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ERRATUM

Younis Aslan HI, Buddhadev HH, Suprak DN, San Juan JG. ACUTE EFFECTS OF TWO HIP FLEXOR STRETCHING TECHNIQUES ON KNEE JOINT POSITION SENSE AND BALANCE. International Journal of Sports Physical Therapy, Volume 13, Number 5, October 2018, Pages 846-859. PMCID: 6159495

Mr. Hussain Aslan MA, MS, ACSM-RCEP was incorrectly identified on this article as Younis Aslan, Hussain I, and should have been listed as Aslan, HIY. This change does not affect any other aspect of this publication.

ABSTRACT

**Background:** Variations in vertical loading rates have been associated with overuse injuries of the lower extremity; however, they are typically collected using 3-dimensional motion capture systems and in-ground force plates not available to most clinicians because of cost and space constraints.

**Purpose:** The purpose of this study was to determine if kinetic measures commonly used to describe lower extremity loading characteristics could be estimated from step rate and specific sagittal plane kinematic variables captured using 2-dimensional motion analysis during treadmill running.

**Study Design:** Observational Study

**Methods:** Ten high school cross-country runners (4 men and 6 women) voluntarily consented to participate in this study. Reflective markers were placed on each lower extremity over multiple anatomical landmarks. Participants were then asked to run on the instrumented treadmill at their preferred running speed. When the participants indicated they were in their typical running pattern, they continued to run at their preferred speed for a minimum of five minutes. After three minutes of running at their preferred running speed, the participant's step rate was counted and after running for four minutes, video and ground reaction force data were recorded for 60 sec. All running motion data were recorded using a single high-speed camera at 240 frames per second and ground reaction force data were sampled at 1000 Hz.

**Results:** Mean kinematic values between the left and right extremities for all 10 participants were not significantly different. Consequently, data for the left and right extremities were grouped for all further analyses. The stepwise forward regression to predict vertical ground reaction force resulted in a five-variable model (step rate and four kinematic variables) with $R^2 = 0.56$. The stepwise forward regression to predict average loading rate also resulted in a five kinematic variable model with $R^2 = 0.51$.

**Conclusions:** Step rate and sagittal plane kinematic variables measured using a simplified 2-dimensional motion analysis approach with a single high-speed camera can provide the clinician with a reasonable estimate of ground reaction force kinetics during treadmill running.

**Level of Evidence:** 4, Controlled laboratory study

**Keywords:** gait analysis, loading rate, running assessment
INTRODUCTION
While previous research suggests that the development of running-related overuse injuries is multifactorial with a wide range of suspected risk factors, it is important to note that many of these investigations have been conducted retrospectively. Davis et al conducted a prospective investigation to assess vertical impact loading in female runners with medically diagnosed injuries. They found that impact loading was greatest in the injured runners and lowest in the never-injured group and higher impact loading was associated with bony and soft-tissue injuries. These authors concluded that reducing vertical loading rates associated with impacts could be an effective means to reduce injury risk in female runners.

High school cross country runners have been shown to have increased injury rates in comparison to other sports with the knee and leg being the most frequently reported injury locations. Running-related lower extremity overuse injuries include anterior knee pain, medial tibial stress syndrome, stress fractures, and compartment syndromes. Other research findings have supported that higher average vertical loading rates are associated with anterior knee pain and leg pain in female runners.

Based on current research, it would appear to be important for clinicians to be cognizant of and if possible, assess ground reaction forces and loading rates in high school cross-country runners either as part of a management program or during pre-season screening. Unfortunately, ground reaction forces are seldom evaluated in the typical clinical setting because of the cost of required equipment (3-dimensional multiple camera system with in ground force plates), space limitations, and time constraints as well as the complexity of the data analysis. As a result, clinical running analyses are usually limited to a qualitative 2-dimensional kinematic analysis using a single video camera.

In an attempt to address a practitioner's ability to obtain kinetic measurements for runners in the clinical setting, Wille and colleagues assessed if lower extremity kinetic measures typically used to describe lower extremity loading during running could be estimated from sagittal plane kinematic variables. Using a linear mixed effects model, they found that selected kinetic variables could be obtained from step rate and a subset of sagittal plane kinematic variables common to a clinical running analysis. These authors reported an adjusted R² value of 0.48 for estimated peak vertical ground reaction force and an adjusted R² of 0.04 for estimated average loading rate. In their conclusion, the authors suggested that although they had used kinematic variables captured using 3-dimensional motion analysis to predict running kinetic variables, 2-dimensional motion analysis would likely be sufficient to capture step rate and the sagittal plane kinematic variables required for predicting running kinetics. Wille et al also noted that the relationships they identified in their study could be generalized to a simplified 2-dimensional approach if a single video camera with an adequate frame rate (greater than 100 frames per sec) was used for motion capture. These conclusions are supported from prior research that has demonstrated a strong correlation between 2-dimensional and 3-dimensional sagittal plane motions during running.

Accurate prediction of kinetic measurements using 2-dimensional motion analysis would be highly beneficial in the management of running-related injuries and would be especially advantageous for those clinicians working with high school cross-country runners in light of the higher rates of lower extremity overuse injuries identified with this population. Thus, the purpose of this study was to determine if kinetic measures commonly used to describe lower extremity loading characteristics could be estimated from step rate and specific sagittal plane kinematic variables captured using 2-dimensional motion analysis during treadmill running. It was hypothesized that 2-dimensional sagittal plane kinematic variables would more accurately predict peak vertical ground reaction force as compared to predicting average loading rate.

METHODS
This cross-sectional study was conducted at the Regis University biomechanics research lab in August and September 2017. A sample of convenience was used based on a three-month period of subject recruitment and excluding those high school athletes who did not meet inclusion criteria. Participants were recruited from local area high schools through community
Once all markers were attached, the participant was then asked to resume running on the treadmill at his or her pre-selected running speed. When the subject indicated they were in their typical running pattern, they continued to run at their preferred speed for a minimum of five minutes. After three minutes of running at their preferred running speed, the participant's step rate (STEP_RATE) was counted by one of the investigators (MFR). After running for four minutes at their preferred running speed, video data were recorded for the left and then right sagittal plane (side view) for 60 sec using a single high-speed camera (Model# EX FH25, Casio America Inc., Dover, NJ 07801) at 240 frames per second. Three dimensional ground reaction forces were recorded (1000 Hz) through the instrumented treadmill deck for 10 sec.

Variables and Data Analysis
The left and right sagittal video clip for each runner was assessed by a single rater (TGM) with over 12 years of experience performing 2-dimensional video-based running analyses on collegiate and recreational runners. The rater selected a stride for analysis after the third foot strike on the video clip to allow an opportunity to observe the runner’s gait pattern and enhance the rater’s ability to identify initial foot contact. The following six sagittal plane kinematic variables were assessed on the left and right lower extremities for all 10 runners: 1) angle of the shoe to treadmill at initial contact (SHOE_ANG), 2) angle of the lower leg at initial contact (LEG_ANG), 3) knee flexion at initial contact (KN_FL_IC), 4) knee flexion at midstance (KN_FL_MS), 5) vertical position of the estimated center of mass (center of line connecting ASIS and PSIS) at midstance, and 6) vertical position of the estimated center of mass at double float. KN_FL_IC was subtracted from KN_FL_MS to calculate total knee flexion (KN_FL_Tot). The vertical position of the estimated center of mass at double float was subtracted from the vertical position of the estimated center of mass at midstance to calculate total vertical excursion of the center of mass (COM_VtEx). All angles were measured in degrees and all distance measurements were recorded in centimeters using a free-access video analysis software program (Kinovea, version 0.8.15, http://www.kinovea.org). In a previously published study, in comparison to another rater with a
similar level of experience, the rater in this study (TGM) demonstrated intra-rater levels of reliability between 0.75 to 0.98 (ICC) and inter-rater reliability values between 0.76 to 0.97 (ICC) for all kinematic variables assessed in the current study.¹⁰

Ground reaction force data were filtered using a fourth-order, zero-lag low-pass Butterworth filter at a 30 Hz cutoff. The peak vertical force component of the ground reaction force (Vert_GRF) and the average loading rate (AVG_Load_Rate) were measured for five consecutive running cycles for the left and right lower extremities with the average of the five cycles used for further analysis. The Vert_GRF was reported in N x body weight in kg (BW) and AVG_Load_Rate was reported in N/kg/sec. As in the Wille et al study,⁷ the AVG_Load_Rate was defined as the rate of change in the vertical GRF from 20% to 80% of the period beginning with initial contact to the vertical force impact peak.

### Statistical Analysis

In addition to descriptive statistics, a series of t-tests were performed to determine if there were differences between left and right extremities for all six kinematic variables assessed in this study. Seven variables (SHOE_Ang, LEG_Ang, KN_FL_IC, KN_FL_MS, KN_FL_Tot, COM_VtEx, and STEP_RATE) were entered into a stepwise forward linear regression to determine the most parsimonious set of variables associated with Vert_GRF and AVG_Load_Rate. To permit comparison to published studies,⁷ the amount of variance in the kinetic parameters explained by the kinematic measures and step rate for each particular model was reported as the R² value as well as the adjusted R² value. All statistical analyses were performed using SPSS software, Version 23 (IBM, Armonk, NY, 10504). An alpha level of .05 was established for all tests of significance.

### RESULTS

Participant characteristics (mean ± SD) for the 10 runners included age (15 ± 1.2 years), height (163.8 ± 10.2 cm), mass (49.4 ± 7.6 kg), preferred step rate (176 ± 5.3 steps per minute), and running speed (3.01 ± 0.4 m/s). Descriptive statistics for all kinetic and kinematic measurements are listed in Table 1. The data for each of the seven variables were normally distributed and t-tests used to determine the mean values between the left and right extremities.
for all 10 participants were not significantly different. Based on these results, data for the left and right extremities were grouped (n = 20) for all further analyses. The stepwise forward regression to predict Vert_GRF resulted in a five-variable model (F = 3.62; p < 0.02) with R² = 0.56 and the adjusted R²=0.41. The five measures that were included in the model were SHOE_Ang, LEG_Ang, KN_FL_Tot, COM_VtEx, and STEP_RATE. The stepwise forward regression to predict AVG_Load_Rate also resulted in a five-variable model (F = 2.89; p < 0.054) with R² = 0.51 and the adjusted R²=0.33. The five measures that were included in the model were SHOE_Ang, LEG_Ang, KN_FL_IC, COM_VtEx, and STEP_RATE.

DISCUSSION

Previous researchers using kinematic measures obtained from 3-dimensional motion analysis were able to explain approximately 50% of the variance associated with VERT_GRF during treadmill running and suggested that 2-dimensional motion analysis would likely be sufficient to capture the sagittal plane kinematic variables required for predicting running kinetics. The ability to predict running kinetics would be especially advantageous for those clinicians working with high school cross-country runners since previous research has identified higher rates of lower extremity overuse injuries with this population. Thus, the intent of this study was to determine if kinetic measures commonly used to describe lower extremity loading characteristics could be estimated from step-rate and six sagittal plane kinematic variables captured using 2-dimensional motion analysis during treadmill running.

Based on the findings of the regression analysis, the use of the following five variables, SHOE_Ang, LEG_Ang, KN_FL_Tot, COM_VtEx, and STEP_RATE, assessed using 2-dimensional kinematic analysis can explain 56% of the variance of Vert_GRF. Using these results, the clinician can predict the Vert_GRF using the following formula:

\[-1.094 + (0.007 \times \text{SHOE}_\text{Ang}) + (-0.001 \times \text{LEG}_\text{Ang}) + (-0.021 \times \text{KN}_\text{FL}_\text{Tot}) + (0.108 \times \text{COM}_\text{VtEx}) + (0.018 \times \text{STEP}_\text{RATE})\]

Using this prediction formula, the mean value was calculated for the predicted Vert_GRF (2.31 N x BW) and compared using a t-test to the actual measured mean obtained for Vert_GRF (2.40 N x BW) for 14 randomly selected extremities. The results of the t-test were not significant (p = 0.15) and the error of the mean (0.04) was small which further validates the prediction formula for Vert_GRF.

Based on the findings of the regression analysis, the use of SHOE_Ang, LEG_Ang, KN_FL_IC, COM_VtEx, and STEP_RATE assessed using 2-dimensional kinematic analysis can explain 51% of the variance of AVG_Load_Rate. Using these results, the clinician can predict the AVG_Load_Rate using the following formula:

\[-200.80 + (1.070 \times \text{SHOE}_\text{Ang}) + (-3.316 \times \text{LEG}_\text{Ang}) + (-1.349 \times \text{KN}_\text{FL}_\text{IC}) + (2.620 \times \text{COM}_\text{VtEx}) + (1.487 \times \text{STEP}_\text{RATE})\]

Using this prediction formula, the mean value was calculated for the predicted AVG_Load_Rate (47.50 N/kg/sec) and compared using a t-test to the actual measured mean obtained for AVG_Load_Rate (46.38 N/kg/sec) for 14 randomly selected extremities. The results of the t-test were not significant (p = 0.43) and the error of the mean (2.98) was small which further validates the prediction formula for AVG_Load_Rate.

The outcomes of the current study are similar to the findings reported by Wille et al. In their study using 3-dimensional motion analysis, they reported that 48% of the variance for peak vertical ground reaction force could be explained using the kinematic variables shoe inclination angle at initial contact and the center of mass vertical excursion. They also reported that none of the kinematic variables assessed could be used to predict loading rate between 20% to 80% from initial contact to the vertical impact peak. In the current study, at least 50% of the variance associated with VERT_GRF and AVG_Load_Rate could be explained using a five-variable model. Based on these findings, the authors rejected the study hypothesis that 2-dimensional sagittal plane kinematic variables would be more predictive of peak vertical ground reaction force in comparison to average loading rate.

The results of this investigation would support the suggestion by Wille et al that 2-dimensional motion
analysis would likely be sufficient to capture the sagittal plane kinematic variables required for predicting running kinetics. Using the prediction models provided, a clinician can reasonably predict the Vert_GRF and AVG_Load_Rate in high school cross-country runners using 2-dimensional kinematic variables readily collected in a clinical setting without the need for an expensive force platform or 3-dimensional motion analysis system. Although a small sample of high school runners was used in the current investigation, the results of this study may also be applicable to collegiate and adult recreational runners, but further research is required with these specific populations.

A limitation in the current study was the use of treadmill to assess both kinetic and kinematic variables during running. Several studies have reported on the validity of using a treadmill for running analysis with the major concern being the alteration of the runner’s pattern of lower extremity movement as well as ground reaction forces. In one of the only studies to compare overground versus treadmill running kinematics and kinetics using a force-transducer instrumented treadmill, Riley et al. reported that a treadmill-based analysis of running mechanics can be generalized to overground running mechanics, provided the running speed on the treadmill is similar to individuals overground running speed. Another limitation was the use of a single high-speed camera to capture sagittal plane (2-dimensional) kinematics of the lower extremities during running. As previously noted, McClay and Manal as well as Areblad et al. have reported that the use of 2-dimensional techniques to assess angular values in the sagittal plane during running are similar to values obtained using 3-dimensional motion analysis techniques.

CONCLUSIONS
The results of this study indicate that step rate and sagittal plane kinematic variables measured using a simplified 2-dimensional motion analysis approach with a single high-speed camera can provide the clinician with a reasonable estimate of ground reaction force kinetics during treadmill running. The clinician can use the predictive models provided in this paper to estimate running kinetics when treating high school runners with lower extremity injuries or as part of a pre-season screening assessment.

REFERENCES
ORIGINAL RESEARCH

VALIDITY OF HAND-HELD DYNAMOMETRY IN MEASURING QUADRICEPS STRENGTH AND RATE OF TORQUE DEVELOPMENT

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Terry L. Grindstaff, PT, PhD, ATC¹

ABSTRACT

Background: A hand-held dynamometer (HHD) offers a reliable and valid method to quantify quadriceps strength in a clinical environment. While measures of peak strength provide functional insights, most daily activities are performed quickly and do not require maximum strength. Rate of torque development (RTD) measures better reflect both the demands of daily activity and athletic movements. The capacity to obtain RTD measures in clinical settings is possible with an HHD, but the validity of RTD measures has not been quantified.

Hypothesis/Purpose: To determine the validity of an HHD to measure quadriceps isometric strength metrics compared to isometric strength measures obtained on an isokinetic dynamometer. It was hypothesized that the HHD would be a valid measure of peak torque and RTD at all time intervals when compared to the isokinetic dynamometer.

Study Design: Descriptive laboratory study.

Methods: Twenty healthy participants (12 male, 8 female) (age=23.7±2.9 years, height=174.6±10.1 cm, mass=76.4±15.9 kg, and Tegner=6.7 ±1.2) performed maximum isometric quadriceps contractions on an isokinetic dynamometer and with an HHD. Outcome measures included quadriceps peak torque and RTD at three intervals (0-100, 0-250 ms, and average). Pearson product-moment correlation coefficients and Spearman’s rank correlation coefficient were used to determine relationships between devices. Bland-Altman Plots with Limits of Agreement (LOA) calculations were used to quantify systematic bias between measurement techniques.

Results: There was a significant correlation between the isokinetic dynamometer and the HHD for peak torque (p<.001, r=.894) and all RTD measurements (p<.002, r=.807; ρ=.502-.604). Bland-Altman plot LOA indicated the HHD overestimated peak torque values (19.4±53.2 Nm) and underestimated all RTD measurements (-55.2±190.7 Nm/s to -265.2±402.6 Nm/s).

Conclusion: These results show it is possible to obtain valid measures of quadriceps peak torque and late RTD using an HHD. Measures of early RTD and RTDAvg obtained with an HHD were more variable and should be viewed with caution.

Level of Evidence: Diagnostic, Level 3

Key Words: dynamometry; explosive strength; lower limb; knee extension

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INTRODUCTION
Insights into functional ability and health status may be estimated based on isolated muscle function measures, such as hand grip strength or quadriceps strength (e.g. isometric, isokinetic).\(^1\) Quadriceps strength is a prognostic indicator for chronic diseases including coronary artery disease,\(^5,6\) chronic obstructive pulmonary disease,\(^7-9\) and knee osteoarthritis.\(^10,11\) Since quadriceps strength reflects health status and contributes to function it is an objective measure widely used in rehabilitation settings.

Currently, the gold standard method to quantify quadriceps strength utilizes an isokinetic dynamometer. However, this option lacks clinically applicability due to cost and size. A hand-held dynamometer (HHD) provides a valid and reliable testing alternative.\(^12,13\) Although maximum quadriceps strength is an important measure of function, an activity such as walking requires submaximal (<60%) quadriceps activation\(^14\) and is accompanied with rapid joint loading (~200 milliseconds [ms]).\(^15\) From an injury perspective, non-contact anterior cruciate ligament (ACL) injuries have been shown to occur within the first 100 ms after initial foot contact with the ground.\(^16,17\) Quantifying the capacity to quickly develop muscle tension better reflects the demands of daily and sport activities.\(^16-21\) Since quadriceps peak torque measured isometrically is typically performed by asking the participant to gradually increase muscle contraction intensity over a period of 1-5 seconds, it is not an accurate measure of an individual’s ability to quickly develop muscle tension. Rate of torque development (RTD) is an alternative measure of quadriceps strength that quantifies how quickly muscle tension is developed. RTD is the change in torque relative to time and provides insights into different neuromuscular properties that contribute to muscle force production. Specifically, neurological properties have been shown to correspond with early RTD (<100 ms) and structural properties with later RTD (>150 ms).\(^22\) These insights can provide clinicians with information to select interventions to better address underlying causes of impairment.\(^23,24\)

Since RTD is calculated from an isometric contraction, an HHD provides a clinically feasible method to determine RTD. However, the validity of RTD measures obtained using an HHD has not been quantified. Therefore, the purpose of this study was to determine the validity of an HHD to measure quadriceps isometric strength metrics compared to isometric strength measures obtained using an isokinetic dynamometer. It was hypothesized that the HHD would be a valid measure of peak torque and RTD at all time intervals when compared to the isokinetic dynamometer.

METHODS
Twenty physically active adults (12 males, 8 females; age = 23.7 ± 2.9 years, height = 174.6 ± 10.1 cm, mass = 76.4 ± 15.9 kg, and Tegner = 6.7 ± 1.2) volunteered for the study. Inclusion criteria was age between 19 and 40 years. Exclusion criteria included a history of traumatic spine or lower extremity injury within the past six months. The Institutional Review Board at Creighton University approved the study (IRB 960835) and informed consent forms, which were compliant with the Declaration of Helsinki. Prior to testing, all participants completed an approved informed consent form, standardized health history form, and a form to quantify physical activity level (Tegner Activity Scale).

First, participants were tested on an isokinetic dynamometer (Biodex System 3; Computer Sports Medicine Inc., Stoughton, MA, USA) (Figure 1). The dynamometer was interfaced with a data acquisition system (MP150; Biopac Systems, Inc., Goleta, CA, USA), sampled at 2000 Hz, and recorded using AcqKnowledge software (version 4.2, Biopac Systems, Inc., Goleta, CA, USA). Torque signals were low-pass filtered at 15 Hz. Measures were obtained on both limbs, with the dominant limb tested first (leg used to jump). Participants completed a standardized warm up consisting of four submaximal isometric contractions, three at 50% effort and one at 75% effort, and two maximal isometric contractions with one minute of rest between each contraction. Loud verbal encouragement and real-time visual biofeedback (two lines, 100% and 90% of peak torque obtained during warm-up) were
provided to ensure maximum effort during each trial. If a participant was unable to perform near-maximum capacity (<90% peak torque) or if initial countermovement was identified via visual inspection of torque tracing, the trial was repeated until the six successful trials were completed. Initial countermovement occurs when a participant initially contracts the hamstring muscle, producing a stretch shortening cycle, prior to quadriceps maximum isometric contraction. This countermovement leads to inaccurate measures of quadriceps RTD due to the quadriceps isometric contraction not starting from rest. Once testing was completed on the dominant limb, the nondominant limb was tested using the same methods.

Participants then transitioned to a treatment table for isometric testing using an HHD (microFET2, Hoggan Scientific, LLC; West Jordan, UT) (Figure 2A). The HHD has a fixed sampling frequency of 100 Hz and the capacity to wirelessly transmit force signal data to a laptop computer via a manufacturer-supplied USB receiver. A modified belt-stabilized configuration was used to interface the HHD against a treatment table leg (Figure 2B). This testing configuration removes the limitation of tester strength present during a traditional non-belt stabilized testing configuration. This configuration also helped maintain the position of the tibia pad and HHD during rest intervals. Participants performed a warm up consisting of three isometric contractions at 50% effort, 75% effort, and 100% effort with one minute of rest between each contraction. After the warm up, participants completed six maximal isometric contractions, holding for approximately 3 seconds, with one minute of rest between each contraction. Methods were consistent with the isokinetic dynamometer trials, but did not include visual biofeedback.

