) filled with dry, soft river bed sand to a depth of .46m. The three test sessions (familiarization, baseline, post-test) included anthropometric measures and performance measures. The functional test protocol was administered using the following test order to minimize the effects of fatigue: vertical jump, standing long jump, t-test, 5 repetition maximum (RM) back squat, 40-yd dash, and 300-yd shuttle.

Body mass was measured (to the nearest 0.5 kg) without shoes in light clothing using a digital scale (Detecto, Webb City, MO). Subjects were asked to refrain from eating or drinking for at least one hour before their body mass was measured. Standing height was measured (to the nearest 0.5 cm) without shoes using a stadiometer (Accustat, Genentech Stadiometer, San Francisco, CA). Percent body fat was assessed using a BIA 310 bioimpedance analyzer (Biodynamics, Seattle, WA). The manufacturer’s proprietary equation was used to estimate
percent body fat and required the input of the subject’s age, height, body mass, and gender. Subjects were positioned supine and electrodes were placed on the ipsilateral wrist and ankle. Care was taken to insure that the extremities were positioned on the table without contacting the torso or opposite extremity during testing.

The Vertec (JumpUSA, Sunnyvale, CA) was used to measure vertical jump height. The test was performed as described by Baechle and Earle [175]. Athletes were instructed to jump off of two feet without a preparatory step, but were allowed to squat to the depth of their choosing and utilize a self-selected arm swing motion. Each athlete completed three trials and the greatest value was used for the data analysis. A fifteen-second recovery period was allowed between each repetition. The test-retest reliability for the vertical jump test was (intra-class correlation coefficient: ICC) 0.865.

In order to assess the standing long jump, subjects stood with their toes behind a pre-marked starting line on the hardwood competition court. Each subject then performed a counter-movement followed by a maximum effort forward jump. The distance from the starting line to the back edge of the rearmost heel was recorded as the jump length. Each subject completed three trials and the longest trial was used for data analysis. A fifteen second recovery period was allowed between repetitions [175]. The calculated ICC for standing long jump was 0.833.

As part of the familiarization session subjects were instructed in proper technique for the five repetition maximum parallel squat (5RM) as defined by Baechle and Earle in Essentials of Strength and Conditioning (2008) and ample practice time and instruction were provided to ensure their familiarity and safety. Prior to baseline testing, subjects were reminded of proper technique and any questions were answered before the testing procedure began. The 5RM was conducted according to the protocols provided by Baechle and Earle [175]. A three-minute rest period was allowed between each 5RM attempt. The test-retest reliability for the back squat was ICC = 0.948.

Using a course set up according to the specifications explained by Baechle and Earle [175], each athlete was instructed in the proper completion of a t-test. Subjects began behind the starting line in a three point stance with the index finger of the support hand on the touch pad of the Speedtrap I digital timing system (Gill, Champaign, IL). Each athlete was provided with time to warm-up and stretch and one practice trial at sub-maximal speed was completed.
The faster of two maximum effort trials was recorded and a recovery period of two minutes was allowed between trials [175]. The test-retest reliability of the t-test was ICC = 0.667.

The 40-yd sprint was conducted on the hardwood competition surface. Subjects were allowed time for warm-up and stretch prior to completing the test, as well as two practice trials at sub-maximal speed. A digital timing system was used to record each athlete’s time. The subjects began in a three-point stance with the toes of both feet behind the designated starting line and the index finger of the support hand on the touch pad of the digital timing system. Upon hearing an auditory signal of “go,” the subjects sprinted 40 yards at maximal speed. The average of two maximum effort trials was recorded [175]. A rest period of two minutes was allowed between trials. The test-retest reliability of the 40 yd sprint was ICC = 0.936.

The 300-yard shuttle was performed on the hardwood competition surface and conducted as described by Baechle and Earle [175]. A digital timing system was used to record each subject’s time. After trial one, subjects were given a five-minute rest period and then completed a second trial. The time of each trial was recorded to the nearest 0.5 seconds. The average of the two times was calculated and recorded. A recovery time of two minutes was allowed between trials two and three. The test-retest reliability of the 300-yd shuttle was strong at ICC = 0.859.

Over a period of four weeks, subjects completed nine training sessions that lasted approximately 50 minutes each. The training program for the two groups was identical in terms of exercise prescription and volume. Five minutes were allotted at the beginning of the workout for a dynamic warm-up. Each dynamic exercise was performed over a distance of ten yards, followed by a jog of equal distance. The exercise sessions were completed with a five-minute cool-down session which included repeating a portion of the dynamic warm-up, followed by a static stretch of all of the major muscle groups in the lower extremity. Each static stretch was completed once and held for 30 seconds. Fifteen to twenty seconds of recovery time were allotted between each exercise and a two-minute water/recovery break was granted between each ten-minute section of the exercise session. Subjects in the SG performed all training activities barefoot, with the option of wearing athletic shoes if desired, and the HG wore athletic shoes of their choice. Subjects were instructed to complete all exercises at a maximum effort level and received verbal encouragement throughout the exercise session.

The training protocol was broken into two five-session sections. The training program was periodized such that the intensity and volume of training increased for all exercises after
the fifth session, but an effort was made to control the overall duration of each session. The first five sessions included the exercises listed in Table 3.1 and the second five workouts included the exercises listed in Table 3.2. Ultimately, all subjects in both groups completed nine workouts. Only four sessions utilizing the intervention listed in Table 3.2 were completed due to weather constraints on the SG and the need to keep the training schedule identical between the two groups.
<table>
<thead>
<tr>
<th>Warm-up</th>
<th>Agility</th>
<th>Muscular Power</th>
<th>Anaerobic Endurance</th>
<th>Cool-down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt kicks/high knees</td>
<td>T-test: 2 trials, with opponent (modified to 6x6 yds)</td>
<td>Bounding (10yds) 4 trips</td>
<td>Sprint/backpedal repeats: 3 trials of 2 consecutive trips over 10yd distance</td>
<td>Quad walk/hamstring march</td>
</tr>
<tr>
<td>Quad walk/hamstring march</td>
<td>Pro-agility: 2 trials, with opponent</td>
<td>Squat jump w/ standing long jump x10</td>
<td>Medicine ball backwards throw and sprint: 2 trials of 5 reps (3kg ball)</td>
<td>Walking lunge/single-leg swing</td>
</tr>
<tr>
<td>Walking lunges/single leg swing</td>
<td>Ladder drills: 3 trials of hop scotch, lateral scissor, 2 foot diagonal shuffle on 15-ft ladder</td>
<td>Cycled split squat jump: 2 sets of 10</td>
<td>X sprints: 6 trials (3L, 3R) (10yds, 5 yds, 10yds)</td>
<td>Knee hug/alternating squats</td>
</tr>
<tr>
<td>Knee hug/alternating squats</td>
<td>Cone drills: 2 trials of front jumps, side jumps (2 L, 2 R), forward weave for 10 ft (followed by 5yd sprint)</td>
<td>Single-leg hop for speed: 3 trials for 10 yds. with each leg</td>
<td>Modified shuttle: 2 trials (120yds)</td>
<td>Static hamstring</td>
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<tr>
<td>Power skips/backpedal</td>
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<td>Static quad</td>
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<td>Shuffle L/shuffle R</td>
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### Table 3.2 Training Protocols for Session 6-9 Stratified by Targeted Biomotor Ability.

<table>
<thead>
<tr>
<th>Warm-up</th>
<th>Agility</th>
<th>Muscular Power</th>
<th>Anaerobic Endurance</th>
<th>Cool-down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt kicks/high knees (stationary) x 30s each</td>
<td>T-test: sprint all directions x 3 trials</td>
<td>Wall/net jumps (max height x 5) 4 sets</td>
<td>Sprint/jump squat x 5 repeats: 2 trials (down/back) 10yd distance</td>
<td>Quad walk/hamstring march</td>
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<td>Walking lunge/single-leg swing</td>
</tr>
<tr>
<td>Jump squats (stationary) x 30s</td>
<td>Pro agility: shuffle all directions x 3 trials</td>
<td>Single-leg broad jump 10yds x 2</td>
<td>Medicine ball backwards throw and sprint: 2x5 (5kg ball)</td>
<td>Hips open/hips closed</td>
</tr>
<tr>
<td>Jumping jacks x 30s</td>
<td>Ladder drills: 3 trials hop scotch, single-leg diagonal hop, 2 forward/1 back</td>
<td>Cycled split squat jump: 2 sets of 15</td>
<td>Diagonal sprints (2L and 2R) down and back</td>
<td>Static hamstring</td>
</tr>
<tr>
<td>Plank jacks x 30s</td>
<td>Stationary sprint (foot fires) 3 x 30s</td>
<td>Single-leg hop for speed: 4 trials for 10 yds. with each leg</td>
<td>Modified shuttle (10 yd. distance) one trial w/ 8 trips, one trial w/ 4 trips</td>
<td>Static quad</td>
</tr>
<tr>
<td>Shadow jump rope (30s B, 15s L, 15s R)</td>
<td></td>
<td></td>
<td></td>
<td>Static calf</td>
</tr>
<tr>
<td>Jog/backpedal x 2 (10yds)</td>
<td></td>
<td></td>
<td></td>
<td>Static groin</td>
</tr>
</tbody>
</table>

### Statistical Analysis

Basic statistics (mean ± standard deviation) were used to describe subject demographics and outcome variables. Independent t-tests were used to determine whether any physiological or performance differences existed between the two groups prior to testing. The test-retest reliability of the performance outcomes was assessed using the intra-class correlation coefficient (ICC). A 2 X 2 mixed factor analysis of variance (ANOVA) was used to evaluate the effects of the training surface (hard court vs. sand) on performance outcome measures for within (i.e., baseline vs. post-test) and between group comparisons for each of the dependent variables. Power and effect size estimates were also calculated for each variable. Effect sizes (partial eta-squared) were interpreted as small ($\approx 0.02$), medium ($\approx 0.13$), or large ($\approx 0.26$). The
level of significance was set a priori at \( p < 0.05 \) for all analyses. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) Version 20 (IBM Corporation, Armonk, NY).

In addition to statistical significance, minimum detectable change (MDC) was calculated. Minimum detectable change is defined as an estimate of the smallest change in a score that can be detected objectively. This can also be described as the amount of change that must be present in order to ensure that the change is greater than the measurement error. MDC is calculated by first calculating the standard error of the mean (SEM). This is done by taking the mid-point between the two measures of a given variable (i.e. baseline and posttest for vertical jump) and multiplying it by the square root of \((1 \times ICC)\) for that variable. Next, the SEM is multiplied by the number of test sessions (i.e., 2 testing sessions). The minimum detectable change for each variable, except where no ICC was available, was calculated as described by Donoghue et al. [176].

RESULTS

At baseline, there were no significant differences in the physical characteristics and performance variables between groups (Table 3.3). All other results are presented in Table 3.4. There was a significant group by time interaction effect for the standing long jump (\( p = 0.047 \)). Specifically, the SG improved in the standing long jump significantly more than the HG. There were favorable significant main effects for time for the standing long jump (\( p = 0.015 \)), 300-yd shuttle (\( p = 0.039 \)), and 5RM squat (\( p = 0.002 \)) demonstrating the overall positive effect of the training protocol. The within subjects effect for the 5RM squat (3.68 kg) surpassed the calculated MDC value of 2.92 kg. This further strengthens the already statistically significant finding that the training protocol was effective at improving 5RM squat performance in both groups. No other variables surpassed their respective MDC values. The calculated effect sizes for all interaction effects were small (< 0.02) except for the standing long jump, which was moderate to large at 0.24. Large (> 0.26) effect sizes were calculated for the main effect for time in the standing long jump (0.33), 300 yd. shuttle (0.25), and 5RM squat (0.52). No significant changes occurred in regards to the t-test, 40 yd sprint, vertical jump, BMI or relative body fat of the subjects during the study.
Table 3.3 Descriptive Comparison of Subject Characteristics at Baseline.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean ± SD</th>
<th>Mean ± SD</th>
<th>p-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (n = 8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (yrs)</td>
<td>19.56 ± 0.73</td>
<td>19.50 ± 0.93</td>
<td>0.89</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>166.50 ± 4.12</td>
<td>169.79 ± 4.68</td>
<td>0.15</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>63.49 ± 9.92</td>
<td>70.71 ± 13.91</td>
<td>0.25</td>
</tr>
<tr>
<td>Percent Fat (%)</td>
<td>22.40 ± 2.99</td>
<td>24.44 ± 4.76</td>
<td>0.32</td>
</tr>
<tr>
<td>Body Mass Index (kg·m⁻²)</td>
<td>22.75 ± 2.88</td>
<td>24.49 ± 4.70</td>
<td>0.38</td>
</tr>
<tr>
<td>Vertical Jump (m)</td>
<td>0.38 ± 0.06</td>
<td>0.41 ± 0.05</td>
<td>0.28</td>
</tr>
<tr>
<td>Long Jump (m)</td>
<td>1.68 ± 0.23</td>
<td>1.67 ± 0.16</td>
<td>0.91</td>
</tr>
<tr>
<td>T-test (s)</td>
<td>11.74 ± 0.52</td>
<td>11.75 ± 0.42</td>
<td>0.96</td>
</tr>
<tr>
<td>40-yd sprint (s)</td>
<td>6.45 ± 0.31</td>
<td>6.40 ± 0.44</td>
<td>0.78</td>
</tr>
<tr>
<td>300-yd Shuttle (s)</td>
<td>73.17 ± 4.27</td>
<td>77.00 ± 6.72</td>
<td>0.19</td>
</tr>
<tr>
<td>5 Rep Max Squat (kg)</td>
<td>52.25 ± 6.61</td>
<td>54.25 ± 10.61</td>
<td>0.66</td>
</tr>
<tr>
<td>Hard Court (n = 9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (yrs)</td>
<td>19.50 ± 0.93</td>
<td>19.56 ± 0.73</td>
<td>0.89</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>169.79 ± 4.68</td>
<td>166.50 ± 4.12</td>
<td>0.15</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>70.71 ± 13.91</td>
<td>63.49 ± 9.92</td>
<td>0.25</td>
</tr>
<tr>
<td>Percent Fat (%)</td>
<td>24.44 ± 4.76</td>
<td>22.40 ± 2.99</td>
<td>0.32</td>
</tr>
<tr>
<td>Body Mass Index (kg·m⁻²)</td>
<td>24.49 ± 4.70</td>
<td>22.75 ± 2.88</td>
<td>0.38</td>
</tr>
<tr>
<td>Vertical Jump (m)</td>
<td>0.41 ± 0.05</td>
<td>0.38 ± 0.06</td>
<td>0.28</td>
</tr>
<tr>
<td>Long Jump (m)</td>
<td>1.67 ± 0.16</td>
<td>1.68 ± 0.23</td>
<td>0.91</td>
</tr>
<tr>
<td>T-test (s)</td>
<td>11.75 ± 0.42</td>
<td>11.74 ± 0.52</td>
<td>0.96</td>
</tr>
<tr>
<td>40-yd sprint (s)</td>
<td>6.40 ± 0.44</td>
<td>6.45 ± 0.31</td>
<td>0.78</td>
</tr>
<tr>
<td>300-yd Shuttle (s)</td>
<td>77.00 ± 6.72</td>
<td>73.17 ± 4.27</td>
<td>0.19</td>
</tr>
<tr>
<td>5 Rep Max Squat (kg)</td>
<td>54.25 ± 10.61</td>
<td>52.25 ± 6.61</td>
<td>0.66</td>
</tr>
</tbody>
</table>

