



SEX DIFFERENCES IN FRONTAL AND TRANSVERSE PLANE HIP AND KNEE KINEMATICS DURING THE MODIFIED STAR EXCURSION BALANCE TEST

original paper

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ABSTRACT

Purpose. The modified Star Excursion Balance Test (mSEBT) assesses dynamic neuromuscular control, with predictive ability regarding lower extremity injury risk. Previous kinematic mSEBT analyses are limited to sex differences between injured or fatigued populations or non-fatigued groups in the sagittal plane only. We hypothesize that sex differences exist in the frontal and transverse plane kinematics of the hip and knee in healthy, non-fatigued subjects during the mSEBT.

Methods. The descriptive laboratory study involved 38 healthy subjects: 20 males (aged 24.8 ± 2.7 years) and 18 females (24.1 ± 3.7 years). Peak kinematics, obtained by a VICONTM motion system, of the hip and knee in the sagittal, frontal, and transverse plane were compared during the anterior, posteromedial, and posterolateral reach of the mSEBT. Wilcoxon rank test with significant differences at $p < 0.05$ was used.

Results. Kinematic differences existed between the groups in the frontal and transverse plane of the hip and knee in all reach directions ($p < 0.05$). No differences were found in the sagittal plane of the hip or knee between the groups.

Conclusions. Sex differences exist in frontal and transverse plane kinematics of the hip and knee during the mSEBT. The mSEBT may be enhanced as an injury prediction tool, if frontal and transverse plane kinematics were included during risk assessment screening.

Key words: injury prevention, gender differences, lower extremity, mSEBT

Introduction

A lower extremity injury can be devastating in terms of cost, pain, and impaired function [1, 2]. Current evidence strongly supports a significant bias between the sexes, heavily weighted toward the female athlete, in the incidence of non-contact musculoskeletal injuries of the lower extremity [3, 4]. For example, it has been shown that females are 4–6 times more likely to sustain an anterior cruciate ligament (ACL) injury than males, with a peak age of injury at 16 years [3–6]. The predisposition for such injuries in female athletes has included intrinsic factors, such as joint laxity, limb alignment, intercondylar notch dimensions, ligament size, hormone levels, and biomechanical and neuromuscular

imbalances that alter lower extremity control in the sagittal, frontal, and transverse planes [2, 3, 7]. Of special interest to the investigators is the comparison of previously identified altered mechanics of the lower extremity between sexes, including the presence of increased hip adduction, hip internal rotation (IR), knee abduction, and knee IR [2, 3, 7–9].

Previous investigators have pointed to the presence of dynamic knee valgus as a significant contributor to non-contact ACL injuries and chronic overuse injuries alike, placing female athletes at a higher risk [8, 10, 11]. Fortunately, if individuals are identified early through appropriate screening tests, prevention programs have produced a relative risk reduction in overall non-contact ACL and knee injuries by 40–73%, although concerns

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of existing disparities in funding for female athletic programs have been raised [12–14]. Owing to the increased injury rates in female athletes and the usefulness of prevention programs, the clinical relevance to advance current injury prediction tests is apparent. This makes the development of screening tools aimed at improving early identification of risk factors and prevention vitally important [13, 15].

The Star Excursion Balance Test (SEBT) has demonstrated consistent reliability and validity in the literature as a dynamic test to predict lower extremity injuries [16–18]. Original testing involved reaching the lower extremity in eight directions as far as possible, extending at 45° increments from the centre of the grid, while standing on the limb being tested [17]. Outcome measures of the tested stance limb include reach distance, percentage of reach distance (normalized to leg length), and composite reach [16–18]. This has since been adapted by investigators to reduce the original eight reaches to three for simplicity and reduction of redundancies [17–20]. Plisky et al. [20] found that reaches in the anterior (ANT), posterolateral (PL), and posteromedial (PM) directions were able to successfully predict the risk of lower extremity injury in a group of 235 high school basketball athletes. The modified SEBT (mSEBT) demonstrated that those with a 4-cm discrepancy in ANT reach distance between limbs were at a 2.5 times higher risk of suffering injuries, including, but not limited to, knee strains, meniscal injuries, and patellofemoral pain. Additionally, females who demonstrated less than a 94% composite reach distance of their limb length were at a 6.5 times higher likelihood to sustain a lower extremity injury [20]. The mSEBT has high inter- and intra-tester reliability, in addition to the same lower extremity injury predictive capabilities of the SEBT [20, 21]. Performance on the mSEBT has shown statistically significant differences between controls and those who have suffered an ACL injury, with specific support in using the ANT reach to correlate to other validated measures of neuromuscular control [22–24]. Through the combination of the strong predictive value of the mSEBT, known biomechanical deficits associated with lower extremity injury risk, and the recent advances in kinematic motion capture technology, opportunities to optimize the mSEBT are evident.