Data processing was performed using specific algorithms created in MATLAB (The MathWorks, Inc., Natick, MA, USA). Peak torques were extracted for each isometric contraction and the trials with the two highest peak torques were used for data analysis. Since the HHD measures force (N), torque was
calculated by multiplying the isometric force (N) by the moment arm (distance between lateral knee joint line to distal aspect of the lateral malleolus minus 5 cm).12 The onset of contraction was determined by visual inspection of the torque tracing (1.0 Nm y-axis; 100 ms x-axis) and was defined as the last peak or trough before the torque signal deflected away from baseline noise (< 1 Nm).22,28,29 Repetitions with countermovement (> 2 Nm) were discarded.

In the HHD condition, there was an initial tension (approximately 40 N) created by the resting leg, strap, and bolster that was corrected for during the calculation of peak torque and RTD. RTD was calculated for each contraction by identifying the slope of the force-time curve (Δforce/Δtime) at the time intervals of 100 and 250 ms and to the time of peak torque (RTDAvg) from the onset of each contraction.

Statistical Analysis
Descriptive statistics were calculated for all outcome variables from the two contractions with the highest peak torque values. Additionally, all peak torque and RTD measures were normalized to body mass (Nm/kg or Nm/kg*s⁻¹) to allow comparison between studies which have expressed normative values for healthy individuals. The independent variable was testing method (isokinetic dynamometer, HHD), and the outcome variables were quadriceps peak torque (Nm) and RTD at 100ms and 250ms and RTDAvg (Nm/s). Data were examined for normal distribution using Shapiro-Wilk tests. When data were not normally distributed, nonparametric analyses were conducted. Differences between testing methods were determined using paired t-tests (parametric test) or Wilcoxon signed-rank test (nonparametric test) and validity was quantified using Pearson product-moment correlation coefficient (parametric test) or Spearman’s rank correlation coefficient (non-parametric test). Bland-Altman Plots with Limits of Agreement (LOA) calculations were used to provide insights into systematic bias between measurement methods.30 Significance was set a priori at p<0.05. Statistical analyses were performed with SPSS Version 25.0 (SPSS Inc., Chicago, IL).

RESULTS
Descriptive statistics and statistical summaries are available in Table 1. HHD data from one participant was excluded due to an equipment malfunction. Data for peak torque and RTD250 were normally distributed and analyzed using parametric tests while RTD100 and RTDAvg were not normally distributed and analyzed using nonparametric tests. There was a significant difference between devices for peak torque (p = .03), RTD100 (T < .001), and RTDAvg (T = .002), and no significant difference for RTD250 (p = .09). There was a significant correlation between the isokinetic dynamometer and the HHD for peak torque (p < .001, r = .894), RTD100 (T = .001, ρ = .604), RTD250 (p < .001, r = .807), and RTDAvg (p = .002, ρ = .502). Bland-Altman plot LOA indicated the HHD overestimated peak torque values (19.4 ± 53.2 Nm) and underestimated all RTD measurements (-55.2 ± 190.7 Nm/s to -265.2 ± 402.6 Nm/s) (Figure 3).

DISCUSSION
The purpose of this study was to determine the validity of an HHD to measure isometric quadriceps strength.
peak torque and RTD compared to an isometric measure of the same on an isokinetic dynamometer. The results of this study support the hypothesis that the HHD provides a valid measure of quadriceps peak torque and RTD. Measures obtained using the HHD were significantly correlated with isometric peak torque measures obtained using the isokinetic dynamometer ($r = .894$), which is in agreement with previous research.\textsuperscript{12} The HHD significantly overestimated torque values (Figure 3A) with an average difference of 19.4 Nm (SD = 53.2; 95% CI -87.0 to 125.8). This overestimation is slightly greater than the 15.1 Nm minimal detectable change of an isometric quadriceps contraction measured with an HHD.\textsuperscript{12} Previous studies\textsuperscript{12,13} indicate using a similar belt-stabilized HHD configuration tends to result in an underestimation of peak torque (13-36 Nm; 95% CI -50 to 70 Nm), although the confidence intervals have overlap with results from the current study. The possible cause of this overestimation could be due to the manual calculation of torque for the HHD trials. Torque was calculated by taking the product of the force (N) and the distance (m) from the lateral joint line of the knee to the center of the pad placed just proximal to the lateral malleolus. Recording the distance between the lateral joint line of the knee and the center of the pad, with a flexible tape measure, introduces the possibility of measurement error which could have contributed to the overestimation HHD peak torque relative to values obtained on the isokinetic dynamometer.

RTD values obtained with the HHD demonstrated a significant correlation with the isokinetic dynamometer for RTD100 ($p = .604$) and RTD250 ($r = .807$) RTDAvg ($p = .502$). The HHD underestimated RTD values (Figure 3B-D) with a difference ranging between 55.2 Nm/s to 265.2 Nm/s. The lower correlation for early RTD values and the underestimation of all RTD values (significantly lower early RTD) may be due to differences in testing set-up, specifically the lack of back support for HHD testing (Figure 2A). Since participants were unable to lean against a rigid surface to stabilize their trunk during testing this may contribute to a longer time to peak torque. This is reflected in the lower RTDAvg values obtained with
the HHD despite relatively similar peak torque values. Also, early RTD values have been shown to have lower reliability and higher variability when compared to later time intervals and potentially due to neural factors such as motor unit recruitment and rate. This could be a potential reason for the higher correlation for RTD250 as compared to RTD100. An additional factor contributing to the lower correlation for early RTD values may have been due to slack in the belt and elastic properties of the pad, which would alter the sensitivity of the HHD. Although we attempted to minimize this slack (Figure 2B), it is likely there was still a level of compliance with the belt and pad. While customized dynamometers with minimal padding are suggested, researchers should attempt to best identify methods which have the capacity to be replicated in clinical environments and minimize participant discomfort. Another contributing factor to the underestimation of RTD values could be due to the presence of pre-tension in the belt, which has been shown to increase early RTD. While participants were instructed to start from a relaxed state, it is possible participants were extending their knee to maintain constant tension on the belt. Pre-tension was limited by placing a small elastic wrap between the leg of the table and the triceps surae muscle. This created enough tension to keep the HHD secured against the table, allowing the participant to relax between trials. All trials were visually inspected for pre-tension and countermovement during data processing. Since RTD was lower with the HHD relative to the isokinetic dynamometer, it is likely pre-tension was not a consistent issue, but may have contributed to the variance in values. Future studies may incorporate the use of electromyography for visual biofeedback and verification that trials start from a relaxed state.

The results from this study indicate that an HHD can be used, as a substitute for an isokinetic dynamometer, to obtain measures of quadriceps peak torque and later RTD values but not for early RTD and RTDAvg values. This study showed a significant difference between isokinetic dynamometer and HHD for RTD100 (T < .001) and RTDAvg (T = .002) values. To determine an individual's early RTD values, it may be more appropriate to test them on a more stable or less compliant testing device. The advantage is that the HHD offers a less expensive and time-consuming way to obtain measures in a clinical environment. Quadriceps RTD measures can be used to monitor rehabilitation progress and inform clinical decisions regarding treatment approaches and offer insights beyond peak torque. Deficits in early RTD are due to neuromuscular properties, such as neural drive, while RTD at later stages is due to contractile properties, such as cross-sectional area. Training programs that focus on both peak torque and reaching maximum force as quickly as possible have shown to lead to increases in peak torque and RTD in healthy populations and individuals with ACL reconstruction.

A limitation of this study was that the sample population only consisted of young, healthy individuals. Thus, results cannot be extrapolated to individuals beyond this age range or those with pathology such as knee injury (e.g., ACL, osteoarthritis). Additionally, the knee angle for quadriceps strength was only tested at 90° of flexion. While quadriceps peak torque values are highest around 60° of knee flexion versus other angles (e.g. 30°, 90°), the selected knee joint angle for testing varies across studies. Knee flexion angle of 90° was selected because it is easier to reproduce in the clinic and eliminates the need to correct for gravity (limb mass). Future research should study individuals with knee joint or other lower extremity pathologies, quadriceps strength at different knee joint angles, and different muscle groups using similar testing configurations.

CONCLUSIONS
These results show that measures of quadriceps peak torque and late RTD (RTD250) obtained with an HHD are valid compared to an isokinetic dynamometer. Measures of early RTD (RTD100) and RTDAvg should be viewed with caution. Overall the HHD overestimated quadriceps isometric peak torque and underestimated quadriceps RTD measures. The relatively wide confidence intervals for the LOA indicate that these results should be interpreted with caution. These inexact estimations of strength need to be kept in mind while progressing patients through rehabilitation programs. By using strength benchmarks for progression, clinicians could either inaccurately advance or block patients from progressing through rehabilitation after ACL reconstruction.
REFERENCES


ABSTRACT

**Background:** A commonly utilized operational definition of lower extremity (LE) dominance assumes the LE with which a participant prefers to kick a ball with is the same preferred LE a participant would choose for a unilateral landing task.

**Hypothesis/Purpose:** The purpose of this study was to determine the relationship between the preferred lower extremity (LE) when performing a unilateral landing and kicking task. The authors hypothesized a strong correlation between the LE the participant chose for the landing task and the LE the participant chose for the kicking task would be evident.

**Study Design:** Repeated measures.

**Methods:** A convenience sample of 50 (age = 21.9 ± 0.9 years; sex = 27 female; 23 male; height = 170.6 ± 10.8 cm; weight = 73.3 ± 18.3 kg) healthy, recreationally active college aged students performed two tasks (kicking a ball; unilateral drop jump landing) in a counterbalanced order.

**Results:** Thirty-three participants kicked and landed with their right LE; 14 kicked with the right and landed on their left; two kicked and landed with their left and one participant kicked with their left and landed on their right LE. The Phi Coefficient (φ = 0.18; p = 0.18) indicated little to no relationship between the preferred LE for kicking a ball and landing from a drop jump. Similarly, the Chi-squared statistic revealed no differences between observed and expected frequencies ($\chi^2 = 1.76; p = 0.23$).

**Discussion:** When studying anterior cruciate ligament injury mechanisms in the laboratory, most investigators examine characteristics of the dominant LE. Dominance is frequently defined by which LE the individual kicks a ball with. The majority of ACL injuries however occur to the landing or plant LE. Hence, LE limb selection based on this approach may be flawed.

**Conclusion:** A significant relationship was not evident between the preferred LE for kicking a ball and a unilateral landing in a group of healthy recreationally active college aged students. The data suggests the preferred LE for kicking a ball and a unilateral landing task is not necessarily the same.

**Level of Evidence:** Level 3

**Key Words:** Dominant limb, kicking, landing, lower extremity, movement system
INTRODUCTION
Investigations into anterior cruciate ligament (ACL) injury risk factors have been at the forefront of the sports and orthopedic community. This line of research has developed as ACL injuries remain common, costly, and present a considerable sex bias. Despite advances in surgical and rehabilitation techniques, ACL injuries frequently lead to knee osteoarthritis. Prevention of ACL injuries has the potential to benefit thousands of individuals and reduce considerable health care costs.

Strategies to prevent ACL injuries require a precise understanding of the injury mechanism. ACL injuries occur more frequently with non-contact mechanisms. Epidemiological data reveals non-contact ACL injuries occur more frequently during single leg deceleration activities such as cutting, pivoting or landing from a jump. As such, unilateral landing tasks are commonly utilized to study non-contact anterior cruciate ligament risk factors. Investigation of unilateral landing tasks often examines data from the participant’s dominant leg. LE dominance is frequently operationally defined as the LE the participant prefers to kick a ball with. The majority of ACL injuries however occur to the landing, or plant leg. The manner in which lower extremity dominance has traditionally been defined in studies and in the orthopedic literature hence may be problematic. The commonly utilized operational definition of limb dominance assumes that the left leg with which the participant prefers to kick a ball with is the same preferred leg a participant would choose for a unilateral landing task. Given the epidemiological data and injury rates, it is apparent that choosing the appropriate LE for testing is imperative.

To date, the authors were unable to identify any studies that examined the relationship between the preferred kicking LE and preferred unilateral landing LE. The purpose of this study was to determine the relationship between the preferred lower extremity (LE) when performing a unilateral landing and kicking task. The authors hypothesized a strong correlation between the LE chosen for each task would be evident.

METHODS
Participants
An a priori power analysis for correlation ($\alpha = .05$), using a medium effect size ($r = .4$) revealed a sample size of 37 subjects was required to achieve a power of .80. Subsequently, a convenience sample of 50 healthy, recreationally active, college-aged students was recruited. Inclusion criteria included no history of lower extremity surgery and no lower extremity injury within the prior six months, which necessitated the use of crutches for more than a day. In addition, participants were excluded from the study if they were unable to perform the drop vertical jump task or kicking a ball without pain.

Design
This investigation utilized a repeated measures counterbalanced design. Specifically, the order in which subjects were instructed to perform the two tasks was alternated from one subject to the next. All data acquisition took place in the Kristen McMaster Human Movement Laboratory and each participant followed identical procedures. Upon participant arrival to the laboratory, inclusion and exclusion criteria were reviewed to ensure eligibility. Prior to any data collection, participants provided written consent to participate in this University Institutional Review Board approved study.

Participants performed the two tasks (kicking a ball; unilateral drop jump landing) in a counterbalanced, alternating order. For the kicking task, participants were asked to kick a stationary soccer ball at a target five meters away using their preferred lower extremity. The participants completed five trials of this activity. The LE the participant chose to kick the ball with three out of the five trials was defined as their preferred kicking LE. For the landing task, the participants were instructed to stand on a 40cm (15.7 inches) high platform. Participants were asked to step off of the platform, land with both legs, immediately jump as high as they were able in a vertical direction and land then on their preferred LE. The participants completed five trials of this activity. The LE the participant chose to land on during three out of the five trials was visually determined by the investigator and defined as their preferred landing LE.

Statistical analysis was completed using commercially available software (SPSS v21, Armonk, New York, USA). Specific analyses included: 1) Standard descriptive statistics of subject characteristics (height, weight, sex, age); 2) Formulation of a 2x2 contingency
table for the kicking and landing tasks by side (right, left); 3) Phi-coefficient was used to determine the strength of the relationship between the landing and kicking tasks and the 4) Chi-Square analysis was used to determine if the two dichotomous variables were associated (test of independence).

RESULTS
Fifty healthy, recreationally active, college-aged students (age = 21.9±0.9 years; sex = 27 female; 23 male; mass = 73.3±18.4 kg; height = 170.6±10.8 cm) participated. Thirty-three participants kicked and landed with their right LE; 14 kicked with the right and landed on their left; two kicked and landed with their left and one participant kicked with their left and landed on their right LE (Table 1). The Phi Coefficient (φ = 0.18; p = 0.18) indicated little to no relationship between the LE with which a participant kicked a ball and performed a unilateral landing. Likewise, the Chi-square statistic revealed both observed and expected frequencies were not different (χ² = 1.76; p = 0.23).

DISCUSSION
The purpose of this investigation was to determine the relationship between the preferred LE for a unilateral landing task and for a kicking task. In contrast to the hypothesis, the results indicated that there was no significant relationship between the two functional tasks.

There is little discrepancy in the literature when defining upper extremity dominance. Defining lower extremity dominance is less clear. Previous investigations have provided clear definitions for LE dominance while others have utilized a battery of tests. Additional investigations have utilized the stance or weight-bearing LE for kicking a ball or the preferred single LE for landing task. The most common LE dominance operational definition however, involves the preferred LE for kicking a ball. Epidemiological evidence on ACL injuries contrasts with the rationale for LE selection in the majority of investigations. Data shows ACL injuries occur more frequently with a unilateral landing during a non-contact mechanism and do not occur as frequently to the kicking LE. The utilization of a consistent and task specific LE selection therefore, is essential for application of any research finding.

Prior work in dancers has suggested level of expertise may affect the preferred LE utilized for skill performance even where bilateralism is expected. While this study did not recruit participants from competitive sport teams or other populations with elevated knee injury risk, the sample was active and healthy. Expectations of possible knee injury risk from this sample although not profound, were not unreasonable. Because of this, research with a competitive athlete population would be indicated for improved application of findings.

The authors believe that this study is the first to examine the relationship between the preferred LE for unilateral landing and for kicking a ball. The results of this study show that the leg one prefers to kick a ball with and the leg one prefers to perform a unilateral landing task with are not necessarily the same. Given this, previous injury risk identification investigations may have obtained results from the LE less likely to be injured as a result. The authors however acknowledge the data are only generalizable to a similar population of healthy college aged individuals. Future study should examine whether the results of this study would hold true in a population of collegiate athletes from various sports (e.g. basketball, volleyball, soccer) where LE injury risk is heightened and preferred lower extremity may be sport specific.

CONCLUSIONS
The results of this study indicate that the lower extremity one chooses to kick a ball with has little to no relationship to the limb one chooses to land on. The authors encourage future investigations which explore lower extremity kinematics and kinetics at

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<th>Table 1. 2x2 Contingency table showing frequency of preferred lower extremity for kicking and landing tasks (n = 50).</th>
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foot contact to consider an operational definition of LE dominance that examines the preferred single LE for landing. The authors feel that information from this study improves clarity for operationally defining LE dominance. Further, the results of this study provide a basis from which future study can determine if LE dominance is associated with the side on which non-contact ACL injury occurs. Clinicians and investigators alike are encouraged to be cognizant how they operationally define lower extremity dominance. This notion is particularly relevant during screenings which attempt to identify and quantify lower extremity injury risk.

REFERENCES

**ABSTRACT**

**Background:** The modified Star Excursion Balance Test (mSEBT) and Y-Balance Test (YBT) are two common methods for clinical assessment of dynamic balance. Clinicians often use only one of these test methods and one outcome factor when screening for lower extremity injury risk. Dynamic balance scores are known to vary by age, sex and sport. The physically active adolescent female is at high risk for sustaining lower extremity injuries, specifically to the anterior cruciate ligament (ACL). Thus clarity regarding the use of dynamic balance testing results in adolescent females is important. To date, no studies have directly compared the various outcome factors between these two dynamic balance tests for this population.

**Purpose:** To determine if there was an association between the mSEBT and YBT scores for measured reach distances, calculated composite score and side-to-side limb asymmetry in the ANT direction in physically active healthy adolescent females.

**Study Design:** Cross-sectional study.

**Methods:** Twenty-five healthy, physically active female adolescents (mean age, 14.0 ± 1.3 years) participated. Reach distances, a composite score and side-to-side limb asymmetry for the mSEBT and YBT, for each limb, were compared and examined for correlation.

**Results:** There were significant differences and moderate to excellent relationships between the measured reach directions between the mSEBT and the YBT. Injury risk classification, based on limb asymmetry in the anterior reach direction, differed between the tests. However, the calculated composite scores from the two tests did not differ.

**Conclusions:** Performance scores on a particular reach direction should not be used interchangeably between the mSEBT and YBT in physically active adolescent females, and should not be compared to previously reported values for other populations.

**Level of Evidence:** Level 3.

**Key Words:** dynamic balance; lower extremity; movement system; screening tool.
INTRODUCTION
Clinicians often use dynamic balance tests as a functional screen to identify athletes at-risk of injury, assess deficiencies following injury, and monitor rehabilitation progress. The Star Excursion Balance Test (SEBT) and Y-Balance Test (YBT) are two reliable methods commonly used to clinically assess dynamic balance of the lower extremity. The time consuming eight-reach direction SEBT is often modified (mSEBT) to use only three reach directions: Anterior (ANT), Posteromedial (PM) and Posterolateral (PL). The commercially available YBT apparatus (Move2Perform, Evansville, IL) is an instrumented version of the mSEBT, designed to improve repeatability and standardize test procedures. Both the mSEBT and YBT simultaneously assess range of motion, flexibility, neuromuscular control and strength. Within each test, there are a number of factors that can be reported and analyzed to assess lower extremity injury risk, such as the maximal reach distance measured in specific reach directions, a calculated composite score and side-to-side asymmetries in the anterior reach direction. Normative dynamic balance performance scores vary depending on the age, sex or specific sport played of the population. Ankle injuries have been linked to a reduced reach distance in the PM direction in recreationally active college students, while ankle sprains in high school and college football athletes were linked to a reduced reach distance in the ANT direction. Normalized composite scores of less than 94% on the mSEBT in high-school female basketball players and less than 86.5% in college football players on the YBT indicate a significant risk of sustaining lower extremity injuries, specifically to the anterior cruciate ligament (ACL) of the knee. Active adolescent females are four to six times more likely than males to sustain an ACL injury when participating in the same sports. Additionally, young female athletes who return to sport following an ACL injury have the highest rate of re-injury (ipsilateral and contralateral) and are at 30-40 times greater risk of ACL injury compared to injured adolescents. Clinicians may be incorrectly classifying young female athletes by inadvertently interchanging indices of performance between the mSEBT and YBT, or using injury-risk thresholds that have been established for a different population.

The purpose of the current study was to determine if there was an association between the mSEBT and YBT scores for measured reach distances, calculated composite score and side-to-side limb asymmetry in the ANT direction in physically active healthy adolescent females. As there are reported inconsistencies between the tests in an adult population, it was hypothesized that measured reach distances, a calculated composite score and side-to-side limb asymmetry for the ANT reach direction will differ between the mSEBT and YBT for physically active healthy adolescent females.

METHODS
Participants
Following approval from the University of Manitoba’s Health Research Ethics Board (H2014:302), 25 recreationally active adolescent females with no...
Recent trauma to the lower extremity were recruited from the community to participate in this laboratory-based study. An a priori power analysis using data from a previous study of healthy recreationally active adults indicated that 22 subjects would be adequate to assess the mSEBT. Inclusion criteria stated that volunteers were required to be female, 12-18 years of age, with no history of a lower limb musculoskeletal injury or concussions in the prior six months. Participants were excluded if they failed a standardized screening criteria protocol by having knee joint effusion, being unable to fully flex and extend the knee joint, demonstrating quadriceps lag with an active straight-leg raise, having quadriceps strength less than 75% of the unaffected leg on manual muscle testing or being unable to perform 10 consecutive pain free hops. Informed consent was obtained from parents and participants prior to initiation of study activities.