yrs=years

cm=centimeter

kg=kilogram

%=% percent

kg·m⁻² = kilogram square meter

m=meter

s=second

*Significance level set at p < 0.05
Table 3.4 Descriptive Comparison of Performance Measures by Training Surface.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sand Group (n=8)</th>
<th>Hardcourt Group (n=9)</th>
<th>p-value*</th>
<th>Partial eta-squared</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Post-test</td>
<td>Baseline</td>
<td>Post-test</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td></td>
</tr>
<tr>
<td>Time^ Interaction#</td>
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<td>0.667</td>
<td>0.17</td>
<td>0.01</td>
<td>0.37</td>
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<td>0.07</td>
<td></td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ICC</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>70.61 ± 13.90</td>
<td>71.34 ± 13.68</td>
<td>63.19 ± 10.06</td>
<td>63.62 ± 9.62</td>
<td>0.102</td>
</tr>
<tr>
<td>Percent Fat (%)</td>
<td>24.65 ± 4.44</td>
<td>23.94 ± 4.36</td>
<td>22.71 ± 3.58</td>
<td>22.21 ± 4.10</td>
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<td>0.806</td>
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<td>0.12</td>
<td>0.00</td>
<td>0.27</td>
</tr>
<tr>
<td>Body Mass Index (kg·m^-2)</td>
<td>24.47 ± 4.73</td>
<td>24.58 ± 4.88</td>
<td>22.81 ± 3.00</td>
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<td>0.09</td>
<td>0.09</td>
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<tr>
<td>Vertical jump (m)</td>
<td>0.40 ± 0.06</td>
<td>0.41 ± 0.06</td>
<td>0.35 ± 0.04</td>
<td>0.37 ± 0.09</td>
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<td>0.06</td>
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<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long jump (m)</td>
<td>1.64 ± 0.11</td>
<td>1.74 ± 0.11</td>
<td>1.68 ± 0.25</td>
<td>1.69 ± 0.21</td>
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<tr>
<td></td>
<td>0.047</td>
<td>0.33</td>
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<td>0.24</td>
<td>0.73</td>
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<td>0.53</td>
<td>0.53</td>
<td>0.53</td>
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<td></td>
</tr>
<tr>
<td>T-test (s)</td>
<td>11.90 ± 0.54</td>
<td>12.04 ± 0.62</td>
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<td>12.12 ± 0.58</td>
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</tr>
<tr>
<td>40-yd sprint (s)</td>
<td>6.46 ± 0.50</td>
<td>6.40 ± 0.44</td>
<td>6.59 ± 0.25</td>
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<td>0.00</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
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<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300-yd shuttle (s)</td>
<td>74.09 ± 6.55</td>
<td>72.52 ± 5.65</td>
<td>73.34 ± 3.45</td>
<td>72.19 ± 3.42</td>
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<td>0.01</td>
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<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 rep max squat (kg)</td>
<td>56.41 ± 9.42</td>
<td>60.67 ± 11.29</td>
<td>53.89 ± 7.93</td>
<td>56.98 ± 7.80</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>0.552</td>
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<td>0.52</td>
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<td>0.09</td>
<td>0.09</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* = significance level set at p < 0.05, ** = Intra-class Correlation Coefficient, *** no familiarization period.

= Time Main Effect
# = Group*Time Interaction

kg = kilogram
kg·m^-2 = kilogram square meter
m = meter
s = second
DISCUSSION

The purpose of this study was to determine if repeated exposure to training on sand resulted in beneficial or detrimental effects on agility, strength, anaerobic power and anaerobic endurance outcomes in female collegiate athletes. It was hypothesized that both groups would demonstrate improvement across all performance variables tested. Additionally, we hypothesized that sand training would produce greater improvements compared to hard court training, with the exception of the 5RM squat. This was based on previous published data making a case for the development of beneficial neuromuscular adaptations after a period of sand training that resulted in an improvement in firm-surface performance [6, 7, 9]. No injuries occurred in either group during training or testing.

Our findings indicate that sand training yielded a significant improvement in hard court long jump performance. These results suggest the ability to combine old and new movement strategies to maximize performance. In this case, the contributions of the SSC from previous hard court training and the proposed increase in concentric force production, along with other adaptations still not fully understood. New movement strategies are developed out of necessity when the system within which the body is operating changes [174]. All subjects participating in this study had a high degree of familiarity with athletic participation on a hard court surface and both groups were given the same movement goals, but the environment was changed for the SG. In order to produce a similar result on the new surface, new motor patterns were likely developed. Once a motor pattern is established, it is available for recall to contribute to successful completion of future movements, regardless of the environment [174]. Creation of this new movement strategy appears to have contributed to the improvement in long jump performance and was therefore transferrable from sand to the hard court. This idea supports the transferability of training adaptations from sand to a firmer surface previously proposed by Gortsila et al [7]. In a recent review, Binnie et al. concluded that sand training may be beneficial for improving what they refer to as “firm-ground performance” by inducing further biomechanical adaptations while limiting the potential for injury during training [5].

The long jump requires upward and forward propulsion of the body which cannot be accomplished without appropriate power production by the involved skeletal muscles. However, propulsion is also determined by the GRF provided by the surface and the effectiveness of the SSC. A firm, rigid surface produces higher GRF as compared to a sand surface [16]. This means that on sand, force production, and subsequently power, are
negatively affected by its displacement. However, our results indicate that this change in surface leads to development of a movement strategy that is synergistic to long jump performance on a hard court surface.

The SSC is a countermovement mechanism used to produce maximal propulsive force. It has been established that rapid concentric muscle action immediately preceded by an appropriate eccentric action produces more power than concentric action alone [177]. The SSC is hindered when jumping in sand as a result of the displacement of the surface upon force application. Additional elastic energy may be stored in the series elastic component (SEC; fiber cross-bridges, aponeurosis, tendon) since there is a longer contact time during the eccentric phase, but it is lost during the lengthened amortization phase and this is commonly cited as a main contributor to decreased jump performance on sand [8, 17, 30]. In order to produce adequate propulsive force to complete the task, the concentric phase of the SSC must make a greater contribution to overall force production [8, 23].

Slippage of the foot during the amortization and concentric phases of the SSC results in a longer foot contact time and may in turn result in increased angular velocity during plantar flexion [6, 23, 26]. This may ultimately limit net power production at the ankle and limit jump performance [177]. As an adaptation to the surface change, greater force production may be required of the proximal muscles such as the quadriceps, hamstrings, and gluteal muscles, or force from all lower extremity musculature may be applied in a more vertical direction [9]. The increased EMG activity in the lower extremity musculature during sand activity reported by Pinnington et al. suggests greater recruitment of motor units in stabilizing muscles during activity on sand that occurs in response to the instability of a sand surface [20]. If this increased activity is sustainable with training and transferable to performance on a firmer surface, the increased muscle recruitment may lead to improved performance.

Also, an increase in antagonist muscle activity (i.e., dorsiflexors) may occur to control the increased rate of plantar flexion of the foot. To date, no research has been identified quantifying dorsiflexor activity during movement on sand. However, Richie et al. suggested a surface that allowed greater penetration of the forefoot (carpet over concrete vs. concrete) may result in increased muscle activity of the lower leg in an attempt to control the excessive foot motion compared to that of the lower leg [178]. A decrease in dorsiflexor activity on concrete, as compared to a more absorptive surface (spring-loaded wood floor) was also reported. The
decrease in antagonistic muscle activity may partially account for the improved long jump performance on a hard court after sand training [178].

The exact mechanism responsible for the improvement of the long jump task in the SG is not totally understood at this time. Increased motor unit recruitment and firing frequency occur as a result of training and allow for greater force production prior to onset of muscular hypertrophy. Increased motor unit synchronization will lead to greater ability to produce force, along with an improved efficiency of movement by coordinating motor nerve impulses. Improved inter-muscular coordination is evidenced by greater synergistic muscle activity and less inhibitory activity from antagonistic muscles [35]. Less opposing torque being produced during the movement results in a greater net force. Sand training may increase antagonistic muscle activity in an effort to control slippage of the foot during plantar flexion, which helps to explain the decrease in horizontal take-off velocity, shorter stride length, and decrease in vertical displacement during the flight phase of running [24]. The reduction of this antagonistic activity upon the return to a hard court surface would allow for greater net propulsive force and therefore a greater jump distance. In addition to these potential neuromuscular adaptations, there have been some reported instances in the literature suggesting the improvement in anaerobic capacity may result from an increased lower leg muscle activity necessitated by the unstable surface [6, 20].

There was a significant effect for time in regards to the 300 yd. shuttle. This result does not support our hypothesis, but does indicate the effectiveness of the training intervention and its implementation. Our hypothesis was based on the thought that increased metabolic demand during sand training, and improved concentric force production from lower extremity muscles would result in improved anaerobic performance on a hard court. Alcaraz et al. and Wise both suggest that the kinematic changes that occur while running on sand may be detrimental to firm-surface sprinting, and therefore warn against maximum speed training in sand [24, 33]. However, Impellizzeri et al. proposed that other training methods in sand, such as plyometrics, yield faster sprint times on a firmer surface [8]. Despite the differing duration and energy system contributions seen in these two activities (20 yd. sprint vs. 300 yd. shuttle), both are maximum effort tasks and therefore may be similarly affected by sand training as reported in the studies mentioned above.

The discrepancies in the literature regarding the positive and negative effects of sand training on sprint performance arise from differing training methods, testing populations,
intervention durations, and outcome measures. It is quite possible that our subject population varied too much in terms of physical ability and applied effort for us to identify any significant differences between the groups. No other studies were identified that used the 300 yd. shuttle related to sand training.

Our results demonstrated a significant effect for time for the 5RM squat, as well as a positive change great enough to surpass the MDC threshold. This is an important indicator of true change that occurs outside of the existing measurement error [176]. The stationary nature of the parallel squat and vertical direction of force application may explain why the unstable nature of sand does not appear to come into play as a primary factor affecting strength gains. No external resistance was utilized except some light-weight medicine balls in a few drills. Despite this, subjects in this study significantly improved their 5RM performance. This indicates that the neuromuscular adaptations necessary to improve 5RM squat performance in novice resistance training participants such as increases in motor unit firing frequency, motor unit synchronization, and inter-muscular coordination, may be developed without a heavy training load.

Despite these findings, an alternative possibility should be considered as well. Subjects involved in this study participated in low-level small college intercollegiate athletics. The significant, real-world change in their squat performance may have been a result of their low starting point in terms of overall strength and squat ability. Although many athletes at a variety of competition levels may not be proficient in proper squat mechanics, the primary investigator observed deficiencies in strength, stability, and movement control in some subjects during the familiarization session. Attempts were made to correct these issues, and one subject did not participate in the 5RM testing for safety reasons due to inadequate form. Evidence exists in the literature that untrained individuals are more likely to demonstrate larger strength gains earlier in a training program than more highly trained individuals [9].

Performance of the vertical jump, 40-yd sprint, and T-test did not change significantly from baseline to post-test in either group. In addition, the effect size (partial eta squared ≤ 0.10) and observed power (≤ 0.23) calculations were small for all three variables. These non-significant results could be attributed to the limited sample size, lack of specificity in the training protocol, or insufficient dose-response. Nine sessions over a 4-week period were completed for the purposes of this study. An increase in training volume may have led to more significant improvements. It is important to note that sand training did not result in any significant
decreases in performance for these tasks as compared to the performance of the hard court group.