Previous studies comparing the sagittal, frontal, and transverse plane kinematics during the mSEBT between sexes were primarily devoted to fatigued or injured populations only [18, 24–28]. Although investigators have performed kinematic analysis on healthy, non-fatigued individuals during the mSEBT, they limited their analysis to lower extremity sagittal plane angles [27]. Gribble et al. [27] found that women demonstrated increased reach distances as compared with men in all three reach directions and attained a greater degree of hip and knee flexion at the maximal displacement following a fatigue inducing protocol. In contrast, Doherty et al. [26] com-

pared performance on the mSEBT between men and women after acute lateral ankle sprain, and found no significant difference in reach performance. However, Gribble et al. [17, 29] do point out kinematic reach differences in hip, knee, and ankle flexion between injured and uninjured populations. The investigators believe that by using the predictive ability of mSEBT outcomes – while simultaneously examining known specific non-contact lower extremity biomechanical risk factors – clinicians may further improve identification of those at risk, implementing early and potentially effective exercise prevention programs in future investigations [8, 12, 13, 20, 21]. Recent advances in kinematic motion capture equipment highlight the need to take previously established measures, such as the mSEBT, and further expand predictive values by including biomechanical data in the assessment [30]. To our knowledge, no previous study has examined kinematic differences between the sexes in the frontal and transverse planes among a healthy, non-fatigued population during the mSEBT. This study tests the hypothesis that sex differences exist in the frontal and transverse plane angles of the hip and knee in healthy, non-fatigued subjects during the mSEBT.

Material and methods

The investigators used a descriptive study design within a university biomechanics laboratory. Both groups performed the mSEBT with identical methodology. The performance on the mSEBT for both sexes was also examined to account for potential influence on kinematic strategy. This was completed by examining the percentage of reach distance (normalized to leg length) and composite reach [16–18].

With the Institutional Review Board approval, we recruited 38 healthy volunteer subjects, 20 males (mean age: 24.79 ± 2.68 years; weight: 83.79 ± 14.25 kg; height: 1.80 ± 0.07 m) and 18 females (mean age: 24.1 ± 3.68 years; weight: 65.01 ± 9.58 kg; height: 1.64 ± 0.05 m). Each participant signed an approved consent prior to the study. Participants were excluded if they had a history of neurological illness or a lower extremity injury within the preceding 12 months.

Anthropometric measurements were assessed, including body mass index (BMI), height, inter-anterior superior iliac spine (ASIS) distance, leg length, knee width, and ankle width for both limbs. An 8-camera VICON™ MX-T40S retro-reflective motion capture system (Vicon Motion Systems Ltd., Oxford, UK), widely accepted as the ‘gold standard’ for motion analysis investigations, was used, with data acquired at 100 Hz [8]. Sixteen skin-surface retro-reflective markers were placed on the trunk and legs, in accordance with the protocol of the lower body Plug-in-Gait model [31]. Four additional markers were positioned on the medial epicondyle of the knee and medial malleoli of the ankle to estimate the thigh rotation offset, shank rotation offset, and tibial

torsion. These additional markers were removed after acquiring a static pose. The kinematic data were filtered with the use of a fourth order zero lag low pass Butterworth filter with 6-Hz cut-off and processed with the VICON™ Nexus software.

Verbal instructions and demonstration of the mSEBT were given to each subject in accordance with previous study procedures [17, 27]. Markings for the mSEBT included three lines of tape, with one positioned directly ANT from a centre point, and two oriented at 135° in the PL and PM directions from the ANT line (Figure 1). The participants stood with their left great toe on the centre of these three connecting lines, wearing self-selected athletic shoes. All subjects performed mSEBT testing on their left lower extremity. This was due to the fact that no significant differences in reach performance between the right and left leg were found in a similar study of healthy subjects during the mSEBT [32]. Verbal instructions included asking the participant to reach as far as possible along the line with the reach limb and to lightly touch it with their right great toe, without shifting weight onto the right leg. The subjects then returned to a standing double limb stance position in the centre of the grid. If the participant touched the line heavily, rested the limb at the maximal reach point, or lifted the stance leg, the trial was discarded [17]. The three reach directions, in the ANT (Figure 2), PM (Figure 3), and PL (Figure 4) directions, were completed six times. All subjects carried out the test with their left lower extremity as the stance leg, and right lower extremity performing the reach. It is noted that the testing was completed unilaterally, as opposed to a bilateral comparison of reach performance. The kinematic analysis is of the left (stance) leg, with data acquired at the maximum right leg reach distance. One practice trial was performed, followed by five recorded trials. Five successful trials were averaged for statistical purposes.