**Testing Protocol**

Demographic information, such as age, leg dominance (based on the leg preference for kicking a ball) and sport participation were collected. Maturation status was determined using the self-reported pubertal maturation observational scale (PMOS). The Physical Activity Questionnaire for Adolescents (PAQ-A) assessed physical activity level as a score of 1-5, 1 indicates a subject is minimally active and 5 extremely active. Anthropometric data including height and weight were measured. The mSEBT and the YBT were completed according to previously described protocols, and required subjects to perform testing while barefoot, maintaining their hands on their hips. For the mSEBT, subjects performed a series of single-limb squats using the non-stance limb to touch a point a maximum distance along designated lines on the ground (Figure 1). The mSEBT has been established as a reliable measure of dynamic balance in adolescents, with intra-rater intraclass correlation coefficients (ICCs) ranging from 0.82 to 0.87 and coefficients of variation ranging from 2.0% to 2.9%. Lab pilot study results indicated inter-rater ICCs ranged from 0.69 to 0.95 for the YBT reach directions and from 0.59 to 0.75 for the SEBT reach directions.

The YBT (Move2Perform, Evansville, IL) is a commercially available, instrumented product that is used to evaluate the same three reach directions as the mSEBT (Figure 2). Subjects maintain a one-legged stance on an elevated stance platform from which three pieces of plastic pipe extend in the specific ANT, PM and PL directions. With the non-stance foot, participants push an indicator to a maximum distance along the pipe, marked with 0.5 cm increments. A previous study indicated that the YBT is a reliable method for assessing dynamic balance; within session inter-rater ICCs 0.54 to 0.82 and typical error values of 5.9% in children. For both tests, subjects performed the recommended four practice trials, in each direction prior to completing the three test trials on each limb. A standardized order of testing was utilized, the right stance limb was measured first in the order of ANT, PM and PL. Testing was repeated in the same order for the left stance limb. If the subject removed their figure.

**Figure 1.** Modified star excursion balance test (mSEBT) for the left stance limb. a: Anterior reach direction; b: Posteromedial reach direction; c: Posterolateral reach direction.
hands from their hips, lost their balance or rested their reaching foot on the ground (mSEBT), kicked the reach-indicator plate to gain more distance (YBT), made contact with the ground on the reach or return to bilateral stance to gain balance, or lifted or shifted any part of the stance foot the trial was considered incomplete, and was repeated. The distance of the toe touch reached along each direction was marked and subsequently measured by an investigator for the mSEBT, while the most proximal edge of the reach indicator from the apex of the YBT was recorded.

The average of three successful test trails for each reach direction was used for data analysis. Limb length (LL) was measured from the anterior superior iliac spine to the most distal aspect of the ipsilateral medial malleolus in supine lying. All reach distances were normalized as a percentage of the stance limb length using the formula \[\% = \left( \frac{\text{ excursion distance}}{\text{LL}} \right) \times 100\]. A composite score, which is an average of all three reach distances, \[\text{Comp} = \left( \frac{\text{ANT} + \text{PM} + \text{PL}}{3 \times \text{LL}} \right) \times 100\] was also calculated for each limb. The absolute difference in the anterior reach direction distance (centimeters) between limbs was calculated to assess side-to-side asymmetry.

Statistical Analysis

Descriptive data for both the mSEBT and YBT were calculated. Student paired t-tests were used to test the differences in reach distance scores between limbs and between the mSEBT and YBT. For the measured reach distance scores of the mSEBT differences of at least 6-8% are needed to feel confident that a clinical change in performance has occurred. A Bonferroni correction alpha level of \(p < 0.004\) (0.05/12) was used to compare the right and left limb because of the standardized test order of mSEBT followed by YBT, with the right limb reach directions always tested prior to the left limb. An alpha level of \(p < 0.05\) was set for all other comparisons. Effect sizes (Cohen’s d) for the differences between the mSEBT and YBT scores were calculated with values less than 0.2, 0.21 to 0.79, and above 0.80 considered to represent weak, moderate and strong effects, respectively. Pearson correlations and Bland-Altman assessments of agreement were used to compare performance on all three reach directions and the composite score for the mSEBT and YBT. Correlation coefficients \((r)\) of 0.25-0.49, 0.50-0.74, and 0.75-1.0 were considered to represent weak, moderate and excellent relationships, respectively. The absolute difference in the anterior reach distance (centimeters) between limbs was assessed with Student paired t-tests, and compared with the established absolute side-to-side asymmetry injury risk cut-off value of greater than 4 cm.

RESULTS

Demographic information and anthropometric data for participants are presented in Table 1. Results indicate that participants were predominantly post-pubertal adolescents with a normal BMI, right leg dominant and participated in a variety of sport activities. Separate 1-way analysis of variance based on maturation status and activity level indicated that these factors had no significant impact on dynamic...
balance reach direction scores, thus all subjects were grouped together for comparison of the tests. Comparison between the right and left limb indicated that there were no statistically or clinically significant between limb differences for either the mSEBT or the YBT. Statistically and clinically significant differences were observed between the mSEBT and YBT for all three measured reach directions. However, no significant differences were noted between the two procedures for the calculated composite scores or absolute asymmetry in the anterior direction (Table 2). Effect size calculations indicated that results were moderate to strong for all three measured reach distances, but weak for the composite score and absolute asymmetry. Pearson product-moment correlation coefficients between the mSEBT and YBT indicated a moderate to excellent relationship for all the measured reach directions, except the left limb in the anterior direction and the right limb in the posterolateral direction which both had a weak relationship (Table 3). Bland-Altman assessments of agreement between the mSEBT and YBT indicated that there was a bias between the three reach directions, however the calculated composite scores showed good agreement (Table 4). Two subjects had a greater than 4 cm absolute asymmetry in the anterior direction for the mSEBT and a different two subjects for the YBT (Figure 3).

**DISCUSSION**

This is the first report to compare the results from the mSEBT and YBT with a healthy physically active

<table>
<thead>
<tr>
<th>Table 1. Participant demographic and anthropometric information, reported as mean ± SD, (95% confidence interval).</th>
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<tbody>
<tr>
<td><strong>Adolescent Females (N=25)</strong></td>
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<tr>
<td><strong>Age, y</strong></td>
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<tr>
<td>Maturation status, n</td>
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<tr>
<td>Pre-pubertal</td>
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<tr>
<td>PAQ-A scale</td>
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<td>Leg dominance, n</td>
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<td>Right</td>
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<td>Sports, n</td>
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<td>Basketball</td>
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<tr>
<td>Cross country running</td>
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<td>Tennis</td>
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BMI= body mass index; PAQ-A= physical activity questionnaire for adolescents
female adolescent population that is at significant risk for lower extremity injury. The main finding of this investigation was that measured participant scores for the three reach directions differ between the mSEBT and YBT. The anterior reach distance was greater for the mSEBT than the YBT, interestingly the posteromedial and posterolateral distances were less for the mSEBT than the YBT. In contrast, the opposing skewness of the measured reach directions resulted in similar values for the calculated composite scores for the tests. Also the established injury risk cut-off score of greater than 4 cm absolute asymmetry in the anterior direction identified different subjects at-risk of injury depending on the test method. As a consequence, caution should be used when comparing the results from the mSEBT and the YBT for a healthy physically active adolescent female population. When comparing these scores to the reported values for other populations within the literature, the test scores should remain exclusive to their specific population and test method.20,21,23

Demographic data confirmed that participants were young, physically active individuals engaged in

| Table 2. Measured reach distances, calculated composite scores and absolute side-to-side asymmetry for the mSEBT and YBT, reported as mean ± SD, (95% confidence interval). |
|-------------------------------------------------|---------|--------|--------|--------|
| Anterior direction, % limb length                |         |        |        |        |
| Right limb                                      | 94.9 ± 6.4 (92.2, 97.5) | 65.6 ± 5.1 (63.5, 67.7) | < 0.01* 5.1 |
| Left limb                                       | 96.1 ± 5.1 (94.0, 98.2) | 57.0 ± 4.5 (55.1, 58.9) | < 0.01* 8.1 |
| Posteromedial direction, % limb length           |         |        |        |        |
| Right limb                                      | 90.1 ± 10.8 (85.6, 94.6) | 100.3 ± 7.0 (97.4, 103.2) | < 0.01* 1.1 |
| Left limb                                       | 90.7 ± 9.2 (86.9, 94.5) | 101.0 ± 6.9 (98.1, 103.8) | < 0.01* 1.3 |
| Posterolateral direction, % limb length          |         |        |        |        |
| Right limb                                      | 83.2 ± 11.9 (78.3, 88.1) | 98.5 ± 7.8 (95.3, 101.7) | < 0.01* 1.5 |
| Left limb                                       | 83.8 ± 11.9 (78.8, 88.7) | 101.0 ± 7.9 (97.7, 104.3) | < 0.01* 1.7 |
| Composite score, % limb length                   |         |        |        |        |
| Right limb                                      | 103.5 ± 10.9 (99.0, 108.0) | 102.1 ± 8.7 (98.5, 105.7) | 0.62 0.1 |
| Left limb                                       | 104.6 ± 10.7 (100.2, 109.0) | 103.6 ± 8.8 (100.0, 107.2) | 0.44 0.1 |
| Absolute asymmetry, cm                          |         |        |        |        |
| Anterior direction                              | 2.1 ± 1.8 (1.4, 2.8) | 2.0 ± 1.3 (1.5, 2.5) | 0.68 0.1 |

mSEBT= modified star excursion balance test; YBT= Y-Balance Test
* p < 0.05
† Cohen’s d
a wide range of sporting activities. This finding is important as it serves to extend the findings of other investigations on the YBT and mSEBT which focused on sport specific populations (such as basketball or soccer), age specific populations (i.e., college-aged or young adults), or specific competitive levels within sport (i.e., Division I or elite athletes). Data presented are representative of a typical adolescent female population that participates in a variety of sporting activities and is nearing or has recently reached physical maturation. Anthropometric data also help to confirm that our adolescent females were representative of a healthy population that included individuals with various body types (tall/short; thin/muscular, etc.). Again, this finding serves to enhance the overall generalizability of our results to a broad population of adolescent females. Clinical measures of dynamic balance are a

<table>
<thead>
<tr>
<th>Table 3. Correlation (r) between reach distances for the mSEBT and the YBT.</th>
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<tr>
<td>Anterior direction, % limb length</td>
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<td>Posteromedial direction, % limb length</td>
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<td>Posterolateral direction, % limb length</td>
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<tr>
<td>Composite score, % limb length</td>
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Abbreviations: mSEBT, modified star excursion balance test; YBT, y-balance test
* p < 0.05

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<th>Table 4. Bland-Altman assessments for agreement between the mSEBT and the YBT.</th>
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<td>Anterior direction, % limb length</td>
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<td>Posteromedial direction, % limb length</td>
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<td>Posterolateral direction, % limb length</td>
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D= mean difference; SDdiff = standard deviation of the difference
critical component of pre-participation screening in this population. If clinicians can accurately identify healthy adolescent female athletes who may be at an increased risk of sustaining lower extremity injuries, they can then advise and implement intervention strategies to address the factors associated with the epidemic of lower extremity injuries (especially to the ACL) seen in this population.

Two previous studies compared performance on the SEBT versus YBT for healthy active male and female adult populations. For reach in the anterior direction, both studies found a difference between the SEBT and YBT.\textsuperscript{20,21} One suggested that disparities in posture control strategies may be responsible for the differences between the tests, and hypothesized that the SEBT predominately relies on a feed-forward control strategy until contact is made with the toe touch.\textsuperscript{20} By comparison the same report suggested that during the YBT, constant proprioceptive feedback is received as the reach-foot toe remains in contact with the reach-indicator throughout the excursion (feedback control).\textsuperscript{20} Additionally, while the stance platform is relatively low, the slight elevation in stance position maintained during the YBT may also contribute to the decreased reach distance.\textsuperscript{20} The other study\textsuperscript{21} reported that the performance of the SEBT and YBT differed in relation to dynamic neuromuscular demands, as evident by the difference the anterior reach distances and associated kinematic profiles. For anterior reach, there was a negative correlation between reach distance and hip-joint sagittal plane angular displacement for the SEBT (i.e., as hip joint flexion increased, reach distance decreased). In contrast, there was a positive relationship between reach distance and hip-joint sagittal plane angular displacement during performance of the YBT (i.e., as hip joint flexion decreased, reach distance decreased).\textsuperscript{21}

In addition to anterior direction differences, the results indicate that the reach distances for the posteromedial and posterolateral directions also differed between the mSEBT and the YBT. This is not consistent with the findings of the two reports noted above.\textsuperscript{20,21} The sensorimotor system that regulates balance and postural awareness relies on information from the visual, vestibular and somatosensory subsystems.\textsuperscript{33} When reaching in the anterior direction subjects receive visual feedback on their performance. However, in the posteromedial and posterolateral directions visual awareness is lower, which places a greater reliance on the non-visual somatosensory system. Coughlan et al.\textsuperscript{20} reported that the reach distance achieved in the anterior direction was less for the YBT compared to the SEBT. When visual awareness was decreased in the posterior directions, a similar score was achieved between the SEBT and YBT. Their report suggested this increase in YBT performance relative to SEBT was due to the increased somatosensory feedback for the YBT due to the constant toe contact with the reach-indicator.\textsuperscript{20} An important difference between the previous studies and the present investigation is the demographic characteristics of participants. Subjects in that study were healthy adult males 22.5±3.05 years of age while this investigation assessed healthy adolescent females. Pubertal growth is reported to inhibit the sensorimotor functions of the lower extremity; thus, during dynamic postural control tasks adolescents heavily rely on visual cues.\textsuperscript{34} The impaired non-visual somatosensory systems in adolescents may be the reason why the same increase in YBT performance relative to the SEBT is not demonstrated in our population. This may explain why performance in the posterior reach directions of the mSEBT and YBT were different for subjects in this investigation, yet were the same in an adult population.\textsuperscript{20} Protocol variations in which testing in this investigation occurred during one session while these other two studies\textsuperscript{20,21} conducted each dynamic balance test a week apart may
have also contributed to the differences observed in the posterior reach directions. The present results indicate that female adolescent subjects performed differently on both the SEBT and YBT assessment methods when compared to an adult population. Caution should be used when interpreting and comparing reach distance performance for adolescents to those achieved by adults.

In addition to the measured reach directions, a composite score was calculated for both the mSEBT and YBT. Bland-Altman analysis of the data indicated that for the anterior reach direction, the mSEBT distance was greater than YBT. However, the mSEBT reach distances were less than the YBT for both the posteromedial and posterolateral reach directions. Thus, when the composite score was calculated, the positively and negatively skewed reach values resulted in a value which was similar between the two tests. The inherent scoring differences in different reach directions, and possible differences in overall dynamic balance, are concealed when the assessment only includes the composite score values. Therefore, it is recommended that when assessing dynamic balance, participant performance on the individual reach directions should be analyzed, in conjunction with the calculated composite scores, as results of this investigation indicates that examination of only the composite score may not accurately reflect the true differences in dynamic balance performance for each test. Composite score values alone are often used in the literature to assess sport-specific risk of injury. A normalized SEBT composite score of less than 94.0% was shown to indicate the risk of a lower extremity injury in high school basketball players. College football players who score less than 89.4% on the normalized YBT composite score are also at an increased risk of injury. As dynamic balance scores vary based on age, sex and sport it is unknown if this established injury risk cut-off value is appropriate for female adolescent athletes. This is the first report to compare injury risk classification based on limb asymmetry between the SEBT and YBT for the recreationally active female athlete. Analysis of raw anterior scores indicated that two subjects using the mSEBT and a different two subjects using the YBT had asymmetries of more than 4cm. Once again, results indicate that there is a difference between the two test methods for the specific population in this investigation. Further investigations of this population with a larger sample size are required to assess healthy and injured subjects to determine an appropriate cut-off value for each of the test methods.

Asymmetries between limbs is also often used as a screening tool to determine those who may be at increased risk of sustaining an injury. A difference in the raw anterior reach distance of more than 4cm between limbs for either the mSEBT or the YBT is clinically significant, and suggests a greater likelihood of sustaining a noncontact lower limb injury. Recently, Stifler et al. found that in Division I collegiate athletes' side-to-side asymmetry in the anterior reach direction of the SEBT was associated with injury. As dynamic balance scores vary based on age, sex and sport it is unknown if this established injury risk cut-off value is appropriate for female adolescent athletes. This is the first report to compare injury risk classification based on limb asymmetry between the SEBT and YBT for the recreationally active female athlete. Analysis of raw anterior scores indicated that two subjects using the mSEBT and a different two subjects using the YBT had asymmetries of more than 4cm. Once again, results indicate that there is a difference between the two test methods for the specific population in this investigation. Further investigations of this population with a larger sample size are required to assess healthy and injured subjects to determine an appropriate cut-off value for each of the test methods.

Typically, clinicians will only complete one dynamic balance test as part of an evaluation. Both the mSEBT and YBT are reliable; as such, either test would be appropriate to assess dynamic balance in adolescent females, however the tests should not be used interchangeably. Each test protocol has its own strengths and limitations. The mSEBT does not require costly equipment and allows an evaluator to assess five reach directions in addition to the three used for the modified protocol. However the toe touch is harder to quantify and control in
balance tests, however sample size was a limitation for the composite score and absolute side-to-side limb asymmetry. While future studies will need a larger sample size to establish normative values for both healthy and injured physically active adolescent females, this investigation is the first to report dynamic balance scores for a recreationally active adolescent female population, drawn from a diverse sporting population. Importantly, placement of the stance limb foot varies between the mSEBT and YBT: in the mSEBT, the heel is aligned to the center of the mSEBT grid, and for the YBT, the toes of the stance limb are aligned to the center of the grid. Differences in the anterior reach distances between the tests may be directly related to this variation. In future studies comparing the test procedures, the mSEBT should adapt the standardized foot position of the YBT.

CONCLUSION

The results of this study suggest that although both the mSEBT and YBT can be used clinically to measure dynamic balance, performance scores on a particular reach direction should not be used interchangeably between the mSEBT and YBT in this population. Since administration of the mSEBT and YBT protocols varies within the literature, specific detailed methodology should be carefully reviewed by clinicians and researchers when interpreting dynamic balance scores and using cut-off values to classify individuals at-risk of injury. Further research is clearly needed in order to establish normative values for the SEBT and YBT in the adolescent female population, and determine the limits of reliability for dynamic balance testing in healthy and ACL-injured individuals.

REFERENCES


28. Davies PL, Rose JD. Motor skills of typically developing adolescents: awkwardness or


ABSTRACT

Background: Adolescence is the stage of development marked by peak rates of skeletal growth resulting in impaired dynamic postural control and increased injury risk, especially in female athletes. Reliable tests of dynamic postural control are needed to help identify athletes with balance deficits and assess changes in limb function after injury.

Purpose: To estimate the interrater and test-retest (intrarater) reliability of the Y-Balance Test in a group of early adolescent females over a one-month period when administered by novice raters.

Methods: Twenty-five early adolescent females (mean age 12.7 ± 0.6 years) participated. Two physical therapy student raters, randomly selected from a pool of five, simultaneously assessed each subject's performance on the Y-Balance Test and were blinded to each other's results. Twenty-one subjects returned for a second session (mean 32.3 ± 9.6 days) and were assessed by the same two raters, blinded to previous measurements. Maximum and normalized reach distances and composite scores of the right and left limbs were collected. Intraclass correlation coefficients (ICC) were calculated for between rater and between session agreement. Measurement error and minimal detectable change values were calculated for clinical interpretation.

Results: Interrater reliability was excellent for all reach directions and composite scores of the right limb (ICC 0.973-0.998) and left limb (ICC 0.960-0.999) except for the day 1 left anterior reach which was good (ICC 0.811). Test-retest reliability were moderate to excellent for the right limb (ICC 0.681-0.908) and moderate to good for left limb (ICC 0.714-0.811). Minimal detectable change values for the right and left limbs ranged between 2.02-3.62% and 2.77-3.63%, respectively.

Conclusions: The Y-Balance Test is a reliable tool to assess dynamic balance in early adolescent females and may be utilized in a clinical setting to monitor function over a one-month time interval. Between rater differences were mainly attributed to disparities in subjective test requirements and not quantitative measures of reach distance.

Level of Evidence: Level 2

Key Terms: adolescent female, dynamic balance, movement system, reliability, Y-Balance Test
INTRODUCTION

Adolescence is the stage of development characterized by accelerated rates of physical growth, redistribution of adipose tissue, increased length of long bones, and increased joint forces and torques. To better attempt to homogenize the wide range of physical, emotional, and cognitive changes that occur during this phase, adolescence is dichotomized into two distinct phases. Though widely variable, early adolescence, typically begins around age 11 in females and 14 in males while late adolescence begins a few years later, and may persist into the third decade of life. Despite the benefits of youth sports participation, adolescent females are at an increased risk of lower extremity injuries in comparison to their male counterparts, and may be partially explained by the absence of a neuromuscular spurt and resultant muscle strength and recruitment pattern deficits. Additionally, the incidence of ACL injuries are greatest during the high school years and recommendations support the implementation of targeted neuromuscular control interventions to high risk populations prior to the time of peak injury risk.

Sophisticated measures of dynamic postural control, such as stabilometry, are able to detect subtle deficits in young athletes, but are expensive and may not be readily available in a clinical setting. The Y-Balance Test (YBT) is a low-cost, clinical measure of dynamic balance that mimics the demands of sports requiring unilateral balance. The YBT assesses limb symmetry utilizing a unilateral lower extremity reaching task in three different directions (anterior [ANT], posteromedial [PM], and posterolateral [PL]) (Figure 1). When used as a screening tool, an anterior reach asymmetry greater than 4cm between limbs has been associated with an increased risk of sustaining a lower extremity injury in division I collegiate athletes. It has also been used as a clinical outcome measure to gauge functional improvement and guide activity progression following injury. The reliability of the YBT has been studied on various populations by raters of varying levels of experience. Plisky et al reported good to excellent interrater (ICC 0.99-1.0) and intrarater (ICC 0.85-0.91, 95% CI 0.62 -0.96) reliability in individual reach directions and composite scores when assessed by experienced raters in a group of healthy young adults with a mean age of 19.7 years old. Similar findings of interrater (ICC 0.85 to 0.93, 95% CI 0.75-0.96) and intrarater (ICC 0.80-0.85 , 95% CI 0.68-0.91) reliability have been reported when the YBT was administered by raters with minimal testing experience. Additionally, Faigenbaum et al reported excellent interrater reliability (ICC >0.995) and moderate to good between session intrarater reliability (0.907≤ICC≤0.974) in a group of preadolescents ages 6-12 years old.

Though the YBT has been found to be a reliable tool for preadolescent, late adolescent, and adult athletes, developmental differences exist between

Figure 1. Performance of Y Balance Test (A) left anterior reach, (B) left posteromedial reach, and (C) left posterolateral reach.
These populations and the early adolescent female. It is also unknown whether the YBT may be used for pre-participation screening purposes within this population by those with limited experience in assessing human movement such as coaches, physical education teachers, and students. Additionally, due to the rapid growth during this maturational phase, outcome measures should be stable over typical, clinical test-retest time intervals to ensure improvements in test performance actually reflect true functional change. Therefore, the purpose of this study was to assess the inter- and intra-rater (test-retest) reliability of the YBT in a group of early adolescents ages 12-14 and over a one month period when administered by novice practitioners. It was hypothesized that YBT is a reliable tool to assess the dynamic postural control of early adolescent female athletes when administered by novice raters.