The training intervention used in this study was not designed to elicit improvement of any one performance outcome, but rather to improve general anaerobic performance across a variety of sport activities. This lack of specificity should not be overlooked in terms of understanding our results. A large portion of the scientific literature related to sand training is made up of studies utilizing highly specific training protocols designed with the goal of improving a specific outcome measure [6-9, 24, 27, 34]. This type of research design often leads to improvement in a particular area of performance, but performance training often only utilizes such specific training interventions during the off-season of a particular sport. Pre-season, in-season and post-season training cycles are not usually geared towards specific performance outcomes, but rather general preparation, maintenance, or recovery of sports skills and sport-specific conditioning.

Yigit and Tuncel investigated the effects of long-distance sand running over six weeks in a group of high school and collegiate male runners [9]. Sand and road runners both exhibited a significant increase in vertical jump performance at posttest compared to the control group. Although the sand training group outperformed the hard court group in vertical jump, the difference was not significant (2.04cm ± 2.36% vs. 1.67cm ± 1.87%). The authors used an alpha level of 0.05 to determine statistical significance. The results of our study were similar to those reported by Yigit and Tuncel. For the vertical jump, the hard court group outperformed the sand group, but the difference between groups was not significant (SG = 1.00 ± 0.06 cm, HG = 2.00 ± 0.04 cm). Our sand subjects demonstrated a 2.5% relative improvement compared to 5.8% in the Yigit and Tuncel [6] study. For the hard surface, the relative improvement from baseline to posttest was similar (5.4% and 5.2%, respectively) in both studies. Yigit and Tuncel proposed that the increased energy demands evident during sand-based activity were responsible for the improvement in muscle hypertrophy and positive trend in jump performance [9]. Despite sharing a common test surface and some similar test variables, these two studies differed in their populations and training protocols and these factors may account for the overall difference in results.

Impellizzeri et al. (7) compared the effects of plyometric training on grass and sand in order to determine the effect of training surface on muscle soreness, and jumping and sprinting ability [8]. They reported a main effect for time for both the 10 m and 20 m sprints, as well as a
group by time interaction effect for the squat jump that approached statistical significance \( p = 0.08 \); stating that performance of these tasks improved as a result of training on both surfaces and the type of training completed. Our results differ from this report in that we did not identify a main effect for time in the vertical jump or the 40-yd sprint. This may have resulted from key differences in design and test populations including number of training sessions, specificity of the training protocol, training state and ability of the subjects and the sprint distances tested. The 10-20 yd. sprint distance is a more refined assessment of power and acceleration than the 40 yd. distance and the different biomotor demands of these two tasks may help to explain why our results are not in agreement. This study also reported significant increases in jump height in both surface training groups [8]. Our findings indicated a non-significant increase in jump height in each group.

Our results indicated no significant change in sprint performance from baseline to post-test in either group. This may have resulted from the relatively small number of subjects, large variances in athletic ability, insufficient duration and/or frequency of training, or lack of sufficient specificity to induce training adaptations. The current view in the literature is that sprint speed in sand will consistently be slower due to the high absorption of force [16], increased energy cost [24], detrimental kinematic changes [24, 33], and loss of elastic energy [5]. As was mentioned previously, the scientific literature is conflicting regarding the effect of sand-based sprint training on firm-surface sprint performance. Further research is necessary to fully understand the kinematic and neuromuscular adaptations that occur during sand training as they pertain to sprint training.

Only one previous study was identified that utilized the T-test as a performance variable in conjunction with sand training [7]. Gortsila et al. (16) reported a significant decrease in T-test time after ten weeks of sand training in pre-pubescent girls \( n=45 \). The intervention included three, 90-minute sessions per week and included volleyball passing drills as well as running and jumping exercises. The study included three groups: sand, indoor (hard court), and control. The results portrayed significant improvements in both training groups, but the sand group improved significantly more. The authors suggested increased exercise intensity on the sand surface as well as a possible improvement in balance after exposure to an unstable surface as possible rationale for their findings [7]. Although the test population here was similar to ours, the training volume and duration were markedly higher. This may explain why our T-test results are not in agreement with those presented here.
The nature and design of the current study resulted in limitations that must be identified. The sand pit utilized for the SG was located outdoors and therefore subject to weather interference. This led to complications in the training schedule and ultimately resulted in completion of only nine of the proposed ten training sessions and inconsistent intervals between training sessions. In order to keep the two groups as evenly matched as possible, the HG was limited to nine sessions as well. The nine sessions were completed over a period of four weeks. This frequency of training may have not provided an adequate training volume to induce additional performance adaptations. Additionally, all nine sessions for each group were not led by the same tester. Two instructors completed the training sessions and all training protocols were reviewed and practiced ahead of time. All data collection at familiarization, baseline, and posttest was completed by the principal investigator. It should be noted that without the presence of a true control group, any training adaptations that occurred could also be attributed to an unknown source.

Athletes from a small-collegiate athletic program demonstrate a wide variety of athletic abilities. The group of volunteer subjects in this study was no different. Specifically, one subject from the HG did not complete pre- or post-testing for the parallel squat since she could not perform the movement safely. This subject did complete testing for all other performance variables and all training sessions.

Variations in personal motivation and the possible differences in energy cost between the two training surfaces made it difficult to control overall training intensity. The heterogeneity of performance outcomes and the relatively small sample size resulted in a large variance, small effect size, and limited power to detect true changes for the variables tested.

PRACTICAL APPLICATIONS

The consideration of effect size, power, and MDC related to each outcome measure included in this study temper the interpretation of the results. Ultimately, the main effect for training identified in the 5RM is the strongest finding. The training protocol led to a significant improvement in 5RM squat performance, regardless of training surface. This finding highlights the effectiveness of the training protocol and indicates that sand training did not directly affect performance of the squat.

The periodized training protocol utilized in this study focused on improving several different biomotor abilities. This exercise program is simply a guideline that can be used for
sand training. Certified strength and conditioning professionals can and should alter their training protocols to maximize the training effect for their specific population and training goals. It is important to note that these benefits occurred after only nine sessions spread out over a 4-week period and were combined with only minimal additional team workout sessions.

Practitioners desiring to train athletes on a sand surface may find it difficult to convince coaching staffs that a new surface will be beneficial to their athletes. It is important to assure them that sand training does not appear to result in a decrease in performance or present an increased risk of injury to healthy athletes that are prepared for intense training. Additionally, benefits of sand training may include reduced muscle soreness after training and improved concentric force production upon return to firm-surface participation. The rate of injury occurrence during sand training appears to be no higher than that seen on a firm surface. As with all training programs, athletes should be properly instructed in form, and supervised to ensure they are continually participating in a safe environment.
CHAPTER 4
EFFECT OF TRAINING SURFACE ON POSTURAL CONTROL OUTCOME MEASURES IN FEMALE ATHLETES

INTRODUCTION

Sand is an unstable, inelastic, and absorptive surface [23, 28-30]. It is composed of a large number of individual, freely movable parts that are repositioned in all planes of motion when stressed, depending on the direction of force application [38]. Sand training does not result in the complete absence of ground reaction forces (GRF), but does attenuate them to a large extent [16, 20, 23]. Sand is not an assistive, elastic surface, but instead an absorptive, dampening surface that requires constant neuromuscular adaptation and additional force output for task completion [40]. These characteristics make it unique compared to other commonly used lower extremity rehabilitative and training tools and surfaces.

Balance training on unstable surfaces is widely used in rehabilitation protocols for the purposes of restoration, as well as in training protocols designed to prevent, lower extremity injury [179]. A variety of tools are commonly used to accomplish this goal [180-183] and as a group, they differ from sand in two key ways. They are often elastic (foam pad) or rigid (balance board) and they are usually uniform in composition. Exceptions include air-filled implements such as the BOSU® ball (Hedstrom Fitness, Ashland, OH) and DynaDiscs® (Exertools, Inc, Petaluma, CA) which allow for more severe multi-directional instability, but are still limited in terms of application to training since they only allow for static or stationary repetitive activities. In contrast, a sand pit or beach area allows for dynamic multi-planar movements over an extended distance, such as sprinting, cutting, repetitive long jumping, and single-leg hopping, as well as stationary training [8, 9, 29].

The body maintains balance by interpreting information from three sources of input: visual, vestibular, and somatosensory [42]. When the surface underfoot changes from rigid to unstable, the somatosensory input becomes less reliable and the body must rely more heavily on visual input [183]. This makes balance a more challenging task and over time the exposure to an unstable surface may potentially result in improved balance on rigid surfaces [51, 179]. Training on sand introduces a variable environment for the body to adapt to while attempting to complete specific, repetitive tasks. When placed in this environment, the body must dynamically adapt to construct a new movement pattern in an attempt to duplicate the
performance previously achieved on a rigid surface [17]. This introduction of error to the movement system will result in the creation of additional movement strategies and may better prepare athletes for dealing with unstable surfaces and unpredictable situations during rehabilitation and athletic competition.

The successful completion of a movement is less dependent on the ability to replicate a particular motor pattern and more reliant on the body’s ability to find a movement solution that achieves the goal while working within the constraints of the surrounding environment [173]. When the environment changes and different movement constraints are placed on the body, new motor patterns emerge [174]. This occurs with the introduction of sand as a training surface as the body attempts to compensate for reduced GRF, level of friction, and surface stability while maintaining the ability to achieve the movement goal.

Female athletes demonstrate a high incidence of lower extremity injury while participating in sports such as soccer, basketball and volleyball [1]. Improvements in postural control have been shown to have a high positive correlation with a reduction in lower extremity injuries [1, 73]. Therefore, it is plausible that improving components of postural control through sand training may reduce the incidence of lower extremity injuries. In addition, although currently unknown, it is possible that individuals with recurring lower extremity injuries such as chronic ankle instability may benefit more from participation in functional training on an unstable surface, such as sand, versus a stable surface and compared to those without history of prior injury.

A single study was identified evaluating the effects of sand training on postural control. Latour et al. reported significant improvements in SEBT performance in a group of sand training subjects compared to those completing the same intervention on a firm surface [95]. Further details were not available since this was a foreign language manuscript. Given the dichotomy of concerns and excitement over this training modality, more research is necessary to support its use. The use of sand training as a performance-improvement medium consists of large quantities of time spent on sand without a high degree of specificity of training related to postural control. A clearer understanding of the potential effects of sand training will guide future rehabilitative or preventive training programming for these athletes and an important step is to understand the degree of training specificity necessary to cause the desired improvements. Therefore, the purpose of this study was to investigate the effect of an anaerobic-based sand training program on specific static and dynamic measures of postural
control and functional range of motion (ROM) of the ankle commonly used in rehabilitation and laboratory settings. We hypothesized that anaerobic, non-specific sports-performance training in sand would result in improved postural control due to the instability of the surface and subsequent increased demands placed on the visual, vestibular, and somatosensory systems.

**Delimitations**

1) Collegiate varsity female athletes.
2) Participation in volleyball, basketball, or soccer.
3) Free of balance disorders or other conditions known to affect postural stability.

**Assumptions**

1) Assumed maximal effort for performance measures.
2) Assumed compliance with request to refrain from additional lower body training outside of team sponsored off-season activities.

**METHODS**

**Experimental Approach to the Problem**

A longitudinal design was used to determine the effect of training surface on ankle functional range of motion (ROM), postural control, and static balance. The independent variable for this study was training surface; sand vs. hard court. The dependent variables were the weight-bearing lunge test (WBLT), star excursion balance test (SEBT) and time-to-boundary (TTB). Subjects were asked to attend 13 sessions (2 d·wk⁻¹) over a seven week period as participants in this study. This included one session each for familiarization, baseline, and post-test, as well as a series of ten 50-minute training sessions.

Training occurred either on a hardwood competition surface or in an outdoor sandpit, depending on group assignment. Group assignment was randomized within each team to make sure that subjects from each sport were evenly stratified between the two training groups. Every effort was made to ensure equity between the two groups in terms of their training volume and exercise selection in order to isolate training surface as the primary variable between the two groups. Both groups were trained by the same individual throughout the study and given similar verbal instruction and encouragement throughout each workout. All subjects were encouraged to work at a maximum effort. A true control group was not used in this study as it was considered detrimental to the subjects for them to abstain from training.
during the off-season. Therefore, the hard court group represented the standard treatment
group and the sand group represented the experimental treatment group. Testing for all
subjects took place on a hardwood competition surface in a climate-controlled gymnasium.

Subjects

A convenience sample composed of 17 female collegiate athletes representing the
sports of volleyball, soccer and basketball volunteered to participate. Their mean age, height,
and body mass were (mean ± SD) 19.53 ± 0.78 yr., 168.05 ± 4.45 cm, and 66.89 ± 11.79 kg,
respectively. A summary of subject demographic data broken down by group assignment is
provided in Table 4.1. All subjects provided written informed consent after a detailed
explanation of the aims, benefits, and risks associated with the study. The study was completed
during the subjects’ off-season with prior approval of the respective coaching staffs. Subjects
were randomly assigned to either the sand training group (SG) (n = 8) or the hardwood training
group (HG) (n = 9) with equal representation of each sport in the two groups. Group assignment
was randomized within each team (volleyball, soccer, basketball) to make sure that subjects
from each sport were evenly dispersed between the two groups. Further randomization by
position was not conducted. The hard court group represented the standard treatment group
and the sand group represented the experimental treatment group. There was no
differentiation by position within a given sport.
All subjects were tested individually, but completed training workouts in a group setting.