The performance on the mSEBT for males and females was examined by recording the percentage of reach distance (normalized to leg length) and compos-

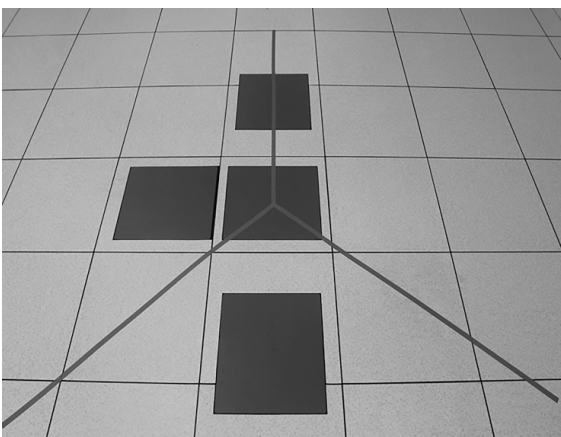


Figure 1. Testing setup for the modified Star Excursion Balance Test



Figure 2. Demonstration of the anterior reach in the modified Star Excursion Balance Test

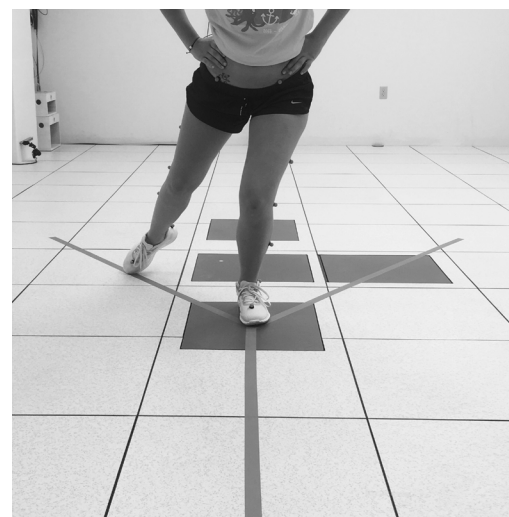


Figure 3. Demonstration of the posteromedial reach in the modified Star Excursion Balance Test

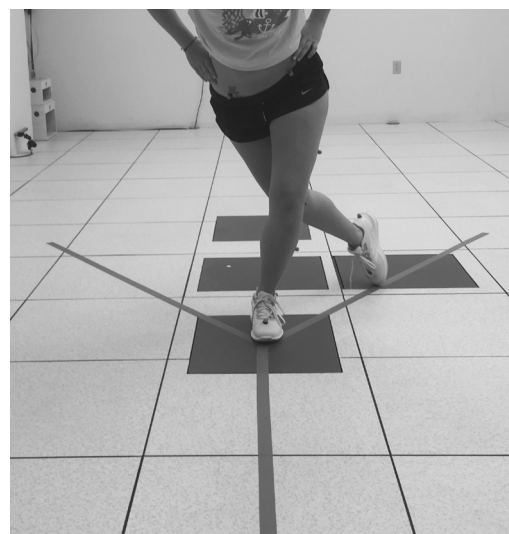


Figure 4. Demonstration of the posterolateral reach in the modified Star Excursion Balance Test

ite reach throughout the testing [16–18]. The percentage of reach distance was calculated by dividing the reach distance by the leg length for each reach direction [16–18]. The composite reach, considered an overall performance measure for the three directions, was calculated as the sum of the ANT, PM, and PL reach distances divided by three times the leg length and multiplied by 100 [16–18]. Single limb reach distance in isolation was not examined because of the unilateral nature of the testing. The performance from the five recorded trials was then averaged for statistical purposes. Kinematic differences, as well as differences in the percentage of reach distance and the composite reach between the groups were examined with Wilcoxon rank tests, with statistical significance accepted at the $p < 0.05$ level.