METHODS

Participants

A convenience sample of 26 multisport female athletes, ages 12-14, was recruited from local community-based recreational programs between May and September of 2017. Participants had no prior experience performing the YBT. To be included in the study, participants demonstrated > 35 degrees of ankle range of motion on the dorsiflexion lunge test, with no more than a 5-degree side-to-side difference, and ability to stand unsupported on one leg for at least five seconds without a loss of balance. Exclusion criteria included lower extremity amputation, cognitive deficits, vestibular disorders, blindness in at least one eye, current or undergoing treatment for inner ear, respiratory infection, or head cold, cerebral concussion within the prior six months, lower extremity injury in the prior three months (diagnosed by a medical professional and missed day of athletic or recreational activity), or lack of medical clearance for athletic participation. This study was approved by the New York Institute of Technology Institutional Review Board and written informed consent was obtained from parents/legal guardians along with subject verbal and signed assent prior to study participation.

Study Protocol

Participants were asked to perform the YBT on two separate days, three to five weeks apart. After screening for inclusion and exclusion criteria, each subject viewed a standardized video recording outlining the YBT testing procedure. Any questions regarding YBT performance were answered at this time. Two raters were randomly selected from a pool of five raters. Raters were all students in their second-year doctor of physical therapy program and were trained to administer the YBT via a one hour web-based tutorial. Raters had an additional two-hour practice session to familiarize themselves with the YBT procedure and instrument. Supervision was provided by a licensed physical therapist with 13 years of clinical experience who utilizes the YBT clinically.

YBT Protocol

YBT testing protocol was similar to the one previously described by Plisky, et al.23 All practice and testing was performed on the commercially available Y-Balance Test Kit™ (Move2Perform, Evansville, IN). To perform the YBT, the participant stood barefoot with one foot on the center foot plate and the most distal aspect of the toes just behind the starting line. Reach side and direction was operationalized in reference to the stance limb. While maintaining single-leg stance, the subject was instructed to push the reach indicator with the reach foot as far as possible and return to the original start position. A trial was determined unsuccessful if the subject failed to maintain unilateral stance on the platform, kicked the reach indicator, used the reach indicator for support, or did not return to the start position under control.23 Reach distance was measured at the nearest edge of the reach indicator to the closest 0.5 centimeter.

Prior to formal testing, each subject performed six practice trials in each of the three reach directions on each leg.24,26 During practice trials, raters highlighted the importance of maintaining single leg stance and offered feedback regarding errors in test performance. Following the these trials, a rest period was allotted where one rater recorded the subject's height to the nearest 0.5 cm using a wall mounted measuring tape, body mass to the nearest 0.1 kg using a digital scale, and leg length in supine to the nearest 0.5 cm, measured from the subject’s ASIS to the medial malleolus.
Testing order for formal test trials was standardized across all subjects and included three sequential reaches in each of the six directions; right ANT, left ANT, right PM, left PM, right PL and left PL. Each rater was blinded to the other’s results and no feedback was offered as they simultaneously observed a single trial. To reduce bias and analyze reasons for interrater discrepancies (quantitative measurement error or subjective decisions regarding test success) each rater recorded the distance reached and if the trial was successful or unsuccessful, but did not share this information with the subject or other rater. After three trials, the raters were asked if they had recorded a least one successful trial for the respective reach direction. If they did not, the subject was asked to perform an additional trial, in that particular direction, until a successful trial was recorded. Three to five weeks later, an identical testing protocol was performed by the same two raters, blinded to the first day results. (Figure 2) This test-retest time frame was chosen to mimic a typical interval between reassessments often utilized in a clinical setting.

The maximum reach distances for each direction and composite (COMP) scores (sums of the maximum distances for each limb) were utilized for analysis. To allow for between subject comparisons, both individual reach and COMP scores were normalized by dividing by the leg length of the contralateral (reaching) limb. Scores were calculated with trials that were deemed successful and adhered to all YBT standards. To examine differences between raters’ ability to determine test success, “modified” YBT scores were also calculated. These scores differed from typical YBT protocol as they utilized maximum reach distances from both successful and unsuccessful trials and disregarded raters’ subjective decisions pertaining to trial success (i.e. inability to maintain unilateral stance on the platform, kicked the reach indicator, used the reach indicator for support, or did not return to the start position under control).

The Guidelines for reporting reliability and agreement studies (GRRAS) was used to ensure the quality of reporting the findings of this study.27

Figure 2. Schematic of Study Protocol.
Statistical Analysis
Means and standard deviation or medians and the range as the interval from minimum to maximum were computed to describe demographic data and the outcome measurements. Paired t-tests were applied to test the significance of change between sessions for the demographic variables. Intraclass correlation coefficient (ICC) in an appropriate model was computed to assess the reliability as the agreement between raters (ICC 2, 1) and between sessions (ICC 3, 1). 95% confidence interval of the ICC was also computed to estimate its precision. The range of ICC values was described using the classification described by Fisher, where ICC < 0.5 was considered poor, 0.5 < ICC < 0.75 was considered moderate, 0.75 < ICC < 0.9 was considered good and ICC > 0.9 is was considered excellent. Measurement error was assessed by the square root of mean squared error (RMSE) and the standard error of measurement (SEM). The minimal detectable change (MDC) computed as $1.96 \times \sqrt{2} \times$ SEM was reported for clinical interpretation. All statistical procedures were performed using SPSS version 23 (IBM SPSS Statistics., Armonk, NY).

RESULTS
Of the twenty-six subjects recruited and screened, one subject was deemed ineligible (did not meet dorsiflexion ROM requirements) for a total of 25 participants. Of those 25 that participated in the first day of testing, two subjects did not return for the second day of testing while two others sustained a lower extremity injury between testing sessions (toe fracture and ankle sprain) for a total of 21 participants who completed both days of testing. Subject characteristics (Table 1) and performance data were analyzed and subgrouped to correct for subjects lost to drop out: first day of testing for all 25 subjects, first day of testing of those subjects that returned for the second day of testing, and those that returned on the second day of testing. There were significant differences in height ($p=0.016$) and weight ($p=0.003$) between sessions in the subgroup of 21 subjects that participated in both test days.

YBT mean reach distances, standard deviations, median reach distances, range, and normalized reach distances of each limb and direction are reported in Table 2. Interrater reliability calculations were calculated separately for the 25 pairs of observations from day one and 21 pairs of observations from day 2. Test-retest (intrarater) reliability calculations included the 21 pairs of between session observations made by the same rater, for a total of 42 data points.

Interrater reliability
Interrater reliability of YBT scores are presented in Table 3. Day 1 values were excellent for the all reach directions and COMP scores of the right limb (ICC 0.973-0.992) and left limb (ICC 0.960-0.989) except for the left ANT reach which was good (ICC 0.811). For day 2, interrater reliability of YBT scores were excellent for all reach directions and COMP scores of the right limb (ICC 0.988-0.998) and left limb (ICC 0.993-0.999).

Within session total error expressed as a percentage of the mean reach distance was greatest for the left ANT direction of day 1 of testing (6.26%) with all other reaches for both days being less than 3% error. SEM was less than 2% of the mean reach distance for all directions and limbs.

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<th>Table 1. Subject Demographics.</th>
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<td>Day 1 (n=25)</td>
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<td>Day 1 (n=21)^‡</td>
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<td>Day 2 (n=21)^†</td>
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<td>p value between day 1 and 2^†</td>
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* SEM = centimeters; kg = kilograms
‡ Subgroup of subjects from day 1 not lost to follow up
† Average time between test days 1 and 2 = 32.3 days (9.6)
directions and COMP scores of the right limb and left limb (ICC 0.998-0.999)

**Test-retest (intrarater) reliability**

Test-retest (intrarater) reliability, measures of error, and MDC scores are represented in Table 5. Test-retest (intrarater) reliability of YBT scores were moderate to excellent right limb (ICC PM 0.681-ANT 0.908) and moderate to good for left limb (ICC PL 0.714 - ANT 0.811). Less than 10% between

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**Table 2. YBT Reach Distances.**

<table>
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<th>Mean reach cm (SD)</th>
<th>Median Reach cm (range)</th>
<th>Normalized mean reach (SD)</th>
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<tbody>
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<td>Day 1 (n=25)</td>
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<tr>
<td>Right</td>
<td>LEFT</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>ANT</td>
<td>56.5 (6.2)</td>
<td>57.5 (5.8)</td>
<td>57.3 (43.0, 67.3)</td>
</tr>
<tr>
<td>PM</td>
<td>84.4 (9.6)</td>
<td>85.8 (8.8)</td>
<td>84.0 (64.8, 106.0)</td>
</tr>
<tr>
<td>PL</td>
<td>83.8 (8.7)</td>
<td>85.3 (10.6)</td>
<td>83.3 (63.0, 102.0)</td>
</tr>
<tr>
<td>COMP</td>
<td>224.7 (21.0)</td>
<td>228.6 (22.8)</td>
<td>226.8 (179.0, 265.8)</td>
</tr>
<tr>
<td>Day 2 (n=21)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>LEFT</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>ANT</td>
<td>57.0 (6.6)</td>
<td>57.1 (5.9)</td>
<td>58.0 (43.0, 67.3)</td>
</tr>
<tr>
<td>PM</td>
<td>84.0 (9.7)</td>
<td>85.0 (8.9)</td>
<td>84.0 (64.8, 106.0)</td>
</tr>
<tr>
<td>PL</td>
<td>83.4 (8.3)</td>
<td>85.3 (10.7)</td>
<td>83.3 (63.0, 98.3)</td>
</tr>
<tr>
<td>COMP</td>
<td>224.4 (21.6)</td>
<td>227.4 (23.6)</td>
<td>227.8 (179.0, 265.8)</td>
</tr>
</tbody>
</table>

Means, standard deviations, medians, normalized mean reach distances, and ICC values were calculated for “modified” YBT scores from day 1 and 2 and are expressed in Table 4. Interrater reliability of “modified” YBT scores from day 1 were excellent for all reach directions and COMP scores of the right limb (ICC 0.973-0.992) and left limb (ICC 0.999-1.000) except for the left ANT reach which was good (ICC 0.860). Interrater reliability of “modified” YBT scores on day 2 were excellent for the all reach directions and COMP scores of the right limb and left limb (ICC 0.998-0.999)

---

**Table 3. YBT reach distance intrarater reliability and error.**

<table>
<thead>
<tr>
<th></th>
<th>ICC (21) (95% CI)</th>
<th>Within session total error (mean reach distance)</th>
<th>SEM (mean reach distance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td></td>
<td>Day 1</td>
<td>Day 2</td>
</tr>
<tr>
<td>Right</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANT</td>
<td>0.984 (0.965, 0.993)</td>
<td>0.995</td>
<td>0.988</td>
</tr>
<tr>
<td>PM</td>
<td>0.992 (0.981, 0.996)</td>
<td>0.988</td>
<td>0.971</td>
</tr>
<tr>
<td>PL</td>
<td>0.973 (0.940, 0.988)</td>
<td>0.998</td>
<td>0.996</td>
</tr>
<tr>
<td>COMP</td>
<td>0.987 (0.972, 0.994)</td>
<td>0.996</td>
<td>0.990</td>
</tr>
<tr>
<td>Left</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ANT</td>
<td>0.811 (0.616, 0.912)</td>
<td>0.993</td>
<td>0.982</td>
</tr>
<tr>
<td>PM</td>
<td>0.960 (0.911, 0.982)</td>
<td>0.997</td>
<td>0.993</td>
</tr>
<tr>
<td>PL</td>
<td>0.989 (0.976, 0.995)</td>
<td>0.999</td>
<td>0.998</td>
</tr>
<tr>
<td>COMP</td>
<td>0.982 (0.960, 0.992)</td>
<td>0.998</td>
<td>0.995</td>
</tr>
</tbody>
</table>

ICC= Intraclass correlation coefficient; CI= Confidence Interval; SEM= Standard error of measurement; ANT= Anterior; PM= Posteromedial; PL= Posterolateral; COMP= Composite

*Day 1 (n=25) and Day 2 (n=21)
session total error was observed for all reach directions (4.73%-8.48%). SEM percentages were all less than 2% of the respective mean reach distances. Test-retest (intrarater) MDC values for the right limb ranged between 2.02% (ANT) and 3.62% (PM) and 2.31% for the COMP score. Test-retest (intrarater) MDC values for the left leg ranged from 2.77% (ANT and PM) to 3.63% (PL) and 2.57% for the COMP score.

**DISCUSSION**

Reliable clinical measures of dynamic postural control may help identify individuals at higher risk of injury or assist clinicians in determining degree of functional improvement following injury. This study demonstrates that the YBT is a reliable tool for the early adolescent female population, even when administered by novice raters without significant training or experience. The YBT was developed as a modification to the Star Excursion Balance Test (SEBT) originally described by Gray.29 The SEBT assesses reaches in eight different directions, standardizes stance limb heel position, and utilizes a testing grid marked on the ground.30 To improve reliability and facilitate test administration, the YBT limits the amount of reaches to the three
most pertinent directions, does not require the rater to simultaneously monitor stance limb heel position and reach distance, and utilizes a standardized testing device to assist with reach measurement. Though studies have been performed on the reliability of the SEBT in adolescents, the kinematics and muscular demands differed between the SEBT and YBT and therefore should be considered independent assessments.

The findings of the current study are in agreement with other studies examining the reliability of YBT in healthy adults, male collegiate soccer players, and primary school-aged pre-adolescents. Interrater reliability of our study ranged from ICC 0.90-0.99 which is consistent with Plisky et al (ICC 0.97-1.0) where testing procedure utilized the commercially available YBT Testing Kit™. However, van Lieshout et al utilized grid marks on the floor and could explain their slightly lower interrater reliability values (ICC 0.87-0.92). Additionally, measurement error in this study was mostly attributed to discrepancies in rater decisions of test success, as the “modified” YBT scores, that did not account for subjective determinations of trial acceptability, demonstrated nearly perfect interrater reliability values.

Similar to previous findings, test-retest (intrarater) was found to be lower than interrater reliability and can be explained by the added variability of subject performance across testing sessions. Test-retest (intrarater) reliability of the current study ranged from 0.681-0.908 with the right PM reach score demonstrating the least between session reliability and the right ANT reach score being the most stable. These values are significantly lower than those reported by Plisky et al in a population of healthy adults with a mean of 19.7 years old and a test-retest time span of 20 minutes. The sample in the current study was significantly younger, with a mean age of 12.8 years. The adolescent female is a unique population, where dynamic balance deficits are escalated by the interaction of an immature neuromuscular system, peak maturational growth rates, and emergence of sex specific differences. In studies assessing performance of unilateral balance tasks of younger populations, between session reliability measures were also significantly lower than those of adults and further highlights population specific performance variation. Specifically, in a group of healthy adolescents from ages 12-16 years old with a test-retest interval of six days, the SEBT was found to have moderate to excellent interrater (ICC 0.59-0.95) and intrarater (ICC 0.68-0.95) reliability.

The time span between testing sessions in the current study was longer (32.3 ± 9.6 days) than previous studies in an attempt to improve external validity by mimicking a typical time interval between reassessments often performed in a clinical setting. Typically, methodologies in YBT reliability studies compare two separate tests ranging from 20 minutes to 7-10 days apart. Though results indicated moderate to excellent reliability, the time between testing sessions may partially explain why the between session reliability values were slightly lower than previous reports and should be considered when interpreting YBT re-assessments in early adolescent females. Despite slight reliability differences, total error and MDC values in limb reaches were similar between limbs and relative to previous work on the YBT. In the current study, the COMP scores were least sensitive to changes between sessions demonstrating a 5.2% and 5.7% right and left leg normalized score difference, respectively. Interestingly, the ANT reach direction demonstrated the most stable between session measure, requiring the least change in value to reflect true differences in YBT performance. This is helpful as the ANT reach has been able to identify those with a greater risk of lower extremity injury and identify those with chronic ankle instability. and is often utilized as a sports pre-participation screen.

The relative measures of between session total error were similar between right and left limbs, and are slightly elevated from those reported in healthy pre-adolescents. Interestingly, younger preadolescents in Grades 1 and 2 performed with greater error when compared to those in Grades 3-5, and was attributed to somatotype changes during early childhood. Early adolescents undergo similar changes including the redistribution of adipose tissue, increased muscular development, and leg length changes, however at more elevated rates. The fact that this sample had a significant increase in height and weight during the one month time interval is a testament to the rapid skeletal growth at this age. Therefore, it is
not surprising that dynamic postural control variations are pronounced during early childhood, plateau in later childhood, and re-emerge during early adolescence.

This study is not without limitations. Despite a sample size similar to other dynamic balance reliability studies, the small sample size may not accurately reflect the true normative reach scores and MDC values for this age population. Secondly, chronological age was used as a marker of early adolescence instead of more accurate means of assessment, such as Tanner staging, onset of menarche, or radiographs. This may limit results as determination of physical maturation based on chronological age may be highly variable within this population. The sample also included a healthy population of preadolescents, and thus findings may not correspond to early adolescents after injury. Lastly, though the raters had limited experience in YBT administration, they were all second-year doctor of physical therapy students, and had a basic knowledge regarding movement assessment. Thus, extrapolation to other professionals involved in supervising youth athletes, such as coaches, strength and conditioning specialists, and physical education teachers, should be done with caution.

Larger cohort research is needed in the future to better quantify normative values in this high-risk population. Additionally, future studies regarding the role of the YBT in injury screening is warranted to mitigate the negative effects of the maturational changes in females prevalent during this developmental phase. Finally, research pertaining to the responsiveness of the YBT following implementation of targeted neuromuscular training programs in those high-risk individuals is needed to determine the tool’s utility in the prevention and management of lower extremity injury.

CONCLUSION
The results of this study indicate that the YBT is a reliable tool that can be utilized to identify limb asymmetries and dynamic balance deficits in early adolescent females. Differences between raters were mainly attributed to subjective determinations regarding test success and not quantitative measurement of reach distance. Additionally, the YBT is a stable measure of neuromuscular control within this population over one month, and thus may be utilized within a battery of clinical tests to monitor function after targeted interventions and help guide decision-making regarding activity progression.

REFERENCES


ABSTRACT

**Background:** Deficits in dynamic neuromuscular control of the knee may contribute to the higher incidence of the anterior cruciate ligament (ACL), specifically in female athletes. Little is known about the effects of preventive training programs on muscle onset time and activation during functional tasks.

**Purpose:** The purpose of this study was to evaluate the efficacy of perturbation-enhanced neuromuscular training on hamstring and quadriceps onset time and activation, and knee flexion angle in female athletes with quadriceps dominance (QD) deficit during a tuck-jump (TJ) task.

**Study Design:** Quasi-experimental study

**Methods:** Thirty-one collegiate female athletes with neuromuscular quadriceps dominance deficit randomly divided into experimental (n=16) and control (n=15) group. The experimental group performed a six-week perturbation training (18 sessions). Electromyographic (EMG) assessment of quadriceps and hamstring activation and knee flexion angles during a TJ task were completed at baseline and after six weeks.

**Results:** A significant decrease in the preparatory (p=0.003) and reactive (p=0.013) quadriceps-hamstring (Q/H) co-activation ratio was found in the experimental group. Perturbation training markedly decreased latency in medial hamstring (MH) (p=0.001), vastus medialis (VM) (p=0.004) and lateral hamstring (LH) (p=0.031), while latency increased for rectus femoris (RF) (p=0.001) and vastus lateralis (VL) (p=0.023) during a TJ task. The experimental group had average increases of 41.1%, 40.8%, and 39.5% in initial knee flexion, peak knee flexion and knee flexion displacement angle during the TJ task, respectively.

**Conclusion:** Increased preparatory VM and MH activities and decreased Q/H co-activation ratio, decreased VM and MH latency represent preprogrammed motor strategies learned during the perturbation training. This observed neuromuscular adaptation during TJ task could potentially reduce the risk for non-contact ACL injury.

**Level of evidence:** 2

**Key Words:** Anterior cruciate ligament, Electromyography, Female, Knee flexion angle, Movement System, Muscle activation.
INTRODUCTION

Knee joint injuries are one of the most common injuries related to athletic activities, accounting for almost 10% to 25% of all injuries, and anterior cruciate ligament (ACL) comprises approximately 45% of them. ACL injury is associated with long recovery times and high socio-economic costs. Approximately 70% of ACL injury mechanisms are non-contact, and commonly occur during physical activities that require deceleration and acceleration, change of direction, landing, and pivoting maneuvers. Female athletes are two to eight times more likely than male athletes to sustain ACL injury. The reason for this difference could be due to the 2.7° to 5.8° greater quadriceps angle (Q angle), narrower A-shaped intercondylar notch, smaller ACL size, and increased medial posterior tibial slope. Analyses of videos recorded during non-contact anterior cruciate ligament (ACL) injury have repeatedly shown that awkward movements (i.e., decreased knee, hip, and trunk flexion which imply decreased sagittal-plane movement control) are potential risk factors for ACL injury. Electromyographical (EMG) studies have demonstrated that females may have sex-related differences in the muscle onset time during the athletic movement. Wojtys et al. reported that female athletes have a slower response of hamstring activation to anterior stress on the ACL (using anterior tibia translation tests) compared to male athletes in physical examination. Cowling and Steele reported sex differences in muscle activation strategies of the hamstrings musculature that contradicted the findings of Wojtys et al. Males activated their semimembranosis muscle later than females in the pre-landing phase and reached peak activity sooner. Medina et al. stated that female non-athlete subjects recruited vastus medialis (VM) slower than their athletic peers (127.1 vs 408.1 ms), but not slower than the male athletes (127.1 vs 275.7 ms). No significant differences were seen among the groups for hamstring musculature activation. Medina et al. demonstrated that there were no differences between female and male athletes for time to initial contraction of any muscle groups in a drop landing task. Sex differences in neuromuscular control, including ligament dominance, quadriceps dominance (QD), leg dominance, and trunk dominance likely contribute to ACL injury especially in females. The inter-limb differences in muscle recruitment patterns, muscle strength, and muscle flexibility tend to be greater in females than in males. The second dominance called QD refers to the method of stabilizing the knee joint by primarily using the quadriceps muscles. Females preferentially use quadriceps muscles to stiffen and stabilize the knee joint, as compared to males. Thus, females may exhibit higher activation of quadriceps muscles relative to hamstrings muscles increasing the risk of ACL injury in the landing phase.