Exclusion criteria for this study included: prior history of ACL repair within the past year and/or current enrollment in a rehabilitation program for any lower extremity injury. All subjects were

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sand (n = 8)</th>
<th>Hard Court (n = 9)</th>
<th>p-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>19.56 ± 0.73</td>
<td>19.50 ± 0.93</td>
<td>0.89</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>166.50 ± 4.12</td>
<td>169.79 ± 4.68</td>
<td>0.15</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>63.49 ± 9.92</td>
<td>70.71 ± 13.91</td>
<td>0.25</td>
</tr>
<tr>
<td>Percent Fat (%)</td>
<td>22.40 ± 2.99</td>
<td>24.44 ± 4.76</td>
<td>0.32</td>
</tr>
<tr>
<td>Body Mass Index (kg·m⁻²)</td>
<td>22.75 ± 2.88</td>
<td>24.49 ± 4.70</td>
<td>0.38</td>
</tr>
<tr>
<td>Weight Bearing Lunge Test</td>
<td>8.00 ± 2.14</td>
<td>8.33 ± 2.60</td>
<td>0.93</td>
</tr>
<tr>
<td>Star Excursion Balance Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANT</td>
<td>64.17 ± 4.59</td>
<td>64.76 ± 3.24</td>
<td>0.49</td>
</tr>
<tr>
<td>PM</td>
<td>79.40 ± 9.23</td>
<td>82.83 ± 5.26</td>
<td>0.05</td>
</tr>
<tr>
<td>PL</td>
<td>88.85 ± 6.00</td>
<td>92.28 ± 6.07</td>
<td>0.69</td>
</tr>
<tr>
<td>Time to Boundary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ML MeanMin EO</td>
<td>2.00 ± 0.82</td>
<td>2.06 ± 0.60</td>
<td>0.26</td>
</tr>
<tr>
<td>AP MeanMin EO</td>
<td>5.02 ± 1.98</td>
<td>5.68 ± 1.61</td>
<td>0.46</td>
</tr>
<tr>
<td>ML SD MeanMin EO</td>
<td>1.46 ± 0.67</td>
<td>1.65 ± 0.54</td>
<td>0.44</td>
</tr>
<tr>
<td>AP SD MeanMin EO</td>
<td>3.22 ± 1.39</td>
<td>3.60 ± 1.10</td>
<td>0.43</td>
</tr>
<tr>
<td>ML MeanMin EC</td>
<td>0.73 ± 0.18</td>
<td>0.75 ± 0.17</td>
<td>0.55</td>
</tr>
<tr>
<td>AP MeanMin EC</td>
<td>1.95 ± 0.71</td>
<td>2.06 ± 0.47</td>
<td>0.24</td>
</tr>
<tr>
<td>ML SD MeanMin EC</td>
<td>0.61 ± 0.16</td>
<td>0.65 ± 0.22</td>
<td>0.44</td>
</tr>
<tr>
<td>AP SD MeanMin EC</td>
<td>1.28 ± 0.55</td>
<td>1.35 ± 0.34</td>
<td>0.14</td>
</tr>
</tbody>
</table>

*Significance level set at p < 0.05

yrs=years
cm=centimeter
kg=kilogram
%=percent
kg·m⁻²=kilogram square meter
m=meter
s=second
ANT=Anterior
PM=Posteromedial
PL=Posterolateral
ML=Mediolateral
AP=Anteroposterior
EO=Eyes Open
EC=Eyes Closed
required to be members of their respective varsity athletic teams and have a current sports pre-participation physical on file with the coaching staff per athletic department guidelines. Subjects were asked to abstain from additional lower body resistance training and running while participating in this study. Subjects were permitted to participate in any team-sponsored, sport-specific workouts. During the course of the study, the average time spent participating in team-sponsored workouts was less than three hours per week for all subjects. However, this activity was not monitored and may have varied by team. Approval from the University’s Institutional Review Board was obtained prior to initiation of the study.

**Procedures**

Subjects completed 10 training sessions (2 d·wk⁻¹) over a five week period. Each training session was 50 minutes in duration. Additionally, all subjects were asked to complete a familiarization session, baseline test, and post-test. Training occurred on either a hardwood competition surface or an outdoor sandpit, depending on group assignment. Testing for all subjects took place on a hardwood competition surface in a climate-controlled gymnasium.

The HG completed all training sessions on the test surface. The SG completed all training sessions in an outdoor sand pit that was 24.38 m x 15.24 m (length x width) filled with dry, soft river bed sand to a depth of .46 m. The testing sessions included a weigh-in and measure of height as well as completion of the WBLT, TTB, and SEBT. These tests were completed prior to the anaerobic components in order to prevent fatigue from affecting the outcome of these specific tests. Body mass was measured (to the nearest 0.5 kg) without shoes in light clothing using a digital scale (Detecto, Webb City, MO). Subjects were asked to refrain from eating or drinking for at least one hour before their body mass was measured. Standing height was measured (to the nearest 0.5 cm) without shoes using a stadiometer (Accustat, Genentech Stadiometer, San Francisco, CA). Percent body fat was assessed using a BIA 310 bioimpedance analyzer (Biodynamics, Seattle, WA). The manufacturer’s proprietary equation was used to estimate percent body fat and required the input of the subject’s age, height, body mass, and gender. Subjects were positioned supine and electrodes were placed on the ipsilateral wrist and ankle. Care was taken to insure that the extremities were positioned on the table without contacting the torso or opposite extremity during testing.
Weight-Bearing Lunge Test

This was completed in accordance to the methods described by Bennell et al. [48] All subjects participated in a short training session to familiarize themselves with the test. Marking points were drawn on the tibia 15cm inferior to the tibial tuberosity and bisecting the calcaneus on the heel of the same leg. The tibial mark was the application site for the inclinometer used to measure the angle of the tibia when the ankle is in maximum dorsiflexion. A tape measure was secured to the floor perpendicular to a wall and a vertical line was marked on the wall in line with the tape measure. The subject’s foot was placed on the tape measure, facing the wall so that the great toe and vertical line on the calcaneus were in line with the tape measure and vertical line marked on the wall. They were allowed to place their hands on the wall for support and were instructed to keep the untested foot in a comfortable position on the floor (Figure 4.1). Each subject was given five attempts to achieve maximum dorsiflexion by leaning forward and touching the knee of the involved leg to the wall without lifting the heel (Figure 4.2). The tester lightly held the athlete’s foot during each attempt to properly sense heel lift. The distance between the end of the great toe and the wall was measured along with the angle of the tibia of the tested leg during maximum dorsiflexion. Test/re-test reliability scores (ICC) were .876 and .771 for the left and right sides respectively.

Figure 4.1 Start position of the WBLT.
All subjects completed a modified SEBT as described by Plisky et al. [86]. Each athlete stood on one lower extremity, lining up the most distal aspect of the great toe with the center of the grid laid out with tape on a firm surface (Figure 4.3). Subjects were then instructed to reach in the anterior (ANT) (Figure 4.4), posteromedial (PM) (Figure 4.5), posterolateral (PL) (Figure 4.6) directions while maintaining single-limb balance. Prior to official measurement, four practice trials were conducted on both limbs for each of the three directions. The fifth trial was the test trial and the tester visually identified the most distal point on the grid contacted by the reach foot in each of the three directions. Two additional trials were completed and the mean of the three was calculated and used for data analysis. If any of the following criteria were met during the testing trial, a trial was excluded/omitted and the subject repeated it: 1) athlete was unable to maintain single-leg balance, 2) heel of the stance foot came up off of the floor, 3) weight was shifted onto the reach foot in any of the three directions, 4) reach foot did not return to starting position before attempting to reach in another direction. The process was then repeated while standing on the other leg. In order to score the SEBT, limb length measurements were taken for both limbs. Lower extremity length was measured from the most distal portion of the anterior superior iliac spine to the most distal end of the lateral malleolus. Reach distance was normalized by dividing it by the subject’s lower extremity length and multiplying by 100, which allowed for comparison between subjects [90]. Test/re-test reliability
scores (ICC) were as follows: left ANT (.846), right ANT (.706), left PM (.910), right PM (.872), left PL (.773), and right PL (.543).

Figure 4.3 Start position of the SEBT.

Figure 4.4 Anterior reach of the SEBT.
Figure 4.5 Posteromedial reach of the SEBT.

Figure 4.6 Posterolateral reach of the SEBT.

**Static Postural Control**

For completion of the TTB, subjects were allotted one practice trial before completing three test trials of single-limb stance in two scenarios, eyes open and eyes closed. The length and width of each subject’s foot was measured prior to testing for the purpose of centering the foot on the force plate. Subjects were told that the goal was to stand as still as possible on the stance leg for the duration of each 10 second trial. Subjects were informed of the test position which involved standing on one leg with arms folded across their chest while holding the unininvolved leg at 45° of knee flexion and 30° of hip flexion. A trial was discarded and repeated if
the suspended limb touched down, subjects opened their eyes during an eyes closed trial, or subjects were unable to maintain the appropriate standing posture for the duration of the trial [73]. Time to Boundary variables included the absolute minimum, mean of minimum samples (mean of the minima), and standard deviation SD of minimum samples (SD of the minima) in the mediolateral (ML) and anteroposterior (AP) directions [60]. The mean of three trials was taken for each variable, in each direction, and used for analysis. Time to boundary minima represent the minimum time required for the center of pressure of the foot to reach the boundary of the foot in either the ML or AP direction. The group of minimum values collected is represented by the mean of the minima and estimates the time an individual has to make postural corrections. The SD of the minima represents the variability within all of the minimum values collected during a ten-second trial in either the ML or AP direction. This estimates the variability of an individual’s responses, or the number of different solutions used to maintain postural control in single-limb stance. A higher SD of the minima indicates fewer constraints on the sensorimotor system [60]. Reliability data for the TTB is not available for this study since this measure was only collected on a single occasion. Calculation of TTB variables was based on methods previously described by Hertel and Olmsted-Kramer and computed using a custom MatLab (MathWorks, Natick, MA) code [56].

Training Protocol

Over a period of five weeks, subjects completed nine training sessions that lasted approximately 50 minutes per session. Five minutes were allotted at the beginning of the workout for a dynamic warm-up. Each dynamic exercise was performed over a distance of ten yards, followed by a jog of equal distance. The exercise sessions were completed with a five-minute cool-down session. This included repeating a portion of the dynamic warm-up, followed by a static stretch of all of the major muscle groups in the lower extremity. Each static stretch was completed once and held for 30 seconds. Fifteen to twenty seconds of recovery time was allotted between each exercise and a two-minute water/recovery break was granted between each ten-minute section of the exercise session. Athletes in the SG performed all training activities barefoot, with the option of wearing athletic shoes, if desired, whereas the HG wore athletic shoes of their choice. Subjects were instructed to complete all exercises at a maximum effort level and received verbal encouragement throughout the exercise sessions. The training protocol was broken into two five-session sections. The first five sessions included the exercises listed in
Table 4.2 and the second five workouts included the exercises listed in Table 4.3. Ultimately, all subjects in both groups completed nine workouts. Only four sessions utilizing the intervention listed in Table 4.3 were completed as a result of weather constraints and the need to keep the training schedule identical between the two groups.
Table 4.2 Training Protocol for Sessions 1-5 by Targeted Biomotor Ability.

<table>
<thead>
<tr>
<th>Warm-up</th>
<th>Agility</th>
<th>Muscular Power</th>
<th>Anaerobic Endurance</th>
<th>Cool-down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt kicks/high knees</td>
<td>T-test: 2 trials, with opponent (modified to 6x6 yds.)</td>
<td>Bounding (10yds) 4 trips</td>
<td>Sprint/backpedal repeats: 3 trials of 2 consecutive trips over 10yd distance</td>
<td>Quad walk/hamstring march</td>
</tr>
<tr>
<td>Quad walk/hamstring march</td>
<td>Pro-agility: 2 trials, with opponent</td>
<td>Squat jump w/ standing long jump x10</td>
<td>Medicine ball backwards throw and sprint: 2 trials of 5 reps (3kg ball)</td>
<td>Walking lunge/single-leg swing</td>
</tr>
<tr>
<td>Walking lunges/single leg swing</td>
<td>Ladder drills: 3 trials of hop scotch, lateral scissor, 2 foot diagonal shuffle on 15 ft. ladder</td>
<td>Cycled split squat jump: 2 sets of 10</td>
<td>X sprints: 6 trials (3L, 3R) (10yds, 5 yds, 10yds.)</td>
<td>Knee hug/alternating squats</td>
</tr>
<tr>
<td>Knee hug/alternating squats</td>
<td>Cone drills: 2 trials of front jumps, side jumps (2 L, 2 R), forward weave for 10 ft. (followed by 5yd sprint)</td>
<td>Single-leg hop for speed: 3 trials for 10 yds. with each leg</td>
<td>Modified shuttle: 2 trials (120yds.)</td>
<td>Static hamstring</td>
</tr>
<tr>
<td>Power skips/backpedal</td>
<td></td>
<td></td>
<td></td>
<td>Static quad</td>
</tr>
<tr>
<td>Shuffle L/shuffle R</td>
<td></td>
<td></td>
<td></td>
<td>Static calf</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Static groin</td>
</tr>
</tbody>
</table>
Table 4.3 Training Protocols for Sessions 6-9 by Targeted Biomotor Ability.