Results

No significant difference between the groups was seen for the percentage of reach in any direction or the composite reach on the mSEBT (Table 1). Our findings showed significant differences between males and females in hip adduction/abduction and hip IR/external rotation (ER) of the stance leg ($p < 0.05$) (Table 2). We observed significant differences between the groups in knee frontal planes and transverse angles ($p < 0.05$)

(Table 2). Specifically, a significant difference was noted in hip adduction during the ANT reach and PM reach ($p < 0.05$) (Table 2). Females demonstrated a median hip adduction angle of 8.9° during the ANT reach, while males showed a median hip adduction angle of 3.9° . During the PM reach, women demonstrated a median angle of 2.7° of hip adduction, while the median hip abduction angle in men equalled 6.4° . Statistically significant differences also existed for hip rotation of the stance leg, with females demonstrating greater hip ER during the PM reach and PL reach ($p < 0.05$) (Table 2). Additionally, men showed greater statistically significant amounts of knee varus, as compared with females in the ANT and PM reach ($p < 0.05$) (Table 3). Finally, greater tibial IR was observed in females than in males during the PL reach ($p < 0.05$) (Table 3). No statistically significant differences were seen in any sagittal plane measures for the hip or knee during the ANT, PM, or PL reach in the test ($p < 0.05$) (Table 2 & 3).

Discussion

The primary aim of the study was to investigate whether kinematic differences between males and females exist in the frontal and transverse planes of the hip and knee during the mSEBT for an uninjured, non-

Table 1. Modified Star Excursion Balance Test performance

	Percentage of reach distance: ANT	Percentage of reach distance: PM	Percentage of reach distance: PL	Composite reach
Females	68.3	91.0	81.1	80.1
Males	69.8	94.8	82.4	82.4
<i>p</i> -value	0.33	0.19	0.67	0.31

ANT – anterior reach, PM – posteromedial reach, PL – posterolateral reach

Table 2. Kinematic differences of the hip during the modified Star Excursion Balance Test

Hip	Anterior Reach ($^\circ$)		Posteromedial Reach ($^\circ$)		Posterolateral Reach ($^\circ$)	
	Female	Male	Female	Male	Female	Male
Flex (+) / Ext (–)						
Maximum	42.4	54.1	82.8	109.6	80.1	98.7
Median	22.3	18.6	64.9	64.8	65.9	64.1
Minimum	9.7	–4.83	39.6	45.1	42.9	38.7
Add (+) / Abd (–)						
Maximum	20.5	10.9	15.8	26.9	28.8	23.6
Median	8.9*	3.9*	2.7*	–6.4*	14.5	11.5
Minimum	0.9	–1.4	–11.0	–14.5	0.5	1.6
IR (+) / ER (–)						
Maximum	22.6	35.9	25.6	37.8	9.7	25.2
Median	8.5	12.0	–1.3*	7.6*	–4.8*	0.1*
Minimum	–2.6	–13.2	–10.8	–4.0	–18.7	–18.9

Flex – flexion, Ext – extension, Add – adduction, Abd – abduction, IR – internal rotation, ER – external rotation

* statistically significant difference between sexes, $p < 0.05$

Table 3. Kinematic differences of the knee during the modified Star Excursion Balance Test

Knee	Anterior Reach (°)		Posteromedial Reach (°)		Posterolateral Reach (°)	
	Female	Male	Female	Male	Female	Male
Flex (+) / Ext (-)						
Maximum	72.0	85.7	78.6	87.0	64.7	76.2
Median	59.4	59.1	63.5	61.8	49.1	46.8
Minimum	4.7	40.0	14.5	30.9	9.7	15.1
Varus (+) / Valgus (-)						
Maximum	11.7	21.6	17.2	20.1	28.7	33.9
Median	3.9*	9.6*	1.1*	9.6*	16.6	18.3
Minimum	-9.7	-8.9	-9.0	-8.9	3.1	10.3
IR (+) / ER (-)						
Maximum	43.1	32.0	46.7	28.9	37.5	20.5
Median	25.3	21.3	27.1	22.3	12.9*	7.4*
Minimum	12.1	5.1	10.5	7.4	-4.8	-7.6

Flex – flexion, Ext – extension, IR – internal rotation, ER – external rotation

* statistically significant difference between sexes, $p < 0.05$

fatigued population. The results did indicate that kinematic differences did exist in the frontal and transverse planes during the mSEBT between sexes. Specifically, females demonstrated greater hip adduction during the ANT and PM reach, as well as greater knee IR during the PL reach. Interestingly, though, females in our study did not demonstrate the presence of true knee abduction of the stance leg, simply because they had less knee adduction as compared with men. Females did exhibit significantly increased hip ER in all reach directions during the mSEBT. No difference was seen in the percentage of reach distance or composite reach between the groups, which indicates that varying levels of performance did not factor into the study. As previously discussed, the increased hip adduction and greater knee IR have been linked to increased non-contact injury rates in other functional tasks in females [2, 3, 7, 8, 20]. This reinforces the potential ability to enhance the mSEBT for injury prediction models by correlating reach outcomes with kinematic variables in the frontal and transverse plane.