During a jump-landing task, decreased knee flexion angle (0-30°) is another of the important mechanism for non-contact ACL injuries in females. Diminished knee-flexion angles and QD during the preparatory phase of a jump is influenced by high Q/H co-activation ratio. Furthermore, it seems the high Q/H co-activation ratio was largely influenced by diminished hamstrings activity rather than excessive quadriceps activity during the preparatory phase of a jump task. Walsh et al. performed a correlational analysis of Q/H co-activation ratio during a jump-landing task. The result of Walsh’s study indicated that Q/H co-activation ratio was significantly and negatively correlated with knee-flexion angle at initial contact (r = 0.442). It is also reported that Q/H co-activation ratio was negatively correlated with hamstrings activity, but not quadriceps. These findings suggest that interventions designed to enhance preparatory hamstring activity may be effective in minimizing the Q/H co-activation ratio and placing the knee in a more flexed position at initial contact thereby preventing ACL loading and injury. Walsh et al. suggested that investigations on ACL injury-prevention programs should be conducted to examine strategies to modify preparatory phase, Q/H co-activation ratio, and decrease quadriceps activation after ground foot contact.

In recent years, prevention of ACL injuries has become a key issue among researchers. Plyometric, balance training, agility training, and instructions for landing modifications with knee flexion more than 30° in jump-landing maneuver are common components of ACL injury prevention training programs. An increase in knee flexion has been reported as a...
result of conducting plyometric training,\textsuperscript{13} plyometric or balance training,\textsuperscript{14} and in response videotape feedback.\textsuperscript{15}

It has been suggested that ACL injury prevention programs should target the development of motor programs characterized by coordinated muscle activation.\textsuperscript{9,16,17} Perturbation training is a specialized neuromuscular training program designed to aid in the development of dynamic knee stability among individuals with complete ACL rupture.\textsuperscript{11,17} Although the influence of perturbation training has been studied in varied populations, the effects of this types of training on female athletes with unbalanced hamstring and quadriceps muscle onset time and activation as well as limited knee flexion angles during landing has not been well understood. Letafatkar et al. recommended perturbation training to female athlete's coaches as a means to eliminate the QD deficit and improve athletic performance.\textsuperscript{9} Further research should be performed to focus on how to modify quadriceps and hamstrings muscle onset times, activation, and knee flexion angle.\textsuperscript{5,4,18}

Therefore, the purpose of this study was to evaluate the efficacy of perturbation-enhanced neuromuscular training on hamstring and quadriceps onset time and activation, and knee flexion angle in female athletes with QD deficit during a tuck-jump (TJ) task. The first hypothesis was that the perturbation training group would experience significantly improvement in neuromuscular control and knee flexion angle. The second hypothesis was that the experimental group would experience more changes in neuromuscular control and knee flexion angle than those of the control group.

**METHODS**

**Study Design**

Pre - posttest control-group experimental design.

The independent variables were time (pre-test, post-test) and training intervention. The dependent variables were EMG measures including muscle onset time, average, and Q/H co-activation ratio, and knee flexion angle in initial contact, at peak knee flexion, and total knee flexion displacement. This study was approved by the Ethical Committee of the Tehran Medical University.

**Participants**

Based on the primary evaluation of 60 females, 31 collegiate female handball, basketball and soccer players with QD deficit, between 20 to 25 years of age, volunteered to participate in the study. The number of participants was based on the previous similar research.\textsuperscript{9} All subjects performed a TJ test to determine QD deficit. An experienced TJ tester assessed the test. A failed trial was defined as when the subjects 1) had an excessive landing contact noise, or 2) had peak knee flexion angle less than 30° during landing from TJ.\textsuperscript{9}

All subjects signed the informed consent and completed the health history questionnaires. The questionnaires were reviewed for inclusion and exclusion criteria. Risk and benefits of the study participation were individually explained to the subjects. Exclusion criteria included any lower extremity reconstructive surgery in the prior two years, and any lower-extremity injury or unresolved musculoskeletal disorders that prohibited subjects from sports participation. All subjects participated in off-season training that involved performing three sessions per week, 90 to 120 minutes for every session.

Random assignment was performed by participants selecting a sealed envelope to determine group allocation. Subjects were placed in either the experimental (n=16) group (mean height = 168.03±7.42 cm, body mass = 58.22±6.36 kg) or control (n=15) group (mean height = 167±9.90 cm, body mass = 59.30±7.81). Any subject who missed more than one training session was removed from the study. All control subjects were asked to refrain from any perturbation-type training. (Figure 1)

**EMG Assessment**

Data were collected by a surface EMG system (Mega-win ME6000, Jali Medical, Waltham, MA). The EMG data were collected from five muscles: Rectus Femoris (RF), VM, Vastus Lateralis (VL), Medial Hamstring (MH), and Lateral Hamstring (LH) of the dominant leg.

The dominant leg was defined as the leg used to kick a ball for maximum distance. The skin over the bellies of these muscles was prepared for electrode placement by shaving and cleaning the area
The maximum voluntarily contraction (MVC) values for each muscle were obtained by collecting one maximal five-second trial after a series of three warm-up trials performed at 50%, 75%, and 100% of maximal effort. The first and last seconds of the MVC trials were removed from the data to ensure only steady-state results during MVC test. The average activity during the middle three seconds of the MVC trial was determined for each muscle.

Data normalization was performed by dividing EMG raw signals into MVC data, and for standardization, the following equation was used, and the muscles activation was reported as the percentage of MVC.

\[
EMG = \left(\frac{EMG \text{ from TJ task}}{\text{average MVC in manual muscle testing position}}\right) \times 100.
\]

For MVC of the VMO, VL, MH and LH, the subject was asked to sit on a chair with the hips and knees at 90° and straps around the legs and trunk. The subject kicked forward on the strap to extend the knee for the quadriceps MVC, and pulled back on the strap to flex the knee for the hamstring MVC.

The Q/H co-activation ratios were assessed during the preparatory and reactive phases in a TJ task. The
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Q/H co-activation ratio was computed as the sum of the average EMG amplitude of the quadriceps (RF and VL) divided by the sum of the average EMG amplitude of the hamstrings (MH and LH) for each trial. The Q/H co-activation ratio was computed separately for each of the five TJ repetitions and then the average was taken. The preparatory phase encompassed 150 milliseconds before ground contact; the reactive phase consisted of initial ground contact to 350 milliseconds after ground contact.

The time to initial contraction was based on three standard deviations above baseline, as previously described and recorded during the quiet period before TJ. The footswitch, made by the researchers and placed under the forefoot, simultaneously was used to determine initial ground contact and onset of muscle activity for each trial. Initial ground contact was defined as the initial instant in time when the testing foot first came into contact with the ground.

All EMG data (TJ task and MVC trials) were band-pass filtered (10 to 350 Hz) and notch filtered (60 Hz at 1-Hz width) using a Butterworth filter (4th order, zero-phase lag) in the Megawin software package used for the EMG processing. The data were rectified and smoothed by taking the root mean square average of the EMG signal and using a 50-millisecond sliding window function. The data were exported to technical computing software (MATLAB ver. 7.0) for further analysis.

**TJ task assessment**

The TJ is known as a reliable (ICC = 0.88) measurement test to determine abnormal jump-landing mechanism. In the current study, the TJ was performed to measure the muscle onset time, muscle activation, and knee flexion angle assessment, before and after training. To perform the TJ, subjects started in a position with feet shoulder-width apart. Initially, they jumped from a slight downward crouched position, with extended arms behind the trunk. They then swung their arms forward as they simultaneously jumped straight up and pulled their knees up as high as possible. The subjects were instructed to get their thighs to parallel to the ground at the peak of the jump. The subjects were encouraged to immediately begin the next TJ to decrease downtime (or landing pause) between each jump.

The subjects were also instructed to land softly, using a toe to midfoot rocker landing, and to land in the same footprint with each jump.

**Experimental Procedures**

Subjects were first asked to perform a warm-up (bicycle ergometer for five to seven minutes, and dynamic stretching of both lower extremities for five minutes). Subjects were allowed a one-minute rest between test trials. Each subject then was allowed to practice three-reparation TJ preparation trials before data collection. In the next step, subjects performed the five-repetition TJ task, and the average scores of five repetitions were recorded. Subjects were allowed a one-minute rest between test trials.

During performing the TJ task on the footswitch, the EMG electrodes (as described above) and electrogoniometers (M110, Biometrics Ltd., Gwent, UK; ICC = 0.64-0.9722) applied to the dominant leg. The lower segment of the electrogoniometer (known as the shank) was fixed and the knee movement was obtained by moving the upper segment (known as the thigh). Meanwhile, muscle activation and knee flexion angles were measured. Knee flexion angle at initial contact, peak knee flexion angle, and knee flexion displacement during the landing phase of the TJ task were calculated for each trial. Knee flexion displacement was calculated by subtracting the knee flexion angle at initial contact from the peak knee flexion angle.

**Perturbation- enhanced neuromuscular training**

The subjects in experimental group performed eighteen sessions of perturbation-neuromuscular training over six weeks under the supervision of two investigators at the Physical Therapy Clinic according to the protocol described by Letafatkar et al. and Taylor.

Every training session lasted approximately one hour and consisted of rocker board (Figures 2, 3) roller board (Figure 4) and roller board/BOSU ball (Figure 5) activities with stationary platform perturbation drills. Progression of perturbation drills is shown in Table 1. The verbal instructions were provided to subjects for performing appropriate technique execution. The instructions included "keep your knees soft", "keep your trunk still", and
All subjects regularly participated in the scheduled off-season strength training, practices, and games and tournaments, but the experimental group also participated in a perturbation-enhanced neuromuscular training program three times a week over six weeks. The experimental group was given instructions and illustrations of each perturbation exercise. 

“relax between perturbations”. Ultimately, each subject was free to respond to the perturbation given the constraints of the drill and verbal cuing. Intensity, sport specificity, and the difficulty of the drills were progressed systematically. (Figures 7, 8, 9) Sequencing of each training session consisted of different perturbation drills. 

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**Figure 2.** Two leg rocker board.

**Figure 3.** One leg rocker board.

**Figure 4.** Roller board/stable (weight scale) surface.

**Figure 5.** Roller Board/BOSU ball.
before the first training session. Post-test were taken a day after the training program was completed.

Data Analysis
Descriptive data were calculated for all variables. A mixed-design repeated measure ANOVA (2 × 2) was used to test for interactions and main effects for time (pre- vs posttest) and group (perturbation training vs control) between the knee flexion angle and electromyography variables. Statistical analyses were conducted in SPSS (SPSS, Version 18.0, Chicago; IL). Statistical significance was established a priori at $p<0.05$ to test the directional (one-sided) hypothesis that perturbation training would be more effective than control in improving knee flexion angle and electromyography in active participants.

The effect size (Cohen's $d$) was calculated to determine the standardized mean difference for each variable. Effect sizes were classified as small ($d = 0.20$), medium ($d = 0.50$), or large ($d = 0.80$).

RESULTS
The perturbation training and control groups had a participation rate of 100% during the study period. A significant interaction of group and time was observed following the study with selected knee flexion angle and electromyography measures which indicate that training outcomes were different between perturbation training and control groups.

Table 1. Sample of perturbation training progression.

<table>
<thead>
<tr>
<th>Week</th>
<th>Exercises*</th>
</tr>
</thead>
</table>
| 1    | Two leg/ Rocker Board (A/P; M/L) (2×30-60 s) (Figure 2)  
One leg/ Rocker Board (A/P; M/L) (2×30-60) (Figure 3)  
Thera Band feedback training (A/P) (1×30-60) (Figure 4)  |
| 2    | Two leg/ Rocker Board (A/P; M/L) (3×30-60)  
One leg/ Rocker Board (A/P; M/L) (3×30-60)  
Thera Band feedback training (A/P) (2×30-60)  |
| 3    | Thera Band feedback training (A/P) (2×30-60)  
Roller Board/ Bosu ball (A/P; M/L; Diagonal) (2×30-60) (Figure 5)  
Simple sport specific technique on Rocker Board (2×30-60) (Figure 7)  
Moderate sport specific technique on Rocker Board (2×30-60) (Figure 8)  |
| 4    | Thera Band feedback training (A/P) (2×30-60)  
Roller Board/ Bosu ball (A/P; M/L; Diagonal) (3×30-60)  
Simple sport specific technique on Rocker Board (3×30-60)  
Moderate sport specific technique on Rocker Board (2×30-60)  |
| 5    | Simple sport specific technique on Rocker Board (3×30-60)  
Moderate sport specific technique on Rocker Board (3×30-60)  
Roller Board/ stable (weight scale) surface (2×30-60) (figure 8)  
Advanced sport specific technique on Rocker Board (2×30-60) (Figure 9)  |
| 6    | Simple sport specific technique on Rocker Board (3×30-60)  
Moderate sport specific technique on Rocker Board (3×30-60)  
Roller Board/ stable (weight scale) surface (3×30-60) (figure 8)  
Advanced sport specific technique on Rocker Board (3×30-60)  |

*30 s between sets and 2 min between exercises.  
A/P = anterior/posterior, M/ L = medial/lateral
Muscle Activation and Onset of Muscle Activation
A significant interaction of group and time was also found following the perturbation training program on muscle activation and the onset of muscle activation measures. Relative to control, the perturbation training program showed greater improvement in muscle activation [RF (P preparatory = 0.003, P reactive = 0.001); VM (P preparatory = 0.011, P reactive = 0.003); VL (P preparatory = 0.019, P reactive = 0.021); MH (P preparatory = 0.007, P reactive = 0.001); and LH (P preparatory = 0.023, P reactive = 0.042)] and the onset of muscle activation [RF (P = 0.001), VM (P = 0.004), VL (P = 0.023), MH (P = 0.001) and LH (P = 0.031)] from pretest to posttest.

Q/H co-activation ratio
A significant interaction of group and time was also found following the perturbation training program on Q/H co-activation measure. Relative to control, the perturbation program showed greater improvement in the Q/H co-activation ratio in preparatory phase from a mean (95% CI) pretest score of 1.50 ± 0.29 (1.28–1.63) to 1.18 ± 0.12 (1.03–1.43;
DISCUSSION

The purpose of this study was to determine the efficacy of a perturbation-enhanced neuromuscular training program on knee flexion angle as well as peak knee flexion angle from a mean (95% CI) pretest score of 51.55 ± 2.79 (48–54.21) to 72.59 ± 6.16 (67.13–79; p < .05) and knee flexion displacement angle from a mean (95% CI) pretest score of 24.40 ± 3.69 (21–26.37) to 34.03 ± 5.39 (28.91–39; p < .05).

Kinematic data

A significant interaction of group and time was also found following the perturbation training program on knee flexion angle measures. Relative to control, the perturbation training program showed greater improvement in the initial contact knee flexion angle from a mean (95% CI) pretest score of 28.29 ± 3.83 (25–29.32) to 39.92 ± 2.41 (36.23–42.03; p < .05), peak knee flexion angle from a mean (95% CI) pretest score of 51.55 ± 2.79 (48–54.21) to 72.59 ± 6.16 (67.13–79; p < .05) and knee flexion displacement angle from a mean (95% CI) pretest score of 24.40 ± 3.69 (21–26.37) to 34.03 ± 5.39 (28.91–39; p < .05).

Table 2. Demographic characteristics of participants, reported as mean +/- standard deviations.

<table>
<thead>
<tr>
<th>Variables</th>
<th>muscles</th>
<th>Phases</th>
<th>Group</th>
<th>Pre-test (Mean±SD)</th>
<th>Post-test (Mean±SD)</th>
<th>Intra-group differences</th>
<th>Inter-group differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF</td>
<td>Preparatory</td>
<td>Experimental</td>
<td>122.59±25.10</td>
<td>89.18±20.66</td>
<td>0.001*</td>
<td>p=0.003*</td>
<td>ES: 0.628</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>124.80±24.26</td>
<td>123.84±23.73</td>
<td>0.317</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VM</td>
<td>Preparatory</td>
<td>Experimental</td>
<td>56.51±11.65</td>
<td>78.88±13.76</td>
<td>0.009*</td>
<td>p=0.011*</td>
<td>ES: 0.621</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>51.73±9.07</td>
<td>52.69±9.25</td>
<td>0.315</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VL</td>
<td>Preparatory</td>
<td>Experimental</td>
<td>115.48±25.77</td>
<td>78.07±13.68</td>
<td>0.014*</td>
<td>p=0.019*</td>
<td>ES: 0.527</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>109.61±26.19</td>
<td>108.92±26.84</td>
<td>0.427</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MH</td>
<td>Preparatory</td>
<td>Experimental</td>
<td>40.74±9.78</td>
<td>76.62±13.44</td>
<td>0.002*</td>
<td>p=0.007*</td>
<td>ES: 0.675</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>35.69±7.66</td>
<td>35.53±8.11</td>
<td>0.248</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LH</td>
<td>Preparatory</td>
<td>Experimental</td>
<td>75.03±15.90</td>
<td>56.81±13.96</td>
<td>0.028*</td>
<td>p=0.023*</td>
<td>ES: 0.457</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>71.88±9.96</td>
<td>72.07±10.09</td>
<td>0.412</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q: H co-activation</td>
<td>Preparatory</td>
<td>Experimental</td>
<td>96.14±12</td>
<td>89.11±16.11</td>
<td>0.032*</td>
<td>p=0.042*</td>
<td>ES: 0.367</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>94.38±12.86</td>
<td>95.23±12.80</td>
<td>0.334</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Intra-group difference; † Inter-group differences

Note: All values reported as mean ± standard deviation (95% confidence interval).
The muscle spindles, the higher state of readiness of muscles to respond to disruptive forces and consequently the more improvement in joint stability.11

Muscle onset time of hamstring and quadriceps

In the pretest, there were no statistical differences between the experimental and control groups in the muscle onset time of all five muscles. In both groups, RF and VL demonstrated somewhat earlier recruitment than hamstrings. This improper muscle onset time may be due to the demands of the subject’s sport-specific task (football, handball, and basketball). Insufficient neuromuscular control in females could alter the recruitment of the knee muscles in landing tasks resulting in altered quadriceps and hamstrings activation strategies compared to males. Females may preferentially rely on higher activation of quadriceps muscles relative to hamstrings muscles as on hamstring and quadriceps muscle onset time and activation in athletes with QD deficit during the TJ task. It was hypothesized that a perturbation program would result in improvement of neuromuscular control as measured by EMG parameters and knee flexion angles during the TJ task in experimental group compared the control group.

Statistical analysis revealed that VM and MH pre-activation were significantly different between the experimental and control groups. A significant decrease in Q/H co-activation ratio may lead to improvement of dynamic stability to the sagittal plane at the knee and a significant increase in knee flexion in the decelerating phase of the TJ.

The findings of the current study may relate to ACL injury prevention. Perturbations can excite the afferent pathways that provide information to the muscle spindle. The more increased sensitivity of the muscle spindles, the higher state of readiness of muscles to respond to disruptive forces and consequently the more improvement in joint stability.11

Muscle onset time of hamstring and quadriceps

In the pretest, there were no statistical differences between the experimental and control groups in the muscle onset time of all five muscles. In both groups, RF and VL demonstrated somewhat earlier recruitment than hamstrings. This improper muscle onset time may be due to the demands of the subject’s sport-specific task (football, handball, and basketball). Insufficient neuromuscular control in females could alter the recruitment of the knee muscles in landing tasks resulting in altered quadriceps and hamstrings activation strategies compared to males. Females may preferentially rely on higher activation of quadriceps muscles relative to hamstrings muscles.

### Table 4. Intra- and inter-group differences for onset of muscle activation variable.

<table>
<thead>
<tr>
<th>Variables</th>
<th>muscles</th>
<th>Group</th>
<th>Pre-test (Mean±SD)</th>
<th>Post-test (Mean±SD)</th>
<th>Intra-group differences</th>
<th>Inter-group differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onset of activation (ms)</td>
<td>RF</td>
<td>Experimental</td>
<td>375.8±37.13</td>
<td>240.2±26.80</td>
<td>0.001*</td>
<td>p=0.001†</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>363.0±30.10</td>
<td>370.7±38.72</td>
<td>0.543</td>
<td>ES: 0.718</td>
</tr>
<tr>
<td></td>
<td>VM</td>
<td>Experimental</td>
<td>174.3±18.81</td>
<td>204.4±17.25</td>
<td>0.037*</td>
<td>p=0.004†</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>181.3±15.49</td>
<td>179.7±15.42</td>
<td>0.311</td>
<td>ES: 0.657</td>
</tr>
<tr>
<td></td>
<td>VL</td>
<td>Experimental</td>
<td>204.2±30.93</td>
<td>190.4±19.51</td>
<td>0.026*</td>
<td>p=0.023†</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>268.7±24.24</td>
<td>270.2±27.23</td>
<td>0.256</td>
<td>ES: 0.567</td>
</tr>
<tr>
<td></td>
<td>MH</td>
<td>Experimental</td>
<td>65.4±9.91</td>
<td>157.5±37.03</td>
<td>0.001*</td>
<td>p=0.001†</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>68.3±12.23</td>
<td>66.9±12.53</td>
<td>0.436</td>
<td>ES: 0.711</td>
</tr>
<tr>
<td></td>
<td>LH</td>
<td>Experimental</td>
<td>89.5±14.25</td>
<td>99.8±17.80</td>
<td>0.038*</td>
<td>p=0.031†</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>91.8±11.16</td>
<td>90.3±10.80</td>
<td>0.540</td>
<td>ES: 0.531</td>
</tr>
</tbody>
</table>

* Intra-group difference; † Inter-group differences.
ES= Effect size, RF= Rectus Femoris, VM= Vastus Medialis, VL= Vastus Lateralis, MH= Medial Hamstring, LH= Lateral Hamstring

### Table 5. Intra- and inter-group differences for kinematic variables during the Tuck Jump test.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Group</th>
<th>Pre-test (Mean±SD)</th>
<th>Post-test (Mean±SD)</th>
<th>Intra-group differences</th>
<th>Inter-group differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee kinematic</td>
<td>Initial contact</td>
<td>Experimental</td>
<td>28.2±3.83</td>
<td>39.9±2.41</td>
<td>0.027*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>27.1±3.29</td>
<td>26.0±3.14</td>
<td>0.673</td>
</tr>
<tr>
<td></td>
<td>Peak</td>
<td>Experimental</td>
<td>51.5±2.79</td>
<td>72.5±6.16</td>
<td>0.001*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>52.7±4.97</td>
<td>51.5±6.71</td>
<td>0.458</td>
</tr>
<tr>
<td></td>
<td>Displacement</td>
<td>Experimental</td>
<td>24.4±3.69</td>
<td>34.0±5.39</td>
<td>0.037*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Control</td>
<td>25.4±4.18</td>
<td>24.2±4.06</td>
<td>0.543</td>
</tr>
</tbody>
</table>

* Intra-group difference; † Inter-group differences.
ES=Effect size
Quadriceps earlier activation at knee flexion angles of less than 45° are antagonistic to the ACL, significantly increasing ACL strain. Conversely, the hamstrings are a dynamic ACL agonist. The combination of changes in quadriceps and hamstrings muscle onset time value among subjects after perturbation training resulted in a more balanced activation strategy that has the potential to reduce the possibility of ACL strain. Due to the medium to large effect sizes reported in this study, the increases and decreases in latency of quadriceps and hamstring are a direct effect of the perturbation training.