<table>
<thead>
<tr>
<th>Warm-up</th>
<th>Agility</th>
<th>Muscular Power</th>
<th>Anaerobic Endurance</th>
<th>Cool-down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt kicks/high knees (stationary) x 30s each</td>
<td>T-test: sprint all directions x 3 trials</td>
<td>Wall/net jumps (max height x 5) 4 sets</td>
<td>Sprint/jump squat x 5 repeats: 2 trials (down/back) 10yd distance</td>
<td>Quad walk/hamstring march</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jump squats (stationary) x 30s</td>
<td>Pro agility: shuffle all directions x 3 trials</td>
<td>Single-leg broad jump 10yds x 2</td>
<td>Medicine ball backwards throw and sprint: 2x5 (5kg ball)</td>
<td>Walking lunge/single-leg swing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jumping jacks x 30s</td>
<td>Ladder drills: 3 trials hop scotch, single-leg diagonal hop, 2 forward/1 back</td>
<td>Cycled split squat jump: 2 sets of 15</td>
<td>Diagonal sprints (2L and 2R) down and back</td>
<td>Hips open/hips closed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plank jacks x 30s</td>
<td>Stationary sprint (foot fires) 3 x 30s</td>
<td>Single-leg hop for speed: 4 trials for 10 yds. with each leg</td>
<td>Modified shuttle (10 yd. distance) one trial w/ 8 trips, one trial w/ 4 trips</td>
<td>Static hamstring</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shadow jump rope (30s B, 15s L, 15s R)</td>
<td></td>
<td></td>
<td></td>
<td>Static quad</td>
</tr>
<tr>
<td>Jog/backpedal x 2 (10yds)</td>
<td></td>
<td></td>
<td></td>
<td>Static calf</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Static groin</td>
</tr>
</tbody>
</table>

Statistical Analysis

Basic descriptive statistics (mean ± standard deviation) were used to describe demographic and outcome variables. The test-retest reliability of the primary performance and balance outcomes were assessed using an intra-class correlation coefficient. A 2 X 2 mixed factor analysis of variance was used to evaluate the effects of the training surface (hard court vs. sand) on balance outcome measures for within (i.e., baseline vs. post-test) and between group comparisons for each of the outcome variables. Paired sample t-tests were used to compare data from the left and right sides for each measure. Since no significant differences were found between sides for any of the variables, mean values were pooled and used for the 2 x 2 ANOVA. Effect sizes (partial eta squared) were interpreted as small (≈ 0.02), medium (≈ 0.13), or large (≈ 0.26). The level of significance was set a priori at p < 0.05 for all analyses.
RESULTS

No significant group interactions were present. A significant main effect for time from baseline to post-test was identified for the WBLT ($p = 0.003$), indicating an increase in distance from the wall and subsequently, ankle dorsiflexion. A large effect size (0.456) and observed power (0.912) were calculated for this main effect.

For the TTB assessments, no significant differences were found in the analysis between any of the variables and calculated effect sizes were low for all variables for main effect for time, and group interactions. Observed power calculations for these data were calculated to be weak ($\leq 0.3$) for all variables, for both time main effects and group*time interactions.

For the SEBT, there were no significant ($p < 0.05$) differences for any of the reach directions between baseline and post-test. Calculated effect sizes were low for all variables and statistical power for these data were calculated to be weak ($\leq 0.3$) for all variables for both the main effect for time and group interactions. Results are summarized in Table 4.4.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Sand Group (n=8)</th>
<th>Hard Court Group (n=9)</th>
<th>p-value</th>
<th>Effect Size**</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEBT (pooled) (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>64.17 ± 4.60</td>
<td>65.08 ± 4.49</td>
<td>64.76 ± 3.24</td>
<td>63.96 ± 3.35</td>
<td>0.95</td>
</tr>
<tr>
<td>Posteromedial</td>
<td>79.40 ± 9.23</td>
<td>80.15 ± 7.60</td>
<td>82.38 ± 5.26</td>
<td>82.70 ± 3.80</td>
<td>0.83</td>
</tr>
<tr>
<td>Posterolateral</td>
<td>88.85 ± 6.00</td>
<td>91.08 ± 4.46</td>
<td>92.28 ± 6.07</td>
<td>91.50 ± 4.09</td>
<td>0.55</td>
</tr>
<tr>
<td>WBLT (pooled) (cm)</td>
<td>8.00 ± 2.14</td>
<td>9.35 ± 1.04</td>
<td>8.33 ± 2.60</td>
<td>9.17 ± 2.33</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>TTB (pooled) EO (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Min. TTBML</td>
<td>2.00 ± 0.82</td>
<td>2.03 ± 0.52</td>
<td>2.06 ± 0.60</td>
<td>2.17 ± 0.76</td>
<td>0.61</td>
</tr>
<tr>
<td>Mean Min. TTBAP</td>
<td>5.02 ± 1.98</td>
<td>5.05 ± 1.52</td>
<td>5.68 ± 1.61</td>
<td>5.67 ± 1.59</td>
<td>0.97</td>
</tr>
<tr>
<td>SD Min. TTBML</td>
<td>1.46 ± 0.67</td>
<td>1.57 ± 0.36</td>
<td>1.65 ± 0.54</td>
<td>1.70 ± 0.66</td>
<td>0.57</td>
</tr>
<tr>
<td>SD Min. TTBAP</td>
<td>3.22 ± 1.39</td>
<td>3.25 ± 0.92</td>
<td>3.60 ± 1.10</td>
<td>3.68 ± 0.93</td>
<td>0.80</td>
</tr>
<tr>
<td>TTB (pooled) EC (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Min. TTBML</td>
<td>0.73 ± 0.17</td>
<td>0.76 ± 0.19</td>
<td>0.75 ± 0.17</td>
<td>0.78 ± 0.13</td>
<td>0.39</td>
</tr>
<tr>
<td>Mean Min. TTBAP</td>
<td>1.95 ± 0.71</td>
<td>2.06 ± 0.56</td>
<td>2.06 ± 0.47</td>
<td>2.17 ± 0.76</td>
<td>0.43</td>
</tr>
<tr>
<td>SD Min. TTBML</td>
<td>0.61 ± 0.16</td>
<td>0.62 ± 0.20</td>
<td>0.65 ± 0.22</td>
<td>0.66 ± 0.14</td>
<td>0.80</td>
</tr>
<tr>
<td>SD Min. TTBAP</td>
<td>1.28 ± 0.55</td>
<td>1.40 ± 0.39</td>
<td>1.35 ± 0.34</td>
<td>1.54 ± 0.55</td>
<td>0.55</td>
</tr>
</tbody>
</table>

SEBT = Star Excursion Balance Test
WBLT = Weight-Bearing Lunge Test
TTB = Time to Boundary, EO=eyes open, EC=eyes closed, TTBML = medial/lateral, TTBAP = anterior/posterior

Mean Min. = Mean of the Minima, SD Min. = Standard Deviation of the Minima
% = percent of leg length
cm = centimeter
s = second

* = significance level set @ p < 0.05
** Partial Eta-Squared
^ Time Main Effect
# Group*Time Interaction
DISCUSSION

The purpose of this study was to investigate the effect of an anaerobic-based sand training program on specific static and dynamic measures of postural control, and functional range of motion (ROM) of the ankle commonly used in rehabilitation and laboratory settings. The results indicate that TTB, SEBT, and WBLT performance was unaffected by sand training. However, there was an overall main effect for time related to the WBLT. We hypothesized that anaerobic sports-performance training in sand would result in improved postural control as a result of the instability of the surface and subsequent increased demands placed on the visual, vestibular, and somatosensory systems. These results did not support our hypothesis and the lack of significant findings related specifically to the sand surface suggests two things. First, use of sand as a training surface while completing an anaerobic-based training program not specifically designed to improve postural control may not lead to significant improvements. Second, sand training does not appear to be detrimental to an individual’s postural control.

The WBLT has limitations, but functional activity does not take place in a non-weight-bearing position, so it is only logical to assess ROM in the same manner that it will be utilized. The WBLT has been established as a simple, inexpensive field test that can be utilized to assess functional, weight-bearing dorsiflexion ROM. The structure of the calf complex and the specific roles of the two muscles involved may necessitate the consideration of using both the WBLT as described by Bennell et al. and the knee extended method described by Munteanu et al [48, 71]. Our results indicate that the WBLT is sensitive to changes induced by completion of an anaerobic-based, weight-bearing exercise protocol, regardless of training surface. These findings are supported by a large effect size (0.46) and observed power of 0.91. This may be attributable to repeated exposure to a dynamic warm-up and static stretch cool-down period that were part of each training session. The baseline to post-test improvement (left = 1.0 cm and right = 1.1 cm) was greater than the smallest real difference, described and reported by Simondson et al. to be 8.3 mm (intra-rater) [75] which indicates real clinical change in the dorsiflexion capability of the subjects and supports the use of this protocol as an effective method for improving passive weight-bearing ankle dorsiflexion. No studies were identified examining the effect of a training intervention on the WBLT. Our results indicate that improvement is attainable with a non-specific anaerobic training program regardless of training surface if training is completed at least two times per week for four weeks.
In addition to serving as a reliable [104, 108] assessment of postural stability, previous literature has suggested the SEBT is sensitive to change caused by various therapeutic interventions [1-4, 92-96]. Gribble et al. reported on the SEBT validity in a 2012 review and stated that evidence exists in the literature to confirm the SEBT as a valid test for the prediction of lower extremity injury, and to identify dynamic balance deficits. They also stated that the SEBT has been found to be influenced by training programs in healthy individuals and those with injuries in the lower extremity [85]. Interventions found to be successful at improving SEBT performance included core stability exercise, cycle-ergometer protocols, rocker board and DynaDisc exercises, and balance and strengthening exercises, but these changes were only accompanied by low to moderate effect sizes [85]. In an effort to determine whether or not more generalized athletic performance training on sand had any effect on postural control, our training intervention was designed with overall athletic performance in mind instead of high specificity for balance training.

The training intervention and differing surfaces had no significant effect on SEBT or TTB performance in healthy subjects, and calculated effect sizes and observed power were low (Table 4.4). In contrast, McKeon et al. reported that four weeks of balance training significantly improved static postural control in subjects with chronic ankle instability (CAI) as assessed by TTB and SEBT [51]. Subjects significantly increased the magnitude of their TTB scores (p < 0.05) (mean of the minima and SD of the minima) in the eyes-closed condition, as well as the posteromedial (p = 0.03) and posterolateral (p = 0.01) SEBT reach distances [51] which indicate greater postural control in a single-limb stance [1]. The exercise intervention consisted of 12 sessions over a four-week period and included exercises specifically designed to challenge dynamic balance and landing in a single-limb stance [51]. The difference in injury status (healthy vs. CAI) between the two studies, in addition to the lower training frequency in the current study (two days per week vs. three), may account for the difference in findings. However, the clearest delineation between the two studies is the difference in postural control training specificity. Our training program was not designed to improve postural control and it appears that this lack of specificity was at least partially responsible for our lack of significant findings.

Additional studies have demonstrated a positive effect of specific protocols that included balance training exercises on postural control outcome measures [3, 4, 47, 110]. Kahle and Gribble reported significant improvements (p < 0.05) in SEBT reach distances (anteromedial, medial, posteromedial) in young, healthy subjects that had completed a six-week (3 sessions per
week) core stability exercise protocol. The authors suggest that specific core strengthening exercises led to a greater ability to maintain balance and an improvement in dynamic postural control in healthy subjects [3]. Valovich-McLeod et al. reported similar results, but utilized an expanded exercise intervention over a six-week period (1.5 hours, 2 sessions per week) in a group of female high school basketball players [4]. The protocol included plyometrics, functional-strengthening, balance, and stability-ball exercises. Significant increases in reach distances (lateral, anteromedial, medial, and posterior) were identified and attributed to the likely increase in neuromuscular control and strength in the lower extremity [4]. Leavey et al. reported significant improvements in SEBT performance across three different groups (proprioceptive training, gluteus medius strengthening, or a combined program), with no significant difference between any of the groups [110]. Forty-eight healthy female college students completed three 20-minute sessions per week for six weeks, except for the control subjects which only completed pre- and post-testing [110]. Within a group of healthy female college-aged subjects, it appears that all three of the training interventions utilized were effective in improving SEBT performance. Perhaps future studies utilizing the same protocols may find differences between groups of individuals with varied training backgrounds or injury histories were included.

Fitzgerald et al. recruited 22 healthy adults and randomly assigned them to either the exergaming or control group. The SEBT was used to assess dynamic postural control prior to initiation of the training protocol and again once it had been completed. Training included 12, 15-minute sessions of a highly specific postural stability training program. They reported that both groups demonstrated significant (p < 0.01) improvements in posteromedial and posterolateral reach distances after completion of their respective interventions and there were no significant differences between the two groups. These results build a strong case regarding the importance of training specificity when seeking to improve postural control through an exercise intervention.

Additional studies have cited a lack of training specificity as a primary factor resulting in non-significant changes in postural control after implementation of a training intervention. Zech et al. assessed changes in SEBT performance in a group of 30 youth field hockey athletes after participation in either a 20-minute, two times per week for 10 weeks training intervention and reported similar increases between the control and intervention group [111]. The authors speculated that the training protocol was not specific enough to effect a change in SEBT.
performance despite the fact that it did lead to significant changes in static balance capability (p < 0.001) [111]. Lindblom et al. also reported a lack of significant findings after examining the effect of a neuromuscular warm-up program in 41 youth female soccer players [112]. Subjects in the intervention group participated in 15-minute warm-up program completed two times per week for 11 weeks which included plyometric, agility, and sprint training. The authors reported that poor subject compliance and a lack of training specificity led to the absence of significant findings [112].