Our study results support previous findings by Gribble et al. [27], which show that sagittal plane differences do not exist at the hip and knee between males and females during the mSEBT in a healthy, non-fatigued population. The consistency of these results illustrates the need to move beyond the sagittal plane in kinematic analysis for lower extremity injury risk identification. Alternately, our findings did reflect altered mechanics in the transverse and frontal planes between sexes, showing similar findings to previously identified at-risk movement patterns in either fatigued or injured groups [2, 3, 7]. These altered mechanics – specifically knee abduction, knee IR, and hip adduction – are thought to be linked to proximal neuromuscular deficits and asymmetrical movement patterns, which increase the

risk of injury to the lower extremity (Figure 5) [8, 20]. Hewett et al. [8] found that individuals who went on to suffer from an ACL injury demonstrated 2.5 times greater knee abduction moments prior to injury. Additional work by Paterno et al. [9] also indicated direct evidence for similar multi-planar lower limb control deficits which increased the risk of re-injury following ACL reconstruction. This is further supported by Clagg et al. [22], with the findings that alterations in postural stability and neuromuscular control are a potential predictor of second ACL injuries. Finally, Delahunt et al. [25] recently examined kinematic reach strategies of the hip and knee in the frontal and sagittal plane, comparing a control and ACL reconstructed groups during the mSEBT. They found altered hip frontal, transverse, and sagittal plane mechanics, as well as altered knee joint sagittal plane kinematics in the injured population as compared with the controls [25]. Supporting our results, findings were similar between the current investigation and Delahunt et al.'s [25] female control group in hip frontal and transverse plane kinematics during the mSEBT.

The presence of altered kinematic strategies in the frontal and transverse plane highlights the importance of analysing not just reach distance on the mSEBT, but the variable kinematics applied by each participant. As reflected in the work of Plisky et al. [20], the individual and composite reach distances of the mSEBT are a strong predictor of injury risk. Specifically, differences in ANT reach have been identified as a predictor of lower extremity injury and used as a post injury outcome measure [21–23]. Unfortunately, reach distances alone do not examine potential altered kinematic reach strategies of the stance limb. It has been suggested in previous studies that limitations in sagittal plane ANT reach distance may be compensated by ipsilateral hip adduction [25, 27]. This is believed to be accomplished by creating a Tren-

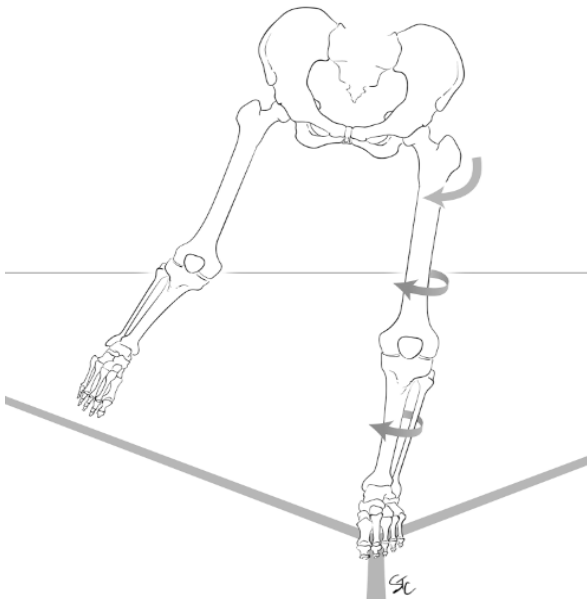


Figure 5. Altered kinematic reach strategies during the modified Star Excursion Balance Test

delenburg position of the ipsilateral leg, thus increasing the length of the contralateral limb and ANT reach distance [25]. Therefore, a participant may have satisfactory performance on ANT reach distance, with adequate symmetry between limbs, but may use poor kinematic strategies of hip adduction, hip IR, knee abduction, and knee IR to achieve such results.