Muscle-Activation
The significant changes in EMG activity after six weeks of the perturbation-enhanced neuromuscular training included increased MH and VL muscle activation during the preparatory and reactive phases of landing. In the training sessions, subjects were instructed to keep a deep knee flexion angle and knees neutral (prevent from any sagittal and frontal-plane displacements by keep their knee in line with their toes) during landings and on the roller board/BOSU ball exercises. It is reported that peak activity of the hamstrings occurs between 50-70 degrees of knee flexion. Therefore, the subjects learned the correct posture and landing technique which could increase hamstrings activity. Nagano et al. suggested that increased hamstrings activity after the jump and balance training resulted from the altered muscular control of the lower extremity. The increased activity of MH and VM EMG could indicate greater functional knee stability at ground contact which may decrease the incidence of knee injury because it provides fast compensation for encountering external loads.

In the current study, the latency of MH decreased after six weeks of perturbation training in the experimental group. Improvement in the activation of MH may decrease the incidence of the ACL injuries at high flexion angles. Decreased hamstring latency may decrease the time required to stabilize the tibia before an anterior translation force occurs. It also, before the loading phase that occurs during ground contact, may help dynamically protect the integrity of the knee joint and surrounding structures. In addition, the decrement of hamstring latency is of particular importance in landing, where the reduction in the response time can lead to a lack of appropriate postural adjustments and increase in the loads experienced at the knee joint.

Consistent with Medina et al. after six weeks of perturbation training, a significant reduction in the muscle onset time of RF and VL was observed while the muscle onset time of VM, LH and MH were increased significantly. The training-induced change in muscle onset time of MH activity is a positive neuromuscular adaptation. Hamstring activation before ground contact (especially in female athletes) is a more desirable neuromuscular characteristic when attempting to reduce ACL injury risks.

Shultz et al. observed that after perturbation, a silent period occurs in the medial and lateral quadriceps. The silent period is likely to be either a function of reflexive inhibition in response to sudden unloading of the contracting quadriceps or a reciprocal inhibition in response to reflexive activation of the hamstring muscle group.
observed after ground contact, when the perturbation group appeared to have more symmetric Q/H co-activation. High Q/H co-activation ratio can increase strain on the ACL and predispose athletes to non-contact injuries. However, perturbation training may produce neuromuscular adaptations that encourage more symmetric quadriceps and hamstrings co-activation and balance joint loads for dynamic restraint. Calculations revealed that the intra-group effect size of perturbation training ranged from 0.06 to 0.61 (small to moderate) (Table 4).

### Knee flexion angle

The pretest initial knee flexion angle, peak knee flexion angle, and knee flexion displacement in the treatment group were 28.29 ± 3.83°, 51.50 ± 5.79° and 24.40 ± 3.69° respectively. At posttest, the initial knee flexion, peak knee flexion, and knee flexion displacement significantly increased to 39.92 ± 2.41°, 72.59 ± 6.16° and 34.03 ± 5.39° respectively in the perturbation training group, reaching a desirable level (50-70 degrees) of peak knee flexion. There were no significant differences from pretest to posttest in the control group. Myer stated that the quadriceps, through the anterior pull of the patellar tendon on the tibia, contributes to ACL loading when knee flexion is less than 30°. Hamstrings contraction cannot reduce ACL strain with the knee slightly flexed because these muscles meet the tibia at a small angle. Increased flexion angle that is seen after perturbation training is described as the best accommodation in female athletes that can somewhat protect the ACL from injury risk.

The results of the present study suggest that, during landing from a jump, one strategy for the prevention of ACL injury is to maintain high hamstring muscle activity. It seems exercises that increase the strength and activation of the hamstring muscle may be an effective method to prevent ACL injury. Hamstring activity was increased after training in both the preparatory and reactive phases both of which could lead to increased knee stability. As previously mentioned, during the perturbation training subjects were instructed to have a deep knee flexion angle and keep their knees in line with their toes without any sagittal and frontal-plane displacements. It is found that increased knee flexion angles may lead to changes in the function of the quadriceps and the hamstrings. Previous authors have shown that subjects in the low flexion angle group during landing demonstrated decreased energy absorption at the knee and hip. Thus, increased knee flexion during landing could increase energy absorption in the knee.

### Limitations of the study

There were some limitations to this study. Firstly, only the short-term effects of the ACL injury prevention training were examined. Examining the long-term effects of the perturbation training program and its effects on ACL injury prevention in a larger sample size is recommended. The effects of the subjects’ menstrual cycle were not considered. Thus, the acquired changes after perturbation training in landing and TJ could be attributable something other than the training.

Considering the small to moderate effect sizes in the perturbation group, it would seem that this program could be used for the correction of QD deficit. However, the mechanism by which this occurs has not been determined and additional larger samples and other EMG factors (muscle activity) should be analyzed. Thirdly, there was likely cross-talk for the muscles used in this study, as is typical in surface EMG. The authors tried to minimize cross-talk by considering and carefully selecting the appropriate electrode size, inter-electrode distance, and the locations of electrode placement for EMG data recordings over each of the muscles. Fourthly, while the authors used a foot switch as the instrument to determine the initial ground contact during landing, this researcher created tool may have had some inherent error, which was a limitation of this study, therefore, using a more accurate and reliable tool such as a force plate is recommended. Finally, because of governmental rules pictures of female participants were not allowed, thus only male participants are shown in figures.

### CONCLUSIONS

The results of the current study indicate that implementation of progressive perturbation training can increase VM and MH muscle pre-activation, decrease quadriceps to hamstring co-activation
ratio, and decrease the latency for MH, LH, and VM in female athletes with QD deficit as determined via a TJ assessment. Significantly increased knee flexion angles during the TJ were also observed after the six-week perturbation training in female athletes with QD deficit. The resultant neuromuscular adaptations support the use of perturbation training to enhance dynamic functional stability at the knee joint during jumping activities.

REFERENCES


ABSTRACT

Background: Several researchers have investigated functional testing with regard to return to sport decision making. Change of direction activities play a role in the advancement of rehabilitation as an athlete progresses towards return to sport. Few studies have assessed tests that measure change of direction tasks.

Purpose: The primary purpose of this study was to establish test-retest and intra- and inter-rater reliability of performing the Change of Lateral Direction (COLD) test. The second purpose was to provide normative data for healthy college aged subjects performing the COLD test. The final purpose of this study was to assess the role of fatigue while performing lateral change of direction tasks.

Study Design: Cross-sectional, descriptive reliability study

Methods: Thirty-three female and 18 male healthy college students (mean age = 25.5) were tested on two occasions, one week apart. Subjects started out standing on a standard 4" step and rapidly altered stepping to tape markers on either side of the step as many times as possible for 30 seconds. The total number of steps achieved in 30 seconds was video recorded and watched later to count steps in order to determine reliability. The effect of fatigue was assessed by subdividing the 30 second trial into three increments: 0-10 seconds (T0-10), 11-20 seconds (T11-20), and 21-30 seconds (T21-30).

Results: Normative data for session 1 and session 2 were 76.0 (±10.9) and 80.1 (±11.2) steps respectively. Inter-rater (ICC: 0.994-0.996) and intra-rater (ICC: 0.930-0.984) reliability was excellent. Test-retest reliability demonstrated a strong correlation (r = 0.88) between session 1 and session 2. A significant decline (p<0.001) in total number of steps was demonstrated between T0-10 and T21-30, as well as T11-20 and T21-30 during both session 1 and session 2.

Conclusions: The COLD test demonstrated excellent inter-rater and intra-rater reliability. A possible fatigue effect occurred at T21-30. Because of the ease of administration, minimal equipment required, and excellent intra and inter-rater reliability, the COLD test provides an excellent functional change of direction test. This test could be used for serial reassessment during pre-season screening, rehabilitation, or return to sport.

Level of Evidence: 2c

Key words: functional testing, lower extremity lateral agility testing, performance testing

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The authors report no conflicts of interest with this manuscript.
INTRODUCTION

Change of direction (COD) and agility drills are commonly used training interventions. Although the terms have been used synonymously, they are distinctly different skills with varied correlation between performance outcomes ($r = 0.321-0.70$).\(^1\)\(^-\)\(^6\) COD has been defined as the specific skills and abilities needed to change movement direction or velocity during a preplanned movement pattern.\(^1\)\(^,\)\(^6\) Conversely, agility is a rapid whole body movement with change of velocity or direction of movement in response to a stimulus. Highlighted in the definition of agility is both the COD component and an added cognitive/perceptual component (visual scanning, anticipation, pattern recognition, and situational awareness).\(^2\)

Successful completion of COD tasks requires rapid and coordinated force to allow a braking phase (eccentric bias), plant phase (isometric bias), and propulsive phase (concentric bias).\(^7\)\(^,\)\(^8\) Several physical characteristics have been correlated with faster COD performances. Lower body power,\(^1\)\(^,\)\(^9\) eccentric and concentric strength,\(^3\)\(^,\)\(^5\)\(^,\)\(^10\)\(^,\)\(^11\) reactive strength,\(^7\)\(^,\)\(^12\)\(^,\)\(^13\) and linear speed\(^2\)\(^,\)\(^5\)\(^,\)\(^6\)\(^,\)\(^11\) have all been demonstrated to positively correlate with time to complete COD tasks. Although important, several of these physical characteristics cannot be trained in injured or early postoperative populations. Therefore, a progression of change of direction tasks would be required for these individuals during the course of rehabilitation.

The ability to change directions is fundamental to several field based sports, especially those that involve an opponent. Sports specific movement analysis has demonstrated COD activities happening frequently (every two to four seconds) and at high volume ($> 1000$/game) in soccer, tennis, rugby and basketball.\(^14\) Given the high prevalence of COD actions in sports, reliable and valid tests of COD ability are important for the rehabilitation and strength and conditioning providers, in order to utilize a low cost and time efficient means to assess the effect of training and rehabilitation programs. Several COD tests have been used as a part of a test battery for athletes returning to sport after injury or surgical procedures (T-test, Pro Agility test, L-Run, 505 and modified 505, Change-of-Direction and Acceleration test (CODAT), and the Illinois agility test).\(^6\)

Although a wide variety of tests have been described in the literature, a specific progression for COD activities has been difficult to determine in athletes and physically active patients during the course of a rehabilitation program.\(^15\)\(^,\)\(^16\) With the shift from time-based to criterion-based rehabilitation protocols, specific tests to assess when an athlete is able to progress from their current level of performance to a more advanced skill or exercise will be important for providers.\(^17\) The heterogeneity between the current tests used to assess COD (distance, number of cuts, angle of COD, speed of performance) may not allow them to be performed in the early or mid-stages of rehabilitation. A well-designed rehabilitation program to return the athlete/patient back to high level COD tasks should include a progression from submaximal to maximal speed efforts, closed preset skills to open skills that require increasing visual processing, timing, reaction time, perception, and anticipation skills, in order to be successful. A progressive evidence-based COD sequence is needed to accomplish this aforementioned task. The lack of such an evidence-based progression represents a gap in the literature that needs to be explored further.

Commonly used COD tests are generally short in duration (2-18 seconds) and require 1-11 changes of direction.\(^6\) Short duration testing is justified in the end stage of rehabilitation and return to sport testing phases as field based sports typically involve short spurts of activity followed by low intensity running or rest.\(^18\) The longest COD test currently available is the Illinois Agility Run (IAR), which takes 14-18 seconds to complete. A common criticism of the IAR is the role that fatigue may play on performance due to its extended test duration.\(^19\) Despite this, fatigue has been shown to affect performance and biomechanics during return to sport testing and has been identified as a possible avenue to identify deficits after injury.\(^17\) In the post-operative Anterior Cruciate Ligament (ACL) reconstruction population, fatigue protocols have demonstrated detrimental effects on hop testing,\(^21\) bilateral drop vertical jump,\(^22\) and unanticipated landing tasks.\(^23\)

The effect of fatigue on COD has received less attention and the literature is conflicting. Greig et al. investigated the effect of a fatiguing protocol on COD
kinematics via a simulated soccer game. As the subjects became more fatigued, knee flexion angle decreased and knee valgus angle increased at touch-down, peaking at the end of both halves. This has important rehabilitation implications as the combination of decreased knee flexion and increased knee valgus has been implicated as an ACL injury mechanism. Alternatively, Sanna and O’Connor failed to demonstrate a change in sagittal and frontal plane knee kinetics and kinematics during cutting after a similar fatiguing protocol performed on a 20-meter course.

The Change of Lateral Direction Test (COLD) is a novel, low intensity lateral COD task performed in a closed environment. It was developed as a way to assess lateral COD performance in a clinical setting. The COLD can be used clinically as a guide for progression of COD tasks while rehabilitating lower extremity injuries in athletic populations. The primary purpose of this study was to establish test-retest and intra- and inter-rater reliability of performing the COLD test. The second purpose was to provide normative data for healthy college aged subjects performing the COLD test. The final purpose of this study was to assess the role of fatigue while performing lateral COD tasks. It was hypothesized that the COLD test would demonstrate good reliability for test-retest, intra- and inter-rater assessments. Additionally, it was hypothesized that the COLD test would demonstrate a decline in scoring from the initial 10 seconds (T<sub>0-10</sub>) to the final 10 seconds (T<sub>21-30</sub>) of test performance.

METHODS
The study used a cross-sectional non-experimental study design to establish reliability and provide normative data for the COLD test. The Georgia Southern University Institutional Review Board approved the study and all participants read and signed an informed consent form prior to participation. Fifty-one asymptomatic subjects (35.3% male) were recruited via convenience sampling. Demographic information indicated that 59% of the subjects ran as a form of exercise, 98% had participated in an agility sport in the prior six months, and 57% had sustained a sports related injury at some point in their lifetime. However, none of the participants had sustained an injury within the 12 months prior to their participation in the study. All participants met the inclusion criteria of being physically active as defined by exercising at least three times per week for 60 minutes, involved in running or sport related activities, being between the ages of 18-35 years old, and having no lower extremity pain at the time of the study. Exclusion criteria included a history of lower extremity ligamentous surgery, spine surgery, pregnancy, or other medical conditions that would prevent them from being able to safely perform a COD test as identified on a medical questionnaire.

Prior to testing, subjects performed a five-minute dynamic warm-up that consisted of jogging, lateral shuffles, and cross over carioca that was standardized based on time and intensity. The dynamic warm up was followed by a lower extremity stretching routine for the quadriceps, hamstrings, iliotibial band, and gastrocnemius and soleus complex for a total of five minutes. Subjects were supervised and given a written handout with pictures of the stretches to follow for bilateral lower extremities.

TESTING PROCEDURES
Once the warm up was completed, the same examiner read the standardized script describing the test procedures, including the criteria for stopping the COLD test. Prior to performing the test, each subject watched a brief video demonstrating correct test performance. After listening to the test procedures and viewing the video, each subject was given a 10 second practice session where the examiners provided verbal feedback regarding appropriate test performance. If the subject did not perform the test appropriately, he/she was given a longer orientation session.

A standard fitness step (AW aerobic fitness®, AWinternational Inc. LaPuenta, CA, USA) was used for testing (length: 63.5 cm, wide: 27.94 cm, height: 10.16 cm). A tape marker was placed on the ground 35.56 cm from the center of the step, on either side of the step. The subject started with both feet on the step and then rapidly alternated stepping (Figures 1b and 1c) to the tape marker on the right and left sides of the step. The subjects were not required to maintain contact with the step at all times and were able to jump with both feet to facilitate the COD task. Subjects were instructed to
alternate touching the tape markers as many times as they could in 30 seconds. The criteria for stopping the test included loss of balance, inability to consistently touch the tape markers for three consecutive trials, or if the subject determined he/she was unable to physically continue the test.

The subjects performed the testing procedure one time at the initial session (session 1) and then again one week later (session 2), in order to establish between session test-retest reliability. The same study procedures were utilized during the second testing session. A sports video analysis application (Coach’s eye®, Techsmith Corp., Okemos, MI, USA) was utilized for 2D image recording on a tablet (Air2®, Apple Inc. Cupertino, CA, USA) for session 1 and session 2 to allow for slow motion counting of the steps at a later time. Coach’s eye has been deemed a reliable means of motion analysis to be used clinically.26 The camera was positioned 3.5 m directly in front of the 10.16 cm step and 30 cm from the ground, as done in previous step test research.27 After the test was completed, a single researcher watched the video and steps were counted for the entire 30 second test. Additionally, the effects of fatigue were assessed by subdividing the 30 second trial into three increments: 0-10 seconds (T₀-₁₀), 11-20 seconds (T₁₁-₂₀), and 21-30 seconds (T₂₁-₃₀).

Intra-rater and inter-rater reliability of the video assessment was assessed for each of the four researchers by individually evaluating the videos independent of each other using the Coach’s eye® video of the first 11 subjects in the sample and each determining the number of steps in the 30 second testing time frame. These procedures were repeated for session 2 for each of the 11 subjects, who were part of the reliability portion, in order to establish

Figure 1. a. Starting position with both feet on the step, b. Start of test with left foot the touching tape on left side of the step, c. Cross over to touch tape on opposite side of step with right foot. The athlete alternates from side to side, touching the tape as many times as they can in 30 seconds.
intra-rater reliability. The researcher who demonstrated the highest intra-rater reliability was selected to perform the step counting for the remaining subjects.

**DATA ANALYSIS**

The total number of steps completed in a 30 second trial served as the normative values for the COLD test. Measures of central tendency were calculated for normative data. Data were assessed for normality using the Shapiro Wilk and Kolmogorov Smirnov tests. Intra- and inter-rater reliability for the COLD test was assessed using intraclass correlation coefficients (ICC, model 3). The actual performance of the COLD for test-retest reliability was measured with Pearson’s correlation coefficients (r). Minimal detectable change (MDC) values were calculated based on a 95% confidence interval. A Repeated measures ANOVA was conducted to assess the effects of fatigue over the 30 second trial. When sphericity was violated, a Greenhouse-Geisser correction was applied. Alpha level was set a priori at 0.05 and SPSS version 24 was used for all statistical analyses.

**RESULTS**

A total sample of 51 subjects participated in the study (mean age = 25.5 years [range 22-35]). Normative values for the total sample of session 1 and session 2 were 76.0 steps (sd = 10.9; range: 53-101) and 80.7 steps (sd = 11.2; range: 61-115), respectively. MDC values ranged from 2.1-2.3. Inter-rater reliability for the COLD test was excellent (0.994 - 0.996), as was intra-rater reliability (0.930 - 0.984). Test-retest reliability demonstrated a strong correlation between session 1 and session 2 (r = 0.88). The repeated measures ANOVA showed a significant decline in the number of steps between T11-20 and T21-30 for both session 1 and 2 (p < 0.001; mean difference 2.4-3.6 steps). There was also a significant decline noted between T0-10 and T21-30 for both session 1 and session 2 (p < 0.001; mean difference 2.8-4.3 steps). No significant difference was found between T0-10 and T11-20 for either session 1 or session 2 (p > .05).

**DISCUSSION**

The primary purpose of this study was to establish test-retest, intra-rater, and inter-rater reliability for the COLD test. The results of this study supported the hypotheses that there would be good reliability of the examiners interpreting the results of the COLD test. This finding is consistent with previous studies looking at inter- and intra-rater reliability with COD tasks with ICC values ranging from 0.73 to 0.99. From a clinical perspective, the majority of COD studies have examined tests that can be used in late stage rehabilitation and return to sport testing. Fewer studies have looked at COD tasks that could be evaluated in the early stages of rehabilitation. This is an important step in the safe progression back to high level functional activity. A novel aspect of this study was the use of a hand-held device (smartphone application) to accurately record foot contacts in a COD task. Several options exist to measure patient/athlete movement (force plates, isokinetic dynamometer, 3-D motion analysis systems, etc), but are cost prohibitive and time consuming for use in a clinical setting. Allowing easy and relatively inexpensive options for clinicians may increase the utilization of formal performance testing. This study adds to a body of literature demonstrating the reliable use of smartphones, tablets, or other hand-held devices to measure patient movement in the clinic. Previous studies have demonstrated reliable and valid hand held device measures when evaluating hip and knee mechanics with running, jumping and landing technique, movement screening, and single leg squatting or step downs.

The secondary purpose of this article was to provide normative data for healthy college aged subjects performing the COLD. This test could be used as a COD test for recreational participants or athletes as a progression criterion for return to sport or activity. Athletes who have sustained lower extremity injuries often return to sport before they have been adequately rehabilitated. Athletes who have undergone anterior cruciate ligament reconstruction (ACLR) are at the highest risk of re-tear in the first 12 months and there is an increased risk of re-injury if the patients are unable to achieve symmetry in strength between the injured and un-injured extremities. Additionally, only 30% of post-operative ACLR patients perform agility training as part of their rehabilitation program. As a result, a low
percentage (13.9%) of ACLR subjects demonstrate the ability to meet all strength and COD milestones at return to sport testing. The data from these articles serve to demonstrate the importance of assessing COD and agility prior to returning to sport. This is an area that has received limited investigation in the past and would benefit from future research to answer questions regarding the readiness of athletes to perform COD tasks after lower body injury and surgery.

The tertiary purpose of this study was to examine the effects of fatigue on performance on the COLD test. One of the unique features of the COLD test is its ability to assess endurance with the COD testing because it lasts longer than any of the previously described COD tests. Although the role of fatigue in biomechanical changes has been questioned, there is evidence to demonstrate the negative effects of acute fatigue on performance parameters and injury risk biomechanics. Iguchi et al. showed a decline in lower extremity muscle electromyography activation (EMG) with fatigue, which could decrease the protective mechanism of the ACL. A study by Liang-Ching et al. found that it took more than 40 minutes of rest for knee kinematics and kinetics during side-step cutting to return to pre-fatigue levels. Finally, Edwards et al. used a validated fatigue protocol and demonstrated alterations in lower extremity kinematics due to fatigue during sidestep cutting movements.