Despite the strong case for specificity of training, some contrasting results have been published. Eisen et al. implemented a four-week balance training protocol in a group of 36 collegiate athletes and reported no significant effects of balance training on SEBT reach distances after completion of the training protocol [47]. Subjects were randomly assigned to one of two training groups, or a control group. The intervention included a single balance task completed on either a rocker board (group 1) or DynaDisc (group 2) three times per week for four weeks. Despite the use of a highly specific exercise aimed at improving postural control, significant changes were not identified. This is likely caused by a lack of training volume, duration, and intensity sufficient to elicit changes in the postural control ability of the subjects. When the pre-test to post-test scores of all three groups were combined and analyzed, a significant (p < 0.05) improvement in overall SEBT performance was identified. This led the authors to suggest that: 1) the balance training intervention used was not sufficient to effect SEBT performance and 2) it is possible that completion of the SEBT once every four weeks may be enough to elicit a training effect [47]. Highly trained athletes may have dynamic balance capability that is developed beyond the point of sensitivity to such a simple intervention. In order to achieve additional improvements in this population, a more advanced training protocol may be necessary.

These studies have developed a framework for future research regarding the design of exercise interventions aimed at improving postural control. Duration of the intervention, along with training frequency, specificity, current postural control capability, and injury status must all be considered in order to affect change. A more encompassing intervention like the one used by Valovich-McLeod et al. [4, 110] may net greater changes due to the multiple aspects of neuromuscular control and strength addressed, but simpler designs that still present sufficient challenge and specificity may also be appropriate [3].
Previous literature has shown that unstable surface training does improve overall balance ability [51, 94], but sand has not been previously studied. The low number of subjects for each group contributed to both the lack of significant findings and the low effect size and power calculations. To the primary authors’ knowledge, this is the first study to assess the effect of training surface on the postural stability variables included in this study. Future research should utilize a larger sample size to provide greater statistical power for select outcome variables. In addition, the training protocol utilized as the intervention must address some specific factors. First, it should include specific exercises targeted at training postural stability. Second, the training frequency should be increased in an attempt to maximize the positive effects of the intervention. Finally, an effort should be made to determine the difference in response to postural control training between those with prior history of injury and those without.

As with any study, certain limitations existed within the design of this study. First, pre-screening subjects for FMS DS performance would have allowed us to achieve equal numbers in each of the three scoring stratifications. Second, subjects were not pre-screened for body mass index or physical activity level. These traits have been shown to affect the composite score of the FMS and may have affected their DS performance. Finally, athletes were only screened for current injury or previous serious injuries such as ACL tears. However, previous research has suggested that other previous injuries such as recurrent ankle sprains, may affect FMS performance.

In conclusion, the purpose of this study was not to assess the effect of a highly specific training protocol, carried out on a sand surface, on postural control. Instead, it was to determine whether or not healthy female athletes participating in common anaerobic training exercises on sand would demonstrate an added effect of improved postural control due to the unique properties of a sand surface and the subsequent increased demands on the visual, vestibular, and somatosensory systems. Our results point to the necessity of training specificity for the improvement of postural control. Future research should evaluate the effectiveness of a highly specific, sand-based protocol designed to improve postural control in at-risk subjects and those that participate in activities with higher lower-extremity injury rates.

**PRACTICAL APPLICATIONS**

The training protocol led to a significant improvement in WBLT performance, regardless of training surface. This finding highlights the effectiveness of the training protocol and
indicates that sand training did not directly affect performance of the WBLT. This finding, in conjunction with the previously reported finding regarding the 5RM squat suggests a link between WBLT performance and the squat movement. Our findings support previous research establishing a connection between dorsiflexion and the ability to correctly perform a squat.

General athletic performance training on sand appears to lack the specificity necessary to improve static and dynamic postural control. Given the established relationship between postural control and risk of injury, practitioners and coaches should create and implement training programs that include tasks specifically designed to improve postural control, with the goal of reducing the likelihood of future injury. At this time it is unknown whether or not sand training, coupled with training specific to postural control, will lead to greater improvements compared to those known to occur on more traditional training and rehabilitative surfaces.

Future training protocols implemented to determine the effect of sand training on postural control should include exercises with a higher degree of specificity. Focus should be on single limb activities including hopping, jumping, and landing. Additional single-limb exercises may include the single-leg squat, dynamic balance exercises such as single-limb balance coupled with a secondary task, and static balance training.
CHAPTER 5

EFFECT OF PERFORMANCE STRATA OF THE FUNCTIONAL MOVEMENT SCREEN DEEP SQUAT EXERCISE ON MEASURES OF POSTURAL CONTROL AND FUNCTIONAL ANKLE RANGE OF MOTION

INTRODUCTION

The Functional Movement Screen (FMS) is an evaluation tool commonly utilized by coaches, clinicians, and strength and conditioning professionals to assess the ability of an individual to perform functional movement tasks and possibly predict injury occurrence and athletic performance [13, 125, 128, 162, 165-167, 184]. It was designed to serve as a bridge between pre-participation exams and performance tests by evaluating individuals in a low-intensity, dynamic, and functional capacity [13]. The FMS was intended to be employed as part of a battery of tests with the overarching goal of achieving a complete evaluation of an individual’s physical health, ability, and readiness for more advanced physical activity [13].

A minimalistic field tests able to identify injury-prone individuals early on and provide foundational information for the construction of a targeted corrective exercise technique aimed at improving functional movement and reducing injury risk would be an invaluable tool for coaches and practitioners. The deep squat (DS), often referred to as the overhead squat outside the context of the FMS, is a bipedal, stationary exercise that involves the entire kinetic chain and is unique within the seven movement components that make up the FMS. It has been reviewed independent of the FMS in previous literature and may be used as a stand-alone assessment of functional range of motion, symmetry of movement, balance, pain-free motion [141], and injury likelihood [161].

The FMS consists of seven movement components including: deep squat (DS), hurdle step (HS), in-line lunge (ILL), active straight leg raise (ASLR), shoulder mobility test (SMT), rotary stability test (RST), and push-up test (PUT). The composite FMS score (7 components x maximum score of 3 = 21) has been shown to be a reliable assessment tool [144, 146, 150]. However, it is may be insensitive to changes in score of individual components, meaning an individual may improve on some components, while performing worse on others and receive the same composite score.

For individual FMS components, the inter-session reliability is varied over a broad range. Onate et al. reported inter-rater kappa scores ranging from 0.16 (HS) to 1.00 (RST) [150]. The
lack of consistency within some of the components may indicate the subjective nature of portions of the scoring criteria and provide evidence indicating that outside influences such as experience with the FMS or background in other movement assessments may influence the consistency of an observer. Further confounding the conversation regarding the effectiveness of the scoring system, Kazman published results indicating disproportionately high numbers of subjects scoring a two on the RST (87%), HS (84%), and DS (63%) which potentially indicates a bias towards this particular score [127]. The FMS creators encourage assigning a score of two if there is any thought on the behalf of the tester that the movement does not meet all criteria for a score of a three, and a score of one is only assigned if a subject is unable to complete the task [13, 14]. By default, this results in an inordinately large number of individuals being scored a two, and may result in inconsistency in scores between sessions.

Little evidence is available in the literature regarding the individual components of the FMS and underlying factors causing movement deficiency or asymmetry. It is intuitive that ankle dorsiflexion, lateral hip and core strength, and dynamic balance would be key determinants of performance for the DS. Dorsiflexion ROM has been linked to performance on the SEBT ANT reach and WBLT [48, 60] as well as overhead squat performance [10, 12, 141]. Postural and neuromuscular control and strength of the hip and core musculature have been cited as potential factors related to injury of the lower extremity [120, 185, 186]. Establishing relationships between these performance measures and classification within individual FMS components may provide clinicians with additional evidence to create targeted therapeutic interventions aimed at improving movement ability.

Although some evidence is now available in the literature providing insight into factors that contribute to the performance of the DS, questions still remain regarding specific, quantitative differences between the general FMS scoring categories. Scoring an individual as a one, two, or three is based on qualitative scoring criteria set by the creators of the FMS. There remains a need for quantitative evidence to help determine specific factors leading to either movement completion with a compensation, or inability to complete the movement at all. Therefore, the primary purpose of this study was to determine whether differences exist in clinical measures of functional range of motion (WBLT), postural control (SEBT), and core muscle capability (LFT) between FMS DS stratifications. A secondary purpose was to establish values for the inter-session reliability of all assessments conducted. It was hypothesized that individuals receiving the highest scores on the DS would also perform best on the SEBT, WBLT, and LFT.
Delimitations

The study was delimited to the following:

1) College students officially enrolled at participating institutions
2) Subjects were 18-25 years of age.

Assumptions

The following were assumptions of the present study:

1) Assumed maximal effort where appropriate during the testing protocol
2) Assumed honest reporting of pain if present during FMS movements

METHODS

Experimental Approach to the Problem

A cross-sectional descriptive comparison of clinical measures of performance was conducted to assess whether differences existed in clinical measures of functional range of motion (WBLT), postural control (SEBT), and core muscle capability (LFT) across FMS DS stratifications. A test-retest design was used to calculate the inter-session reliability of the DS of the FMS as well as the SEBT, WBLT, and LFT.

Subjects attended two identical testing sessions. Each session included completion of the DS along with the clinical measures mentioned previously (SEBT, WBLT, LFT). The second session was completed on a separate day for the purpose of a reliability assessment. Subjects were scored individually on the DS and stratified according to their score. During the first session, body mass was measured (to the nearest 0.5 kg) using a digital scale (Detecto, Webb City, MO) and standing height was measured (to the nearest 0.5 cm) using a stadiometer (Accustat, Genentech Stadiometer, San Francisco, CA). The following assessments have been established as reliable field tests to assess these specific attributes [116, 118, 187, 188].

Subjects

A sample of convenience (N = 101) of 61 female and 40 male healthy college students aged 18-25 years (mean ± SD; age = 20.00 ± 1.7 years, height = 170.43 ± 10.48 cm, mass = 70.64 ± 14.66 kg) volunteered to participate in this study (Table 1). Potential volunteers were excluded if they presented with prior history of anterior cruciate ligament repair within the past year and/or current enrollment in a rehabilitation program for any lower extremity injury, known condition affecting vestibular function or balance, or any musculoskeletal condition that
is known to affect the lower extremity. A score of zero on any of the included components of the FMS resulted in disqualification of a subject from further participation. All subjects provided written informed consent after a detailed explanation was provided about the aims, benefits, and risks associated with the investigation. University Institutional Review Board (IRB) approval was obtained for this study. Written informed consent was obtained for all participants after each subject was fully informed of the procedures and associated risks of participation in the study. All instruction and information regarding the study was provided by the primary investigator.

**Procedures**

**Weight-Bearing Lunge Test**

This test was completed in accordance to the methods described by Bennell et al. [48]. All subjects participated in a short training session to familiarize themselves with the test. Marking points were drawn on the tibia 15cm inferior to the tibial tuberosity and bisecting the calcaneus on the heel of the same leg. The tibial mark was the application site for the inclinometer used to measure the angle of the tibia when the ankle is in maximum dorsiflexion. A tape measure was secured to the floor perpendicular to a wall and a vertical line was marked on the wall in line with the tape measure. The subject’s foot was placed on the tape measure, facing the wall so that the great toe and vertical line on the calcaneus were in line with the tape measure and vertical line marked on the wall. They were allowed to place their hands on the wall for support and were instructed to keep the untested foot in a comfortable position on the floor (Figure 5.1). Each athlete was given five attempts to achieve maximum dorsiflexion by leaning forward and touching the knee of the involved leg to the wall without lifting the heel (Figure 5.2). The tester lightly held the athlete’s foot during each attempt to properly sense heel lift. The distance between the end of the great toe and the wall was measured along with the angle of the tibia of the tested leg during maximum dorsiflexion [48]. Inter-session reliability was calculated to be 0.982 (ICC).
Right and Left Lateral Flexion Tests

The lateral flexion test was chosen as a measure of core muscle capability for two reasons: 1) ease of setup and assessment 2) high reliability [116, 118]. Subjects were allowed a brief familiarization session before completion of this test. The test was conducted as described by Keogh et al [120]. Subjects assumed a lateral plank position with the supporting arm flexed 90-degrees at the elbow and positioned directly under the shoulder. The top foot was positioned directly in front of the bottom foot and both the hips and knees were fully extended. Subjects were allowed to start when they were comfortable and ready. The examiner started the timer when the subject elevated their hips so that their shoulders, hips, knees, and ankles
were in a straight line. The test was considered complete when the subject could no longer maintain the lateral plank position. This test focuses on the endurance and functionality of the lateral hip and core, and hip abductor strength is relevant to all three components of the FMS included in this study. This test was measured on a continuous scale, which is true for the SEBT and WBLT as well. Inter-session reliability for the left and right WBLT were 0.948 and 0.896 (ICC) respectively.

**Star Excursion Balance Test**

All subjects completed a modified SEBT as described by Plisky et al [187]. Each athlete stood on one lower extremity, lining up the most distal aspect of the great toe with the center of the grid (Figure 5.3). Athletes were then instructed to reach in the anterior (ANT) (Figure 5.4), posteromedial (PM) (Figure 5.5) and posterolateral (PL) (Figure 5.6) directions while maintaining their single-limb balance. Prior to official measurement, four practice trials [73] were conducted on both limbs for each of the three directions. The fifth trial was the test trial and the tester visually identified the most distal point on the grid contacted by the reach foot in each of the three directions. Two additional trials were completed and the mean of the three was calculated and used for data analysis. Any test trial was thrown out and repeated if any of the following criteria were met: 1) athlete was unable to maintain single-leg balance 2) heel of the stance foot came up off of the floor 3) weight was shifted onto the reach foot in any of the three directions 4) reach foot did not return to starting position before attempting to reach in another direction. The process was then repeated while standing on the other leg. Subjects completed the test with both lower extremities. In order to calculate a normalized score for the SEBT, limb length measurements were taken for each limb during the initial testing session. Lower extremity length was measured from the most distal portion of the anterior superior iliac spine to the most distal end of the lateral malleolus and this. Inter-session reliability for the anterior, posteromedial, and posterolateral reach distances was calculated to be 0.931, 0.826, and 0.899 respectively.
Figure 5.3  Start position of the SEBT.