It is important to note that several studies have commented on the limitations of injury prevention screening techniques aimed at ACL risk reduction [33, 34]. Bahr [33] explicitly proposes three essential methodological steps to improve the development of injury risk screening procedures. Firstly, initial prospective cohort studies which identify risk factors and cut-off values need to be developed. Secondly, validation testing of the cut-off value in multiple cohorts is required. Finally, the implementation of randomized controlled trials to test the effect of combined screening and intervention programs is warranted. If investigators follow these methodological steps while expanding the scope of the mSEBT to include kinematic analysis of the stance limb, researchers may improve the sensitivity and specificity of the test. Such findings may allow future health care providers to implement more targeted preventative intervention and rehabilitation strategies.

The previous difficulties in widespread use of kinematic analysis for injury prevention include cost, decreased portability, and time intensiveness for advanced marker based systems. Gribble et al. [29] have previously found a reliable and valid 2-D system for sagittal plane analysis of the mSETB. Unfortunately, this system and others like it are designed to analyse the sagittal plane only, missing valuable transverse and frontal plane movement patterns. In a recent meta-analysis, Gribble et al. [17] reported that the advancement of portable motion-

capture equipment to analyse the frontal and transverse plane was of important value. Fortunately, the progress in portable markerless motion capture systems has increased the affordability, portability, and time efficiency of such clinical assessments [30].

Devices such as the Microsoft Kinect™ offer portable motion analysis, including two- and three-dimensional views, thus improving the feasibility of integrating kinematic data into traditional clinic settings [30, 31]. Previous work by Stone et al. [30] has shown good agreement between a Microsoft Kinect™ and a VICON™ motion capture system when analysing frontal plane dynamics of the lower extremity. Additionally, by examining a non-fatigued, uninjured population, the potential to expand injury risk screening techniques to female athletes in a more patient-convenient environment is greatly improved. As confirmed in a recent meta-analysis, Donnell-Fink et al. [12] found protective factors, linked to preventative neuromuscular and proprioception training, reducing the risk of general lower extremity injuries and injuries to the ACL. It is important to note that until advances in markerless motion capture are utilized commonly, providers may desire advances in standardized subjective assessments of the frontal and transverse plane movements during the mSEBT. That being said, continued progress in markerless motion capture technology, validity, and reliability may continue to help bridge the gap between the laboratory and clinic for injury prevention.

This study has several limitations. The authors have identified multiple areas to improve the quality of future investigation. The recommendations to strengthen the study include measuring pelvic obliquity, performing the task with both limbs, examining prior or ongoing athletic participation, increasing the sample size, and using a target population of healthy, non-fatigued 13–19-year-old boys and girls. Notably, the authors wish to underscore the potential influence of pelvic obliquity and anterior-posterior tilt in the three reach directions, recommending further investigations on the relationship between obliquity and lower extremity kinematics. Additionally, the use of self-selected athletic footwear may add a further level of variability in performance during the testing. To further improve this area of study, the investigators recommend prospective data collection of frontal and transverse plane hip and knee kinematics in adolescent female athletes, tracking injury rates, and determining the predictive value of such data with reference to traditional mSEBT outcome measures.

Conclusions

We found that differences between sexes do exist in frontal and transverse plane kinematics of the hip and knee during the mSEBT. This was observed among a non-fatigued, uninjured population. Females demonstrated an increase in hip adduction and IR, as well as

increased knee IR, all known biomechanical risk factors in other functional tasks [2, 3, 7, 8]. These data reveal the need to expand on the mSEBT, moving from simple reach distance performance and sagittal plane measures to the examination of faulty lower limb movement strategies for injury risk prediction in the transverse and frontal plane. Further enhancements of portable, inexpensive motion capture equipment – such as the method proposed by Stone et al. [30] – could be implemented to monitor such kinematic assessments on a widespread scale to examine their potential role in injury risk. Such tools would allow clinicians to target individuals who may receive a satisfactory performance on the standard mSEBT measures but use known kinematic risk factors to achieve such performance. The implementation of targeted prevention programs that involve specific strengthening and proprioception training protocols has shown effectiveness in reducing non-contact lower extremity injuries associated with these altered kinematic movement strategies [12, 13]. By using a quality-over-quantity approach to the mSEBT, clinicians may enhance its already strong predictive value for injury prediction. This may not only aid in the rehabilitative progress for clients, but also help potentially avoid injury altogether.

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