A unique finding of this study was the significant decline in step rate that occurred throughout the COLD test. During the first 0-20 seconds of the test, there was a minimal decrease in the performance of the number of touches, however, after 20 seconds there was a significant decrease in the number of touches indicating a potential fatigue effect had developed. Considering the effects fatigue has on lower extremity kinematics and performance, it is important to know when fatigue possibly occurs in asymptomatic individuals, during this novel COD test. This knowledge will aid clinicians when developing goals for their patients in relation to normative values and fatigue levels. However, more research is required to determine if the decline in step rate was a normal occurrence within the test or a specific effect of fatigue.

LIMITATIONS OF THE STUDY
The COLD test only assesses movement in the frontal plane, which neglects sagittal and transverse plane movements typically seen in sporting activity. The total sample size was relatively small to detect normative data and the majority of participants were female, which may decrease the applicability of this data to males. Although 98% of the subjects participated in an agility sport in the prior six months, none were currently participating in an agility sport at the time of the study. The inclusion of only healthy recreationally active subjects limits the generalizability of the results to athletes that have suffered an injury and those participating in athletics at higher levels of competition.

In the future, it would be beneficial to first perform the COLD test on uninjured athletes of specific sports that involve change of direction. Then, apply the COLD testing to athletes who are recovering from a lower extremity musculoskeletal injury. If the COLD test is to be used as part of a return to play progression, it would be useful to assess lower extremity kinetic data during the performance of the test. This would allow clinicians to evaluate the joint torque and lower extremity muscle forces required to allow proper initiation of this testing/training intervention. It would also be useful to assess COLD test performance in athletes to create valid cut off scores for evaluating the ability to progress to higher level COD/agility tasks.

CONCLUSION
The results of the current study indicate that the COLD test demonstrated good to excellent test-retest, inter-rater, and intra-rater reliability. Additionally, descriptive normative data in healthy college students was included as preliminary data to be used as a reference norm for using the COLD as a COD test in similar populations.

REFERENCES


27. Burnham JM, Yonz MC, Robertson KE, et al. Original research: Relationship of hip and trunk muscle


Background/Purpose: Endurance sports, including cross-country skiing, require long hours of repetitive training potentially increasing the chance of injury, yet injury incidence and risk factors for adult cross-country skiers remain relatively unexplored. Data for elite adult north American competitive cross-country skiers is unexplored. A 12 month prospective surveillance study was undertaken to calculate the injury incidence and exposure of cross-country skiers. Injuries by anatomic location and mechanism of injury were calculated. Further, the relationships between new injury and the participant's demographics and physical assessment parameters were examined. The aims of this study were to determine the injury incidence and any risk factors for injury in elite adult north American cross-country skiers.

Methods: Elite cross-country skiers (35 men, 36 women) self-reported demographics, injury history, and injury and training surveillance monthly over 12 months. t-tests compared the mean number of injuries per individual, per 1,000 training/exposure hours between anatomic regions, type of injuries, and seasons. Spearman's correlation analyses tested the relationship between new injury and Movement Competency Screen (MCS) score, past injury, total training time, and running training time. To determine if new injury could be predicted from any demographic data, intake physical measures, or, monthly injury, training and racing data, a regression model was developed.

Results: Overall, 58% of participants (18 men, 23 women) completed the study, and reported 3.81 injuries per 1,000 training/exposure hours. Over 12-months, lower extremity injury incidence (2.13) was higher than upper extremity (0.46) and trunk injury incidence (0.22) (p < 0.05). Non-traumatic/overuse injury incidence (2.76) was higher than acute injury incidence (1.05) (p < .05). Non-ski-season injury incidence (5.25) was not statistically higher than ski-season injury incidence (2.27) (p = 0.07). New injuries were positively correlated with previous injury (p < 0.05), but not with any other variables (p > 0.05).

Conclusion: In this year-long monthly survey of injuries and training load in elite adult north American cross-country skiers, new injuries were positively correlated with previous injury. Lower extremity, and non-traumatic/overuse injuries had the highest incidence rates. There was no significant correlation between new injuries and physical assessment parameters or training load.

Level of Evidence: Level 3, Prospective Longitudinal Cohort Study

Keywords: Injury burden, Injury rate, Movement System, Nordic skiing

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INTRODUCTION

Endurance athletes such as cross-country skiers, distance runners, swimmers, cyclists, and rowers require high levels of aerobic power and endurance gained from the long hours of repetitive training required to excel at their chosen sport. Previous injury and a high volume of repetitive training are two commonly reported injury risk factors in endurance athletes. There is considerable variation in injury reporting methods used when studying endurance athletes, leading to poor consensus about the incidence of injury and the risk factors for injury in endurance sports.

Cross-country skiing is an endurance sport requiring a range of skiing techniques to cover various types of terrain efficiently. There are two distinct cross-country ski styles, skating and classic, each with sub-techniques. Injuries, and injury risk factors in cross-country skiers have been studied using a variety of methodologies. Previous injury, and a high volume of training are the only identified risk factors for injury in cross-country skiers.

Consistent reporting of injury incidence is necessary for effective monitoring of injury and injury prevention strategies. Two studies have reported injury incidence for cross-country skiers. In the earlier study of 149 cross-country skiers with an average age of 22.7 years the injury incidence rate was 2.10 injuries per 1,000 exposure hours. In the later study of 74 cross-country skiers with an average age of 17 years the injury incidence rate was 2.5 injuries per 1,000 exposure hours. The injury studies thus far have surveyed injury and training using one-time retrospective surveys or one-time in person interviews, or more recently weekly surveys for 12 months. Retrospective approaches can be significantly affected by personal recall bias, and thus, the results should be interpreted with caution. The current study used monthly injury and training surveys for 12 consecutive months to replicate the methodology used in a previous injury incidence study of elite rowers with the aim to minimize the burden of weekly reporting while continuing to reduce the recall bias of the one-time 12 month methodologies. The monthly reporting should improve the accuracy of injury and training reporting, and thus result in more accurate measures of injury incidence and contribute to improved understanding of injury risk.

There may be other risk factors for injury in cross-country skiers related perhaps to movement habits or muscular conditioning that have yet to be detected. One way to examine the potential contribution of habitual movement patterns to cross-country ski injury is to use movement screening. Historically, pre-season screening of athletes, with comparison to established norms, involved impairment level tests for joint range of motion, muscle length, and strength to determine which athletes required further evaluation to optimise their physical functioning. Investigating the relationship between injury and impairment level muscular measures such as hamstring length and trunk muscle endurance ratio contributes to baseline movement pattern data in cross-country skiers.

The Movement Competency Screen (MCS) is a reliable whole body movement screen that can effectively evaluate whole body movement in military recruits, dancers, netball players, and rowers. A low MCS score has been correlated with elevated injury risk in high performance dancers, but not in rowers or military recruits. This is the first study to use the MCS to evaluate movement competency in cross-country skiers.

The aims of this study were to determine the injury incidence and any risk factors for injury in elite adult north American cross-country skiers. A prospective 12-month study was undertaken to collect monthly injury and training load data. Secondarily, injury reports were compared with selected early season physical assessment measures, as well as history of injury, length of career in cross-country skiing, and training hours.

Finally, the injury incidence data from the monthly surveys were used to determine whether there are differences between the mean injury incidence rates during the ski-season and the non-ski-season, for traumatic and non-traumatic injuries, and for injuries by anatomic location.

METHODS

Study design

A prospective longitudinal cohort study was conducted for 12 consecutive months. Ethical approval was
granted by the Institutional Review Boards of the participating institutions. All participants received verbal and written study information and then gave written informed consent. This study replicated the methodology used in previous studies exploring injury risk factors for rowers and dancers. The ski-season for this study was defined as December 2014 to April 2015 based on reported dates of on-snow training, and ski races.

Participants & the enrolment process
A convenience sample of 71 professional or University NCAA (National Collegiate Athletic Association) level cross-country skiers enrolled in this study (35 men, 36 women, age 18-27 years, mean age 20.66 years).

Participant enrolment occurred on a rolling schedule between August and December of 2014 at ski team meetings. After signing the consent form and receiving a unique identifier, participants completed an electronic intake demographic survey (Appendix 1). In addition, they completed the first of 12 electronic monthly injury and training surveys (Appendix 2). Finally, the participant's performance on the chosen physical assessment tests (MCS, hamstring muscle length, and trunk flexor and extensor muscle endurance) were recorded.

Injury Surveillance
To maintain blinding, the REDCap (Research Electronic Data Capture) electronic data capture software, was used to create, administer, and manage all of the submitted surveys. The survey questions were developed by reviewing the current literature, by discussing cross-country skier injury with the coaches of potential study participants, and by reviewing the survey used in a previous injury incidence study conducted on elite rowers.

Consistent with the study design and methodology being replicated, an injury was defined as any episode of pain, ache, or discomfort that lasted for longer than one week (seven days), or an injury that caused the athlete to miss or modify any training or racing sessions. Participants selected the location of their injury from a list of body parts or regions, and a free text box was available to further describe their injuries. Prior to data analysis the body parts were grouped into regions: lower extremity, upper extremity, and trunk. The intake survey was self-reported using the electronic REDCap software (Appendix 1), and included: age, gender, handedness, weight, height, level of competition, type of skiing, age when the participant began cross-country skiing, previous injuries, current injuries, current medications, and occupation. All intake data were retained for initial descriptive analysis.

Using the e-mail address provided by the participants when enrolling, the REDCap software distributed the monthly self-report survey (Appendix 2) to each participant for 12 consecutive months. The REDCap software was programmed to send weekly reminder e-mails to each participant until their survey was completed or the next monthly survey was delivered. The monthly variables of interest were any changes in medications or occupation since the last survey, amount and type of training, amount and type of racing/competing, type and severity of new or ongoing injury, effect of injury on training and/or racing. To ensure results spanned a full calendar year, the data from participants who responded to nine or more of the surveys (18 men, 23 women) were retained for longitudinal analysis of training, racing, and injury reports.

Total monthly training load for each participant for each training activity was calculated from the number of training sessions as well as the duration (in minutes) of each training session. All variables from the intake survey, intake physical measurements, and the monthly surveys were considered to be potential risk factors for predicting new injury. Statistical analyses and clinical considerations were used to determine which variables were relevant risk factors.

Physical assessment testing
A set of physical measurement tests were performed at the start of the data collection period to determine the relationship between these physical measures and the report of a new injury during the 12-month study period. These tests included the Movement Competency Screen (MCS), the Active Straight Leg Raise (ASLR) hamstring length test left and right, the Biering-Sorensen back extensor muscle endurance test, and the McGill trunk flexor muscle endurance test. The tests were selected to replicate...
methodology used to study rowers and dancers, and thus allowed comparison of results among different sports. The standardised parameters for performing and recording these tests have been described previously. The ASLR test was modified according to previous research, and as such, the hip flexion range of motion was recorded for each leg as an indication of the length of the hamstring muscles. The McGill trunk flexor muscle endurance test time was standardized to 360 seconds, and the Biering-Sorensen trunk extensor muscle endurance time was standardized to 180 seconds. The trunk muscle endurance ratio was calculated as flexor to extensor ratio using the standardized scores.

Statistical Analyses
The characteristics of the study population were established using descriptive analysis of intake and monthly data, injury prevalence, injury incidence, and training/exposure hours. Two sample t-tests were used to explore gender differences in the demographic and intake physical measurement data. Injuries were grouped into 3 body regions: 1) the lower extremity including the hip, thigh, knee, lower leg, foot and ankle; 2) the upper extremity including the shoulder, upper arm, elbow, forearm, wrist and hand; and 3) the trunk including the head, neck, upper back, low back and pelvis. Injury incidence was calculated as the number of new injury reports per participant, per 1,000 hours of training/exposure.

Training hours were calculated per participant by multiplying the number of training sessions by the average duration of each training session for that activity per week, and per month. Total training/exposure hours, or specific activity hours, could then be summed per participant. To determine if new injury could be predicted from any demographic data, intake physical measures, or, monthly injury, training and racing data, a regression model was developed. The regression model included age, BMI, gender, number of years of competition, age the participant began competing, past injury report, trunk muscle endurance ratio, hamstring length, MCS score, average monthly time training, average monthly time running, average monthly time roller skiing, average monthly time cycling, average monthly time skiing, and average monthly time lifting weights. The final regression model included variables with statistically significant correlation coefficients, or that were considered clinically important to new injuries based on clinical experience, the review of current literature, or had been included by investigators who used a similar research methodology. The variables represented in the final model were past injury, total training hours, running hours, and MCS score. Spearman's correlation was used to determine if new injury during the 12 months of the study was correlated with past injury, total training hours, running hours, or MCS score. A t-test was used to determine if mean injury incidence per participant per 1,000 hours of training was significantly different between the competitive ski-season and the non-ski-season, and acute/traumatic and non-traumatic/overuse injuries. While this study was not powered to detect differences in mean injury incidence per participant per 1,000 training hours among body regions, we explored these differences in order to better describe the characteristics of the participants and when analysing injury incidence in relation to the current literature.

RESULTS
Participants
Due to participant availability and enrolment time constraints, a total of 71 participants enrolled in the study. Forty-one participants (57.7%) completed sufficient monthly surveys (9/12) to be included in the injury incidence and correlation analysis. Men and women in this study were not significantly different except for the men being significantly taller and heavier than the women (Table 1). From all the prior injuries noted by participants, lower extremity injuries were reported more frequently than other regions (Table 1).

Physical assessment test results
Observed MCS scores ranged from 10/21 to 18/21, with a median score of 13/21. Men had significantly higher MCS scores than women (p < .05) (Table 2). Men also scored higher than women on the individual MCS movements of the push-up, and the twist (of the two-part lunge and twist movement). There were no significant gender differences between the
mean scores on the ASLR test, the Biering-Sorensen test, the McGill test, or the trunk muscle endurance ratio (p > 0.05) (Table 2).

### New injury characteristics

In total, 90 new injuries were reported by 27 of the 41 participants who completed the study over the 12 month period (13 men, 14 women). More injuries were reported for the lower extremity (58) than the upper extremity (19) or the trunk (12) (Figure 1). Men reported a near even distribution of upper and lower extremity injuries, whereas women reported more lower than upper extremity injuries (Figure 1). Ankle and foot injuries accounted for 39.7% of all lower extremity injuries and 25.6% of all new injuries (Figure 1). Shoulder injuries accounted for 36.8% of all upper extremity injuries and 7.8% of all new injuries (Figure 1). Twenty-six of the new injuries were classified as traumatic. Non-ski-season new injuries numbered 67 compared to 23 during the ski-season.

### Injury Incidence

The mean injury incidence was 3.81 new injuries per participant per 1,000 hours of training. There was a significantly higher incidence of lower extremity injuries (Table 2).

### Table 1. Participant demographics at enrolment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Men (SD) n=35</th>
<th>Women (SD) n=36</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age (years)</td>
<td>21.15 (2.48)</td>
<td>20.18 (1.92)</td>
<td>0.07</td>
</tr>
<tr>
<td>Mean height (cm)</td>
<td>177.87 (6.82)</td>
<td>168.46 (6.69)</td>
<td>&lt; 0.05*</td>
</tr>
<tr>
<td>Mean weight (kg)</td>
<td>71.14 (7.26)</td>
<td>62.32 (7.06)</td>
<td>&lt; 0.05*</td>
</tr>
<tr>
<td>Mean BMI (kg/m^2)</td>
<td>22.45 (1.41)</td>
<td>21.93 (1.74)</td>
<td>0.17</td>
</tr>
<tr>
<td>Mean age began competitive skiing (years)</td>
<td>11.6 (2.90)</td>
<td>12.0 (2.74)</td>
<td>0.55</td>
</tr>
<tr>
<td>Mean years skiing</td>
<td>11.4 (5.04)</td>
<td>11.1 (5.45)</td>
<td>0.85</td>
</tr>
<tr>
<td>Number of participants with past history of injury</td>
<td>80% 28/35</td>
<td>80.6% 29/36</td>
<td>0.95</td>
</tr>
<tr>
<td>Number of participants reporting previous trunk injury</td>
<td>12</td>
<td>7</td>
<td>0.50</td>
</tr>
<tr>
<td>Number of participants reporting previous upper extremity injury</td>
<td>10</td>
<td>9</td>
<td>0.50</td>
</tr>
<tr>
<td>Number of participants reporting previous lower extremity injury</td>
<td>21</td>
<td>23</td>
<td>0.50</td>
</tr>
<tr>
<td>Number of participants injured at time of enrolment</td>
<td>25.7% 9/35</td>
<td>27.8% 10/36</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Note: Previous injury by body region is qualitative data from free text survey question "list previous injuries". Many participants reported multiple previous injuries. Only previous injuries from major body regions are reported here.

### Table 2. MCS and muscular measures scores, all participants at enrolment.

<table>
<thead>
<tr>
<th>MCS and muscular scores</th>
<th>Men (SD)</th>
<th>Women (SD)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>35</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>MCS Score</td>
<td>14.43 (1.46)</td>
<td>12.58 (1.40)</td>
<td>&lt; .05*</td>
</tr>
<tr>
<td>Right hamstring length (degrees)</td>
<td>73.69 (12.27)</td>
<td>75.53 (10.99)</td>
<td>.51</td>
</tr>
<tr>
<td>Left hamstring length (degrees)</td>
<td>72.66 (10.82)</td>
<td>76.11 (11.35)</td>
<td>.19</td>
</tr>
<tr>
<td>McGill trunk flexor endurance time (seconds)</td>
<td>227.00 (107.24)</td>
<td>226.42 (112.18)</td>
<td>.98</td>
</tr>
<tr>
<td>Biering-Sorensen trunk extensor endurance time (seconds)</td>
<td>123.91 (28.11)</td>
<td>133.51 (33.95)</td>
<td>.13</td>
</tr>
<tr>
<td>Trunk muscle endurance ratio (flexor/extensor)</td>
<td>0.97 (0.55)</td>
<td>0.85 (0.40)</td>
<td>.25</td>
</tr>
</tbody>
</table>

MCS= Movement Competency Screen; SD = standard deviation. * = significant at p = .05.
extremity injuries (2.13) than other body regions (upper extremity 0.46, trunk 0.22) (p < .05). There was a significantly higher incidence of non-traumatic injuries (2.76) than traumatic injuries (1.05) (p < .05). There was a higher incidence of injuries during the non-ski-season (5.25), but it was not statistically different from injury incidence during the ski-season (2.27) (p = .07) (Table 3).

Training Load
Participants in the current study recorded mean training/exposure hours of 52–56 hours per participant per month, for approximately 600 hours per participant per year.

Correlations with new injury
New injury was positively correlated with previous injury (p = .04), but not with any of the remaining variables: career length (p = .54), training hours (p = .30), running hours (p = .30), roller ski training hours (p = .93), trunk muscle endurance (p = .97), hamstring length (right side p = .17, left side p = .36), or MCS score (p = .63).

Prediction of risk factors for sustaining a new injury
A generalized linear model (GLM) was used to determine the relationship between a new injury and possible risk factors. Possible risk factors included age, gender, BMI, years skiing, age began skiing, past injury, MCS score, hamstring length, trunk muscle endurance ratio, monthly total training hours, monthly running hours, monthly cycling hours, monthly roller ski hours, and monthly ski hours. The best fit GLM included past injury, total training hours, running hours, and MCS score. These

Table 3. Mean injury incidence per participant per 1,000 hours training.

<table>
<thead>
<tr>
<th>Type of injury</th>
<th>Injury incidence</th>
<th>Type of injury</th>
<th>Injury incidence</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>All injuries</td>
<td>3.81</td>
<td>LE</td>
<td>2.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>UE</td>
<td>0.46</td>
<td>&lt; .05*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trunk</td>
<td>0.22</td>
<td>&lt; .05*</td>
</tr>
<tr>
<td>Overuse/Non-traumatic</td>
<td>2.76</td>
<td>Acute/traumatic</td>
<td>1.05</td>
<td>&lt; .05*</td>
</tr>
<tr>
<td>Off season</td>
<td>5.25</td>
<td>Ski season</td>
<td>2.27</td>
<td>.07</td>
</tr>
</tbody>
</table>

LE = lower extremity; UE = upper extremity
* = significant at p < .05

Figure 1. Number of new injuries by anatomic location and gender (numbers in bars show number of injuries by gender).

Table 3. Mean injury incidence per participant per 1,000 hours training.
variables were included for their statistical significance, their clinical relevance to new injuries, or if they had been included in models from previous similar studies of rowers\textsuperscript{29} and dancers.\textsuperscript{34} Past injury was a significant predictor of new injury when accounting for training hours, running hours, and MCS score in the model (p < .05) (Table 4).

**DISCUSSION**

This cohort of elite adult north American cross-country skiers have an injury incidence of 3.18 injuries per participant per 1,000 exposure hours. New injury was positively correlated with a history of injury (p = .04), but not with any other study variables (p > .05). The new injuries reported in this study occurred during non-skiing activities. Taken together these results highlight the importance of injury prevention in all activities that elite endurance athletes participate in not just their chosen competitive sport.

**Participants**

The demographics of skiers in this study were similar to those published in other cross-country ski injury incidence studies of adults.\textsuperscript{6,11,39} The rate of completion in this study was 57.7\%, a minimum of 9 out of the 12 monthly self-report surveys were needed for a participant to be considered complete. Eighty percent (80\%) of the skiers in this study had a history of injury, with lower extremity injuries being the most common, consistent with prior studies.\textsuperscript{6,8,11,16,20,24,25,40} Significance levels in the statistical analyses and their interpretations presented below should be considered in conjunction with the knowledge that 57.7\% of participants completed the study.

**Overall injury incidence and prevalence, and training load**

The overall injury incidence rate in this study was 3.81 injuries per participant per 1,000 exposure hours. This is a comparable but slightly higher rate than previously reported rates of 2.10 – 2.79 injuries per 1,000 exposure hours for cross-country skiers, swimmers, long distance runners, and dancers.\textsuperscript{11,24,31} However other recently published studies have demonstrated that cross-country skiers have the lowest rates of injury relative to other endurance sports (long distance running, swimming, cycling, orienteering), and winter Olympic athletes.\textsuperscript{8,9,11,24,41} The discrepancy in incidence rate between this study and the two previously published cross-country ski incidence rate studies\textsuperscript{11,24} may be explained by the difference in participant age, and the large difference in sample sizes (41 participants aged 18-27 years in the current study, versus 74 aged 16-19 years,\textsuperscript{24} and 149 aged 18-28 years\textsuperscript{11}), and perhaps by the differences in sampling frequency of this study (monthly for 12 months, versus weekly for 12 months,\textsuperscript{24} versus one retrospective survey for the 12 previous months\textsuperscript{11}) leading to different reporting accuracy of injury frequency and training hours. The higher training loads in this study (600 hours per year, versus 509 hours per year,\textsuperscript{24} versus 552 hours per year\textsuperscript{11}) may have also influenced the injury incidence.