Figure 5.4  Anterior reach of the SEBT.
Cook et al. described administration of the assessment and the primary investigator for this study followed their methods [13, 14]. The DS begins with a subject positioned with feet approximately shoulder width apart and facing straight ahead. The subject then positions their hands on a dowel with a wide grip, holding it above their head with palms facing forward. The arms are then fully extended in an effort to raise the dowel as high overhead as possible. Then, while holding the dowel in position, the subject is instructed to descend into a squat position. Correct squat position, given a score of 3, includes the heels remaining on the floor, head and chest facing forward, and the dowel remaining fully pressed overhead (Figure 5.7). If the subject cannot perform the squat properly, the plastic beam included in the FMS kit (152cm x 13.3cm x 4.2cm) is placed under their heels and the movement is repeated. This serves as a
compensatory tool and if the subject is subsequently able to perform the movement correctly with the compensation, a score of two is given (Figures 5.8, 5.9). If they remain pain free, but unable to complete the squat with the compensation, a score of one is given (Figure 5.10, 5.11) [13]. Inter-session reliability, as calculated using the Kappa statistic, was 0.445.

Figure 5.7 Side View: FMS Deep Squat Score of 3

Figure 5.8 Front View: FMS Deep Squat Score of 2
Figure 5.9  Side View: FMS Deep Squat Score of 2.

Figure 5.10  Front View: FMS Deep Squat Score of 1.
The primary investigator attained the FMS Professional, level I certification prior to the start of data collection. The FMS consists of seven movement tasks. However, only the DS was included in this study and a single bi-pedal trial was collected. This included up to three repetitions. A score of zero would have been recorded if the subject experienced pain during any of the movements. However, no subjects reported pain at any point during data collection. The Kappa score for the test/re-test measure of agreement of the DS was 0.445 (moderate). Kappa scores were interpreted using the criteria presented by Viera and Garrett [189].

**Statistical Analysis**

Basic descriptive statistics (mean ± standard deviation) were used to describe subject demographics and outcome measures of the SEBT, WBLT and LFT. The test-retest reliability of all measured variables will be determined by either an ICC (continuous variables) or Kappa score (ordinal variables). One-way analysis of variance was used to compare the mean values of each clinical measure across FMS DS strata (1 vs. 2. vs. 3). Data for the SEBT, and WBLT left and right side trials were pooled since no significant differences (p > 0.05) were identified between sides using paired-samples t-tests. Lateral Flexion Test values were found to be significantly different (p = 0.008) and therefore were not pooled prior to further analysis. For the SEBT, leg length was normalized by dividing the reach distance by limb length and multiplying by 100 [86]. The level of significance was set a priori at p < 0.05. Effect sizes were interpreted as small (≈ 0.02),
A Pearson Product-Moment Correlation was used to determine the relationship between the WBLT and ANT reach of the SEBT. All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) Version 20 (IBM Corporation, Armonk, NY).

**RESULTS**

The primary findings included significant differences (p < 0.05) between DS scores of one versus two, and one versus three for the pooled SEBT ANT reach distance and pooled WBLT distances, with lower SEBT and WBLT scores resulting in lower DS scores. These two variables were strongly correlated (r = 0.67, R² = 0.45, p < .01). This indicates a strong positive relationship between these two assessments.

Additionally, a significant difference was identified between the FMS DS score group of one versus three (p = 0.009) for the right LFT, with no significant differences identified between groups for the left LFT. A near-significant (p = 0.05) difference was identified between scores of one and two. This represents a trend towards these two groups presenting with significantly different LFT hold times. Using a paired samples t-test it was determined that the left and right LFT hold times were significantly (p = 0.008) different. This difference represents an asymmetry in lateral core muscle capability between the right and left sides. The differences between scoring groups of the FMS DS for the measures of postural control can be found in Table 5.1.

Descriptive statistics of these variables separated by FMS DS stratification are presented in Table 5.2.

**Table 5.1 Differences Between Deep Squat Scoring Groups for Measures of Postural Control**

<table>
<thead>
<tr>
<th>Score Comparison</th>
<th>ANT</th>
<th>PM</th>
<th>PL</th>
<th>Pool WBLT</th>
<th>LFT Right</th>
<th>LFT Left</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 vs. 2</td>
<td>0.577</td>
<td>0.958</td>
<td>0.416</td>
<td>0.997</td>
<td>0.050</td>
<td>0.127</td>
</tr>
<tr>
<td>1 vs. 3</td>
<td>&lt;0.001*</td>
<td>0.758</td>
<td>0.056</td>
<td>0.001*</td>
<td>0.009*</td>
<td>0.086</td>
</tr>
<tr>
<td>2 vs. 3</td>
<td>0.001*</td>
<td>0.829</td>
<td>0.270</td>
<td>&lt;0.001*</td>
<td>0.209</td>
<td>0.573</td>
</tr>
</tbody>
</table>

* Significant at p < 0.05

SEBT = Star Excursion Balance Test

ANT = Anterior

PM = Posteromedial

PL = Posterolateral

WBLT = Weight-Bearing Lunge Test

LFT = Lateral Flexion Test
DISCUSSION

The primary purpose of this study was to determine whether differences exist in clinical measures of functional ROM (WBLT), postural control (SEBT), and core muscle capability (LFT) between FMS DS stratifications. A secondary purpose was to establish values for the inter-session reliability of all assessments conducted. We hypothesized that individuals receiving the highest scores on the DS would also perform best on the SEBT, WBLT, and LFT.

Our primary findings included significant differences (p < 0.05) between DS scores of one versus two, and one versus three for the pooled SEBT ANT reach distance and pooled WBLT distances. These two variables were strongly correlated ($r = 0.67, r^2 = 0.45, p < .01$), which indicates a strong positive relationship between these two assessments. This is in agreement with Hoch et al. who reported a similar relationship ($r=0.59, r^2=0.34, p=0.006$) [15].

A secondary finding, which provides additional insight into mechanisms affecting DS performance, was a significant difference between the FMS DS score group of one versus three for the right LFT, but not the left. Also, the results demonstrated a trend towards a significant difference between scores of one and two, and the left and right scores were significantly different. This difference represents an asymmetry in lateral core muscle capability between the right and left sides which, compounded with the dorsiflexion differences identified between

### Table 5.2 Descriptive Statistics of Stability and Mobility Measures by Deep Squat Stratification

<table>
<thead>
<tr>
<th>Variable</th>
<th>Poor (n=29)</th>
<th>Modification (n=51)</th>
<th>Perfect (n=29)</th>
<th>Effect*</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEBT (pooled) (%)</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Mean ± SD</td>
<td>Effect*</td>
<td>Power</td>
</tr>
<tr>
<td>ANT</td>
<td>59.67 ± 4.72</td>
<td>60.96 ± 5.03</td>
<td>65.74 ± 4.20</td>
<td>0.17</td>
<td>0.98</td>
</tr>
<tr>
<td>PM</td>
<td>84.03 ± 12.40</td>
<td>84.87 ± 10.93</td>
<td>86.61 ± 10.69</td>
<td>0.01</td>
<td>0.10</td>
</tr>
<tr>
<td>PL</td>
<td>89.26 ± 6.92</td>
<td>92.05 ± 8.75</td>
<td>95.47 ± 8.05</td>
<td>0.06</td>
<td>0.57</td>
</tr>
<tr>
<td>WBLT (pooled) (cm)</td>
<td>10.27 ± 3.00</td>
<td>10.34 ± 3.24</td>
<td>14.04 ± 2.67</td>
<td>0.20</td>
<td>1.00</td>
</tr>
<tr>
<td>LFT (s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>79.10 ± 33.70</td>
<td>94.25 ± 42.42</td>
<td>99.81 ± 31.70</td>
<td>0.03</td>
<td>0.35</td>
</tr>
<tr>
<td>Right</td>
<td>67.71 ± 31.29</td>
<td>86.97 ± 38.00</td>
<td>99.26 ± 44.74</td>
<td>0.07</td>
<td>0.66</td>
</tr>
</tbody>
</table>

*Effect Size: Partial Eta Squared
SEBT: Star Excursion Balance Test
WBLT: Weight-Bearing Lunge Test
LFT: Lateral Flexion Test
% = percent of leg length
cm = centimeters
s = seconds
scores indicates two particular factors affecting DS capability. Available functional dorsiflexion appears to be a primary factor that delineates between scores of two and three. When core muscle capability asymmetry is also present, it appears that this combination is likely to result in a score of one on the DS.

Restricted mobility at one joint will inevitably lead to compensatory movements at other joints along the kinetic chain [141]. These compensations, if not identified and corrected, often lead to injury or develop into long-term loss of functional movement capability [141]. Dorsiflexion has been linked to squat performance by previous authors [10, 12, 141] and our primary findings indicate that limited dorsiflexion is an important factor in determining functional movement capability for the DS. Subjects scoring one or two on the DS demonstrated a significantly lower amount of dorsiflexion compared to those scoring a three as measured by the ANT reach of the SEBT and the WBLT. In support of these findings Hoch et al. reported that subjects with a history of CAI demonstrated limited dorsiflexion compared to healthy subjects [15]. These findings indicate that adequate distal mobility at the ankle is necessary for completion of the DS without compensatory motion and history of previous injury may increase the likelihood of an individual demonstrating poor performance on the DS. These findings provide concrete rationale for the correction of any movement deficiencies prior to increased participation in physical activity in an effort to prevent injury.

In an effort to better understand the relationship between dorsiflexion and the different scoring clarifications of the DS, Butler et al. published a paper involving 28 subjects recruited based on their DS performance, and used three-dimensional motion analysis to gather kinematic data [10]. Potential subjects were pre-screened and assigned to one of three scoring groups based on their performance. The results demonstrated that peak dorsiflexion excursion was significantly greater ($p < 0.03$) in subjects that scored a three compared to those that scored a one [10]. These results indicate that there are specific differences in joint kinematics between the three scoring groups as applied to the DS and are in alignment with our findings regarding the effect of dorsiflexion on DS stratification.

Our results indicate that the presence of a proximal stability asymmetry will likely affect DS performance. In the case of our study, movement asymmetry is suggested as a primary cause of impaired functional movement. Plisky et al. reported that asymmetry within the ANT reach of the SEBT (4cm difference between left and right) indicated an increased likelihood of injury to the lower extremity of two and a half times those not crossing that threshold [86].
Limited range of motion and lower extremity strength were linked to the decreased ANT reach distance. The proposed increased risk of injury in those with asymmetries in postural control provides further support for the results we found related to asymmetry of core muscle capability. Once identified, these imbalances should be addressed in an effort to be proactive regarding an individual’s potential risk of future injury; whether the imbalance is related to functional movement or postural control.

Our results establish a connection between DS performance and core muscle capability. However, results refuting this link are present in the current literature. Okada et al. reported some significant relationships between athletic performance tests and FMS performance [167]. However, they did not identify any significant relationships between core stability and FMS performance, which the authors themselves described as odd since core stability is hypothesized to be important for the completion of many of the FMS movement tasks [167]. The kinetic chain model operates within a framework that supposes a link between proximal stability and distal mobility, which allows for proper stabilization, transfer of power and positioning of the extremities [10]. The dorsiflexion limitation evident in subjects scoring below three on the DS indicates a loss of distal mobility. Our results indicate the presence of an additional factor that may help differentiate between these scoring categories and was identified as an asymmetry in the hold times of the LFT between the left and right sides in those subjects who scored a one on the DS. The right side was significantly different from the left (1 vs. 2, p = 0.05; 1 vs. 3 p = 0.009), but this asymmetry was not present between scores of two and three. This imbalance in proximal stability appears to be an additional determining factor for DS performance.

It should be noted that other variables not included in this study may contributed to the variations between FMS DS scoring groups. Further research is indicated here to determine what other variables may play a role in determining an individual’s ability to complete the DS. Childhood obesity is a growing concern and its relationship to FMS performance, along with physical activity levels was evaluated by Duncan and Stanley [138]. The primary finding of this study was a significant (p = 0.0001) negative correlation (r = -0.806) between BMI and FMS score and a significant (r = 0.301) moderate positive relationship between physical activity and FMS score [138]. The authors also reported that BMI (52.9%) and physical activity (7.3%), defined by average steps per day, combine to predict 60.2% of the variability in FMS score in this population [138].
Duncan et al. published further results related to the effects of overweight and obesity status on FMS score involving a group of British primary school children [169]. In support of their previous findings, they reported a significant (p = 0.0001), strong negative correlation (r = -0.572) between BMI and FMS score. Additionally, FMS scores were significantly higher in normal weight children compared to overweight and obese children as well as being higher in overweight children compared to obese [169]. No significant difference was identified between boys and girls for the FMS composite score.

A study of military personnel identified additional factors that may play a role in determining FMS performance. Percent fat (r = -0.26) and waist circumference (r = -0.21), were found to be mildly correlated with FMS performance [170]. These results expand the findings of Duncan et al. [169] and Duncan and Stanley [138] related to the negative effect of excess body weight on FMS score. The authors also reported that upper extremity static strength (r = 0.193), flexibility (r = 0.34), and time spent sitting (r = -0.098) were all mildly correlated to FMS performance [170]. These findings all support participation in physical activity as a method to improve FMS score and indicate that factors other than dorsiflexion and core muscle capability affect performance. However, they do not diminish our findings as they do not relate to any specific FMS components, but rather the composite score. These anthropometric and upper extremity strength measures may prove to affect specific FMS components in different ways.

Advanced knowledge of the FMS scoring criteria has been proposed as a factor that may affect the outcome and is not related to functional movement limitations present in an individual. Frost et al. evaluated FMS performance of 21 firefighters on two separate occasions [130]. A standardized script was used for both assessments and no coaching or feedback was provided during assessment, but before the second test session subjects were made aware of the scoring criteria for each of the FMS components. Subjects demonstrated a significant (p < 0.001) improvement in FMS composite score (14.1 ± 1.8 to 16.7 ± 1.9) after receiving instruction [130]. Additionally, there were significant (p < 0.05) improvements in the deep squat (1.4 ± 0.7 to 2.0 ± 0.6) [130]. The authors express concern regarding the apparent effect knowledge of the scoring criteria has on the reproducibility of the FMS and its individual components. Furthermore, they question whether or not the FMS is fully capable of identifying dysfunction since scores were significantly affected by other factors in this study [130]. Our subjects were not provided with advanced knowledge of the DS scoring criteria, but these results indicate the importance of conducting an unbiased FMS and also raise the question of whether or not
subjects may improve their DS performance simply by being made aware of the requirements for the various scoring categories.

In order to address some of these issues raised regarding the simplistic nature of the current FMS scoring system, modifications have been suggested by multiple authors in an effort to provide additional detail about movement quality and deficiencies within the individual FMS components \([127, 131, 133, 153]\). They vary in design, but share a common theme of subdividing each movement component into multiple parts and scoring each one individually, thus providing further diagnostic information that may be useful in the creation of a corrective exercise protocol. These scoring systems require additional research to determine their reliability and efficacy, but hold some promise as they provide more detailed information compared to the original system. The utility and clinical relevance of the FMS scoring system has not been fully vetted in the literature.

Our data suggest that evaluation of the DS may provide valuable insight into the underlying causes of dysfunctional or asymmetrical movement patterns. This information may be used to create corrective exercise programs aimed at reducing improving movement patterns and restoring the stability/mobility relationship. Further research is necessary to determine whether or not there is a predictive value for injury or athletic performance within the individual components of the FMS.

The original goal for the current study was to have three balanced groups of roughly 30 subjects each. However, the subjects did not distribute evenly between the three possible groups. This was an expected result due to the broad scoring criteria for a score of two on the FMS DS and the relatively narrow criteria for scores of one and three, and has been the case in previous FMS studies \([125]\). Prospective volunteers were not screened to determine their ability on the DS prior to participation in the study. The nature of the FMS scoring system results in a large number of individuals scoring a two and our study was no different. Future studies may include an FMS pre-screening in order to achieve equal numbers of subjects in each scoring group. The current study only excluded individuals dealing with recent or current lower extremity musculoskeletal injury. Individuals with chronic ankle instability or other chronic issues affecting their lower extremity were not actively excluded and their presence may have affected results.

Based on our results, it appears that limited distal mobility will result in use of a compensatory strategy to complete the DS, and a combination of limited distal mobility and
asymmetrical proximal stability results in an individual being unable to complete the movement at all. Those individuals scoring a two exhibit adequate neuromuscular control and proximal stability that allows them to correctly complete the DS movement once the mobility limitation is addressed, which in this case is accomplished with a heel lift. However, those scoring a one remain unable to complete the motion, even with compensation and it appears that this inability may result from an imbalance in proximal stability represented by the asymmetry in LFT performance.

Future research is needed to address similar questions regarding factors contributing to performance of the remaining FMS components, as well as identifying other components that may contribute to the DS. The current scoring system does help identify asymmetry and/or deficiency, but it does not point directly to any particular causes. Quantitative data providing insight into specific limitations in muscle strength and endurance, joint mobility, postural control, and others will allow for the creation and implementation of targeted, efficient corrective exercise interventions. Also, further investigation into newly proposed modified FMS scoring systems will establish whether or not they assist in providing further diagnostic and predictive information that may allow for additional specificity in corrective exercise programs or help in further identifying individuals likely to suffer injury in the future.

PRACTICAL APPLICATIONS

Our results provide further evidence to support the established connection between dorsiflexion and squat performance, as well as the relationship between the WBLT and SEBT ANT reach. Specifically, they indicate that decreased performance on the WBLT (< 10cm) and SEBT ANT reach (< 61% of leg length) tended to result in FMS DS stratification at a score of two. Asymmetrical performance on the LFT (right/left difference greater than 8 seconds) coupled with limited WBLT performance, tended to result in FMS DS stratification at a score of one. These results, combined with our previous findings related to WBLT and 5RM squat performance after a period of sand training indicate that WBLT performance may be improved with general athletic performance training and this may in turn result in improved squat performance as measured by the FMS DS. Further research is indicated to determine the best approach for reduction of the LFT asymmetry identified here.

Establishing specific causes for movement deficiencies within the kinetic chain may provide useful information for the design and implementation of targeted corrective exercise
plans aimed at improving proximal stability and distal mobility. Based on the data presented here, coaches and practitioners should address core muscle asymmetry in an attempt to improve DS performance in individuals that exhibit an inability to complete the movement. For those able to complete the movement successfully with the assistance of the compensatory strategy, exercise interventions should be targeted at improving ankle mobility. Potential strategies may include soft tissue stretching, joint capsule mobilization, or referral for correction of skeletal issues such as bone spurs for ankle mobility, and functional core strengthening programs to address the asymmetry.
Summary:

The primary purpose of this dissertation was two-fold. First, to examine the effect of a novel training surface on athletic performance, postural control, and functional ankle range of motion outcomes to determine what, if any, positive or negative adaptations occurred. Second, we set out to determine the effect of stratification by subjects’ performance on postural control and functional range of motion measures using the scoring categories of the FMS DS.

Our results provide further evidence to support the established connection between dorsiflexion and squat performance, as well as the relationship between the WBLT and SEBT ANT reach. Specifically, they indicate that decreased performance on the WBLT (< 10cm) and SEBT ANT reach (< 61% of leg length) result in FMS DS stratification at a score of two. Asymmetrical performance on the LFT (right/left difference greater than 8 seconds) coupled with limited WBLT performance, results in FMS DS stratification at a score of one. These results, combined with our previous findings related to WBLT and 5RM squat performance after a period of sand training indicate that WBLT performance may be improved with general athletic performance training and this may in turn result in improved squat performance as measured by the FMS DS. Further research is indicated to determine the best approach for reduction of the LFT asymmetry identified here. The specific aims will highlight the major findings from each of the manuscripts included in this dissertation. Finally, the limitations, conclusions, and future directions will summarize the findings of our current research and suggest potential directions for future study.

Specific Aim 1: Assess effect of sand as a training surface on anaerobic performance variables in female collegiate athletes.

The consideration of effect size, power, and MDC related to each outcome measure included in this study temper the interpretation of the results. Ultimately, the main effect for training identified in the 5RM is the strongest finding. The training protocol led to a significant improvement in 5RM squat performance, regardless of training surface. This finding highlights the effectiveness of the training protocol and indicates that sand training did not directly affect performance of the squat.
The periodized training protocol utilized in this study focused on improving several different biomotor abilities. This exercise program is simply a guideline that can be used for sand training. Certified strength and conditioning professionals can and should alter their training protocols to maximize the training effect for their specific population and training goals. It is important to note that these benefits occurred after only nine sessions spread out over a 4-week period and were combined with only minimal additional team workout sessions. Practitioners desiring to train athletes on a sand surface may find it difficult to convince coaching staffs that a new surface will be beneficial to their athletes. It is important to assure them that sand training does not appear to result in a decrease in performance or present an increased risk of injury to healthy athletes that are prepared for intense training. Additionally, benefits of sand training may include reduced muscle soreness after training and improved concentric force production upon return to firm-surface participation. The rate of injury occurrence during sand training appears to be no higher than that seen on a firm surface. As with all training programs, athletes should be properly instructed in form, and supervised to ensure they are continually participating in a safe environment.

**Specific Aim 2: Assess effect of sand as a training surface on postural control and functional range of motion variable in female collegiate athletes.**

The training protocol led to a significant improvement in WBLT performance, regardless of training surface. This finding highlights the effectiveness of the training protocol and indicates that sand training did not directly affect performance of the WBLT. This finding, in conjunction with the previously reported finding regarding the 5RM squat suggests a link between WBLT performance and the squat movement. Our findings support previous research establishing a connection between dorsiflexion and the ability to correctly perform a squat.

General athletic performance training on sand appears to lack the specificity necessary to improve static and dynamic postural control. Given the established relationship between postural control and risk of injury, practitioners and coaches should create and implement training programs that include tasks specifically designed to improve postural control, with the goal of reducing the likelihood of future injury. At this time it is unknown whether or not sand training, coupled with training specific to postural control, will lead to greater improvements compared to those known to occur on more traditional training and rehabilitative surfaces.
Future training protocols implemented to determine the effect of sand training on postural control should include exercises with a higher degree of specificity. Focus should be on single limb activities including hopping, jumping, and landing. Additional single-limb exercises may include the single-leg squat, dynamic balance exercises such as single-limb balance coupled with a secondary task, and static balance training.

**Specific Aim 3: Stratify performance on postural control, core muscle capability, and functional ankle range of motion assessments by score categories of the Functional Movement Screen deep squat.**

Our results provide further evidence to support the established connection between dorsiflexion and squat performance, as well as the relationship between the WBLT and SEBT ANT reach. Specifically, they indicate that decreased performance on the WBLT (< 10cm) and SEBT ANT reach (< 61% of leg length) result in FMS DS stratification at a score of two. Asymmetrical performance on the LFT (right/left difference greater than 8 seconds) coupled with limited WBLT performance, results in FMS DS stratification at a score of one. These results, combined with our previous findings related to WBLT and 5RM squat performance after a period of sand training indicate that WBLT performance may be improved with general athletic performance training and this may in turn result in improved squat performance as measured by the FMS DS. Further research is indicated to determine the best approach for reduction of the LFT asymmetry identified here.

Establishing specific causes for movement deficiencies within the kinetic chain may provide useful information for the design and implementation of targeted corrective exercise plans aimed at improving proximal stability and distal mobility. Based on the data presented here, coaches and practitioners should address core muscle asymmetry in an attempt to improve DS performance in individuals that exhibit an inability to complete the movement. For those able to complete the movement successfully with the assistance of the compensatory strategy, exercise interventions should be targeted at improving ankle mobility. Potential strategies may include soft tissue stretching, joint capsule mobilization, or referral for correction of skeletal issues such as bone spurs for ankle mobility, and functional core strengthening programs to address the asymmetry.
Limitations:

Manuscripts one and two were written based on data collected in the first study completed as part of this dissertation. Therefore, the limitations are shared by the two manuscripts and are as follows. The outdoor location of the sand surface utilized for implementation of the sand training intervention resulted in weather affecting the training schedule. The original intent was for both groups to complete ten training sessions. However, inclement weather resulted in only nine outdoor sessions being completed and in an effort to ensure that both groups completed the same training volume the indoor group was limited to nine as well. Additionally, recovery time between workout sessions was not consistent as a result of the inclement weather. This may have affected performance as well. In addition to weather, a small sample size that exhibited a good deal of variability in the areas of athletic ability and training experience may have led to lower effect sizes and potentially affected the significance level of our findings. A pre-screen of athletes may have resulted in less variability in these areas.

Manuscript three was generated from the data collected from our second study. The primary limitation of this study was a lack of pre-screening in order to achieve equal group stratification between the three score categories of the FMS deep squat. The three groups stratified as was to be expected based on previous reports related to FMS performance. Pre-screening would have allowed for equal groups and possibly strengthened the results of the study. Additionally, pre-screening for other anthropometric or subjective characteristics such as body mass index and previous history of injury would have further homogenized the subject population and removed subjects with potential confounding factors that would negatively affect their deep squat performance. Previous research indicates that these factors may affect performance of some/all components of the FMS and future research may be strengthened by some form of pre-screening. Also, subjects were not asked about their previous athletic or physical activity experience. This may have resulted in a broader range of movement capability being represented in the study and may have affected the results.

Conclusions and Future Directions:

Previous research has established the effectiveness of sand training at improving various performance variables and in a small way our results added to this body of knowledge. Our study is one of the first to combine the use of sand training for anaerobic performance as well as
postural control. Future research should continue to evaluate the effectiveness of sand training on both of these performance areas since questions still exist about its efficacy. However, greater specificity of training should be included in the intervention in order to determine whether or not sand has the capacity to improve performance in these areas. Specifically, future research is needed to determine whether or not sand is an effective training surface if combined with appropriate specificity to address the established training goals.

Our second study is one of the first attempts to break down an individual component of the Functional Movement Screen and identify specific mobility and/or stability traits that may contribute to its performance. Future research should focus on identification of additional factors affecting deep squat performance, as well as undertaking similar studies related to performance of the other Functional Movement Screen components. Also, further application of one or more of the proposed modified scoring systems may provide additional information regarding specific factors affecting the outcome of the Functional Movement Screen. Evidence is present in the current literature supporting the use of one or more of these modified systems in an effort to further understand factors resulting in dysfunctional or asymmetrical movement patterns.
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  o Jacobs CA, Lewis M, Bolgla LA, Christensen CP, Nitz AJ, and Uhl TL.
    Electromyographic analysis of hip abductor exercises performed by a sample of