Although not statistically significant, more injuries occurred during the non-ski-season when subjects were running and roller skiing, not snow skiing. The observation of injuries occurring in an exercise mode other than the athlete’s specific competitive sport has been reported before,\textsuperscript{11} and may be an important factor to consider in future injury prevention.

---

**Table 4. Generalized Linear Model.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>B</th>
<th>Std. error</th>
<th>95% Confidence interval</th>
<th>Wald Chi-Square</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total training time</td>
<td>0.00</td>
<td>0.01</td>
<td>-0.02 – 0.03</td>
<td>0.01 – 0.92</td>
<td></td>
</tr>
<tr>
<td>Total run time</td>
<td>0.08</td>
<td>0.12</td>
<td>-0.16 – 0.31</td>
<td>0.40 – 0.53</td>
<td></td>
</tr>
<tr>
<td>Past injuries</td>
<td>1.34</td>
<td>0.67</td>
<td>0.03 – 2.66</td>
<td>4.02 &lt; 0.05*</td>
<td></td>
</tr>
<tr>
<td>MCS Score</td>
<td>-0.01</td>
<td>0.14</td>
<td>-0.28 – 0.27</td>
<td>0.00 – 0.97</td>
<td></td>
</tr>
</tbody>
</table>

Note: * = significant at .05 level
strategies. Movement quality and sport-specific skill in cross-training activities may be as important as it is in the athlete's competitive sport when evaluating injury cause and injury prevention.

**Injuries by gender & anatomic region**
Women in this study reported a greater percentage of lower extremity injuries (90.5% of all their new injuries), than men (42.6% of all their new injuries), a pattern that is consistent with other endurance sports. Across genders, the incidence rate for lower extremity injuries was higher than any other body part, consistent with the previously reported cross-country skier injury incidence patterns, and injury prevalence data for endurance sports. The high prevalence of foot and ankle injuries in this study (40%) was consistent with the reported mechanisms of injury (fall or trip), the participant's sporting activities (running, skiing, roller skiing), and previously reported studies. Similar to other studies, acute foot and ankle injuries reported during this study occurred more often while running than skiing. To reduce injuries in elite cross-country skiers, emphasis must be placed on safety, movement quality, technique, and training programs across all activities, not just their competitive sport of cross country skiing. Given the high foot and ankle injury rates, even moderate reductions to foot and ankle injuries would significantly reduce injury prevalence and incidence in cross-country skiers. Number of injuries reported in this study for the lower back, trunk and upper extremity, were too low to analyse; however, these areas would be worth exploring in future studies.

**Predictors & risk factors of new injuries**
New injuries were positively correlated with previous injury which is consistent with the current endurance sport literature. Considering this result, injury reduction strategies in endurance sports should focus on preventing the initial injury, as well as monitoring those athletes who have been injured previously and are therefore at an elevated risk for subsequent injury. Contrary to previous reports, training/exposure time did not correlate with new injury in this study. In the current study, mean training/exposure hours reported were approximately 600 hours per participant per year (52-56 hours per participant per month). These exposure hours fell below the 700 hours per year previously reported to be to be a risk factor for any new injury in cross-country skiers, swimmers and distance runners.

Past injury report was a significant predictor of new injury in the risk factor analysis that included overall training time, run time, and MCS score. Due to insignificant statistical relationships between new injury and the remaining independent variables, little else can be concluded from the risk factor analysis.

**Study limitations**
Retrospective survey studies have two main categories of recall bias: the loss of information due to failure to recall the event (memory decay), and the tendency to remember events in the past as if they occurred closer to the present than they actually did (telescoping effect). It has been suggested that regardless of sampling frequency the retrospective period of a survey should not extend beyond seven days in order to minimise the risk of recall bias. Therefore, although the monthly survey frequency aimed to reduce the effects of recall bias, the 30 day period between surveys could still be considered a limitation.

A larger study population of cross-country skiers with the monthly survey frequency that lasted for, at least, two competitive seasons and the intervening off-season would increase the statistical power of the study. As it is, the statistical analyses should be interpreted with care as the low number of participants and the low number of new injuries reported have impacted the statistical outcomes.

**Future research**
Investigating relationships between injuries to specific parts of the body and then subsequent injuries to those same areas, especially areas of overuse sustained by cross-country skiers could improve targeted rehabilitation strategies. Recording whether participants met their pre-determined seasonal performance goals, and exploring the relationship between performance and seasonal injury, training, and movement patterns may be a more engaging method of surveillance for athletes and coaches, while also providing researchers,
coaching, and medical staff with practical information for subsequent individual and group injury prevention strategies.

Prior to enrolling in this study, 80% of the elite cross-country skiers, all under the age of 22, had sustained at least one injury. Focusing on technique and movement quality in the developing athlete especially in cross training activities such as running and roller skiing could have a large impact on reducing injuries in the future. Identifying existing problems (such as side differences in strength and balance) and assessing the junior athlete’s movement competence to ensure it is appropriate for their sport may be important in preventing the first sport or training related injury.

CONCLUSIONS

In this year-long monthly survey of injuries and training load in elite adult north American cross-country skiers, new injuries were positively correlated with previous injury, but did not correlate with training load, or any physical assessment tests, including the MCS score in this first report of MCS scores in elite cross-country skiers. Lower extremity, and non-traumatic/overuse injuries had the highest incidence rates. The lower extremity injuries occurred during non-skiing sports used as fitness training when snow skiing was not possible. Coaching staff should ensure each athlete possesses skill proficiency in all sports/activities included in their training program to reduce injury risk. Coaching and medical staff should also consider each skier’s lifetime injury history, when determining which athletes would benefit from further medical team assessments prior to beginning a training programme. Finally, targeted training of developing skiers could be important in long-term injury reduction – an area for future research.

REFERENCES

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34. Lee L. Injury incidence and the use of the Movement Competency Screen (MCS) to predict injury risk in full-time dance students at the New Zealand School of Dance (NZSD): A prospective cohort study.: Health and Rehabilitation Research Institute, Faculty of Health and Environmental Science, Auckland University of Technology; 2015.


**APPENDIX 1. INTAKE QUESTIONNAIRE**

<table>
<thead>
<tr>
<th>Confidential</th>
<th>Page 1 of 1</th>
<th>Confidential</th>
<th>Page 2 of 1</th>
</tr>
</thead>
</table>

**Intake Form**

Complete this intake form to begin the UVM Nordic Ski study. Include your individual identification code given to you when you signed your consent form. You will need this to complete each monthly survey.

Thank you for participating in this Nordic Ski study.

**Section 1: Confidential Athlete Information**

Enter individual study identification code ______________________________

First name ______________________________

Last name ______________________________

Date of Birth (Use this format: 2 digit month-2 digit day-4 digit year) ______________________________

Which gender do you identify with?  ☐ male  ☐ female  ☐ other

Are you right or left handed?  ☐ right  ☐ left

**Information about your skiing**

What is your preferred nordic ski style? (choose all that apply)  ☐ classic  ☐ skate  ☐ both classic and skate about equally

What is your dominant side in classic V1 technique?  ☐ right  ☐ left

In the 2013-2014 ski season what was your level of competition?  ☐ none  ☐ club  ☐ junior  ☐ senior  ☐ other

In the 2013-14 ski season what was your discipline?  ☐ nordic skiing  ☐ biathlon

How many years of nordic skiing experience do you have?  ☐ 0  ☐ 1  ☐ 2  ☐ 3  ☐ 4  ☐ 5  ☐ 6  ☐ 7  ☐ 8  ☐ 9  ☐ 10  ☐ 11  ☐ 12  ☐ 13  ☐ 14  ☐ 15  ☐ 16  ☐ 17  ☐ 18  ☐ 19  ☐ 20  ☐ 21+

**APPENDIX 1. INTAKE QUESTIONNAIRE**

<table>
<thead>
<tr>
<th>Confidential</th>
<th>Page 1 of 1</th>
<th>Confidential</th>
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In the 2013-2014 ski season what was your level of competition?  ☐ none  ☐ club  ☐ junior  ☐ senior  ☐ other

In the 2013-14 ski season what was your discipline?  ☐ nordic skiing  ☐ biathlon

During the 2013-14 ski season, on average how many hours of on snow ski training did you participate in each week? (round up)  ☐ 0-5  ☐ 6-10  ☐ 11-15  ☐ 16-20  ☐ 21-25  ☐ 26-30  ☐ 31+

Do you participate in other sports?  ☐ Yes  ☐ No

List the name of the sport(s) you participate in this sport number of hours per week you participate in for this sport. More than one sport may be listed.

Current Injuries

Do you currently have any injuries?  ☐ Yes  ☐ No
APPENDIX 1. INTAKE QUESTIONNAIRE (continued)

Confidential

Select a body region (or regions) that best fits your current injuries.
- neck
- shoulder
- upper arm
- elbow
- forearm
- hand
- upper back
- mid back
- low back
- pelvis
- abdomen
- hip
- knee
- ankle
- lower leg
- entire & foot

Describe your current injury. What does it feel like?

Are you currently receiving treatment for your injury?
- Yes
- No

Describe the type of treatment you are receiving for your injury. Eg Physical Therapy, massage, Chiropractic, Exercise Therapy, medications ...

Past Injury History

Have you EVER experienced any episodes of pain, ache or discomfort (due to sport or non-sport) that lasted for longer than one week (7 days), or caused you to miss or modify any training or racing sessions?
- Yes
- No

Please list any previous injuries (including type of injury and date).

Please list any previous surgeries (orthopedic or not), include the year of the surgery. (If none, enter none in field)

Current Medications

Please list any current medications you take (prescription and over the counter), use generic or brand name (whichever you can remember). (If no medications, please enter “none”)

Are you taking a contraceptive medication?
- Yes
- No

What is the name of the medication?

What is the date of the first day of your last menstrual period? Use the format: 2 digit month-2 digit day-4 digit year.

Occupation

What is your occupation?
- University student (NCAA athlete)
- Working full time (20+ hours per week)
- Working part time (less than 30 hours per week)
- Professional athlete

Please indicate major subject of study.

Please indicate average number of hours spent on academic work each week.
- 0-5
- 6-10
- 11-15
- 16-20
- 21-25
- 26-30
- 31-35
- 36-40
- 40+

What level of study are you in?
- undergraduate
- graduate

What is your job title? Describe your duties at work (eg: customer service, lifting and carrying, gardening, driving...)

List the average hours per week you spend at your occupation (round up to whole hour)
- 0-5
- 6-10
- 11-15
- 16-20
- 21-25
- 26-30
- 31-35
- 36-40
- 40+

Please indicate activities your non training and racing hours are occupied with.

How many hours per week do you spend on these non training related activities?
- 0-5
- 6-10
- 11-15
- 16-20
- 21-25
- 26-30
- 31-35
- 36-40
- 40+

Emergency Contact Information

Emergency Contact Name

Relationship

Contact Phone number Use the USA 10 digit format eg. (802) 123-1234

Consent to use this information

By signing this form I verify that the above information is correct and, when identified, can be used for research purposes. (Type your first and last name)

Date form completed

Please click “submit” to end the survey and submit your response.

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APPENDIX 2. MONTHLY QUESTIONNAIRE

Monthly Survey

Please complete the monthly survey below.

Thank you for being part of the Nordic Ski study!

Section 1 Background Information

Enter individual study identification code (all 3 digits):

Has there been any change in the medications you are taking?  
☐ Yes  ☐ No

Please explain the medication change (e.g., a new medication, a stopped medication, a change in dose):

Has there been a change in your occupation since the last questionnaire?  
☐ Yes  ☐ No

Please describe your current occupation and the number of hours per week this occupies:

What was the date of the first day of your last menstrual period? (Use this format: 2 digit month-2 digit day-4 digit year):

Training Questions.

Refer to your personal training diary to help answer the following questions.

Which skiing discipline have you predominantly been training for the past month?  
☐ classic  ☐ skate  ☐ both, but classic more than skate  ☐ both, but skate more than classic

On average how long did you spend on snow” skiing per training session in the past month?  
☐ 0-1 hours  ☐ 1-2 hours  ☐ 2-3 hours  ☐ 3-4 hours  ☐ 4-5 hours

What types of cross training have you used in the past month?  
Indicate NUMBER of training sessions for any cross training discipline this month in table below (DURATION is of each session is asked in the next question).  
Multiple cross training disciplines may be chosen.

<table>
<thead>
<tr>
<th>1-6</th>
<th>7-10</th>
<th>11-15</th>
<th>16-20</th>
<th>21-25</th>
<th>26-30</th>
<th>31+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roller skiing</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Road cycling</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Mountain biking</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
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<tr>
<td>Stationary cycling</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
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<td>☐</td>
<td>☐</td>
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<tr>
<td>Road running</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

How many “on snow” training sessions have you completed in the past month?  
☐ 0  ☐ 1  ☐ 2  ☐ 3  ☐ 4  ☐ 5  ☐ 6  ☐ 7  ☐ 8  ☐ 9  ☐ 10  ☐ 11  ☐ 12  ☐ 13  ☐ 14  ☐ 15  ☐ 16  ☐ 17  ☐ 18  ☐ 19  ☐ 20  ☐ 21  ☐ 22  ☐ 23  ☐ 24  ☐ 25  ☐ 26  ☐ 27  ☐ 28  ☐ 29  ☐ 30  ☐ 31  ☐ 32+
APPENDIX 2. MONTHLY QUESTIONNAIRE (continued)

<table>
<thead>
<tr>
<th>Activity</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roller skiing</td>
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<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Road cycling</td>
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<tr>
<td>Mountain biking</td>
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<td>O</td>
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<td>O</td>
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</tr>
<tr>
<td>Stationary bike riding</td>
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<tr>
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<tr>
<td>Treadmill running</td>
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<td>Weight training</td>
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<td>O</td>
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</tr>
<tr>
<td>Other</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
</tbody>
</table>

Describe your "other" cross training activity here.

---

How many races did you participate in this month? 1 2 3 4 5 6 7 8 9 10 11+ Describe the type of races you participated in this month (e.g., 10km run, 50km classic ski race…)

---

Questions about NEW injuries this month.

In the past month have you experienced any NEW episodes of pain, ache or discomfort that lasted for longer than one week (7 days), or caused you to miss or modify any training or racing sessions? Yes No

Indicate where your new pain, ache or discomfort arose from: neck shoulder upper arm elbow lower arm upper back lower back knees lower leg ankle foot other

Describe where your new pain is located.

Describe the new injury/pain/discomfort you experienced this month.

Is this injury the result of an ACCIDENT, TRAUMA or a FALL? Yes No

Describe the incurrence/accident that resulted in your injury.

Have you been examined or treated for this new injury by a physician, physical therapist, athletic trainer or other health professional during the past month? Yes No

Name the type of health professional (not the person’s name), eg, Physical Therapist, Osteopath, Medical Doctor…

---

Racing Questions

Did you race this month? Yes No

What sport did you race in? roller ski classic ski skiskiing biathlon road cycling mountain biking track running triathlon

Describe the "other" sport you raced in this month.
APPENDIX 2. MONTHLY QUESTIONNAIRE (continued)

How many days did this new pain last?

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18
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- 22
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- 25
- 26
- 27
- 28
- 29
- 30
- 31

Rate the intensity of this new pain at the time of completing this survey: no pain at all = 0 (left end of slider bar); worst pain ever = 100 (extreme right end of slider bar).

What is the worst level of this new pain you have experienced this month? no pain at all = 0 (left end of slider bar); worst pain ever = 100 (extreme right end of slider bar).

What is the least (least) level of this new pain you have experienced this month? no pain at all = 0 (left end of slider bar); worst pain ever = 100 (extreme right end of slider bar).

Questions about EXISTING or RECURRENT injuries this month.

In the past month have you experienced ANY episodes of pain, ache or discomfort that lasted for longer than one week (7 days), or caused you to MISS or MODIFY any TRAINING or RACING sessions? If you checked NO for “NEW” injuries above, please now consider recurring/ongoing intermittent episodes of pain, ache or discomfort.

Describe where you felt pain, ache or discomfort (e.g., low back, left shin, right shoulder ...)

Describe the location of your pain.

- Neck
- Shoulder
- Upper arm
- Elbow
- Forearm
- Wrist & hand
- Upper back
- Mid back
- Low back
- Abdomen
- Pelvis
- Hip
- Thigh
- Knee
- Lower leg
- Ankle & foot
- Other

Indicate your current level of pain (right now): no pain at all = 0 (left end of slider bar); worst pain ever = 100 (extreme right end of slider bar).

Indicate your worst (highest) level of pain this month: no pain at all = 0 (left end of slider bar); worst pain ever = 100 (extreme right end of slider bar).

Indicate your lowest level of pain this month: no pain at all = 0 (left end of slider bar); worst pain ever = 100 (extreme right end of slider bar).

Did your injuries impact your TRAINING and RACING this month?
APPENDIX 2. MONTHLY QUESTIONNAIRE (continued)

<table>
<thead>
<tr>
<th>Confidential</th>
<th>Confidential</th>
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</thead>
<tbody>
<tr>
<td>Consider TRAINING sessions only. This month, how many TRAINING sessions have you MISSED due to pain/injury?</td>
<td></td>
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<tr>
<td>○ 0</td>
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<td>○ 1</td>
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Consider RACING this month. 'This month, how many RACES have you MODIFIED due to pain/injury?' (eg opted for a shorter distance, did not use full effort, ...)
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Here is the LAST question this month!

Do you have any other comments this month? Thank you for completing this survey!
ABSTRACT

Background: Hamstring tightness is a common condition typically assessed via the active knee extension (AKE), passive straight leg raise (PSLR), V-sit and reach (VSR), and finger-floor-distance (FFD).

Purpose: The purpose of this study was to investigate the relationships between four common clinical tests of apparent hamstring tightness. A secondary purpose was to compare the differences in correlations between sub-groups based on positive test findings.

Study Design: Descriptive, correlational laboratory design.

Methods: Recreationally active individuals (N=81; 23.7 ± 5.9 years) performed the AKE, PSLR, VSR, and FFD in a randomized order, and subsequent correlational analyses were conducted.

Results: Strong correlations were identified between the VSR and FFD (r = -.798, r² = .637, p < .001); moderate correlations were demonstrated between the PSLR and FFD (r = -.565, r² = .319, p < .001) and PSLR and VSR (r = .536, r² = .287, p < .001). Low correlations were found between the PSLR and AKE (r = -.284, r² = .081, p = .01), AKE and VSR (r = -.297, r² = .088, p = .007), and AKE and FFD (r = .263, r² = .069, p = .018). If one assessment was identified in a subject as dysfunctional, all relationships were affected, regardless of which assessment was dysfunctional.

Conclusions: The AKE, one of the most common measures for apparent hamstring tightness, has low correlations with the other assessments. Based on the findings of this study, it is possible that not all assessments of AHT are measuring the same phenomena, with each involving different factors of perceived hamstring length.

Level of Evidence: Level 2b.

Key Words: Active knee extension, gold standard, hamstring length, treatment-based classification
INTRODUCTION

The descriptors tightness and flexibility, though often used interchangeably, are related, but differing concepts. Muscular “tightness” is traditionally used as a descriptor of a muscle’s physical length, with “tight” muscles having a mild to moderate decrease in length, or a decreased ability to elongate from a normal (neutral) position.1 Flexibility, in contrast, is a physiological concept in which joint excursion is represented by, although not synonymous with, range of motion (ROM) measures, and involves contributions from both joint and soft tissue structures (e.g., nerves, muscles).2

Hamstring tightness, often defined as a lack of ROM with a concomitant feeling of restriction in the posterior thigh, has been documented across all age groups as a potential cause of dysfunctional or restricted movement of the hip.3–11 Hamstring injury, a common occurrence,12–14 often results in lost playing time, decreased performance, and an increased risk of additional injury.15–20 Researchers have prospectively identified that decreased active or passive hip ROM is related to hamstring injury risk;21,22 therefore, clinicians should identify clinical exams that accurately assess apparent hamstring tightness. Apparent hamstring tightness is operationally defined as a multidimensional condition that may include musculoskeletal insufficiency or imbalance,23 neural tension,24 and lumbopelvic dysfunction.25 Several clinical examination tests have been proposed to assess this phenomenon. In research, the active knee extension (AKE)26,27 and the passive straight leg raise (PSLR)28 tests are often considered the gold standards. However, it is also common clinically for apparent hamstring tightness, as well as flexibility, to be assessed using the finger-to-floor distance (FFD) and v-sit and reach (VSR) tests in clinical practice. The AKE test was first described by Gajdosik and Lusin26 as an objective test for measuring hamstring length with the hip held in 90° of flexion as the knee is extended. A knee flexion angle of 20° or less is considered normal ROM on the AKE29 and knee flexion angles of greater than 20° have been used in several studies to identify patients with decreased hamstring extensibility.30–33 The AKE has been found to have high reliability for intra-rater agreement (ICC = .86-.99)26,34 and moderate inter-rater reliability (ICC = .76-.89).35 Variations in testing procedures have been reported in the literature, with some researchers stabilizing the hips using straps26,34 and utilizing a crossbar or box to maintain 90° of hip flexion,26,30,31,33,36,37 while other researchers do not.38

The PSLR is a test that allows for passive assessment of apparent hamstring flexibility. The PSLR is performed with the patient supine and the clinician passively raising the leg with the patient relaxed; care should be taken to avoid rotation of the pelvis or flexion of the uninvolved leg.28,39 Normal ROM for the PSLR has been reported as 80° of hip flexion.29 The PSLR has been reported to have high intra-rater (r = .91) and inter-rater (r = .93) reliability.40 Additionally, the PSLR has been reported to be moderately correlated with the AKE test (r = .72).34

The V-sit and reach (VSR) test, a modified version of the classic sit-and-reach test often used when equipment is not available to perform the traditional test, is also used to assess lower extremity flexibility.41 During the VSR, the patient sits on the floor with the feet separated by 30 cm, forming a V-shaped leg position that is maintained as the patient reaches forward as far as possible.37,38 Intra-rater reliability of the VSR has been reported as high (r=0.98; p<0.05).43 Inter-rater reliability has not been identified in the literature. The VSR has been identified to have a moderate correlation with the PSLR (r = .44-.65).41,44

The FFD is a test used to assess hamstring flexibility during active motion; it requires mobility at the pelvic girdle and lumbar spine, in addition to hamstring extensibility as the individual forward flexes towards the toes. There is conflicting research regarding the validity of determining lumbar motion from the FFD.45,46 The FFD is believed to be a good test for determining hamstring extensibility with intra- and inter-observer reliability ratings of .99.45,46

Although the AKE, PSLR, VSR, and FFD have been identified to have high reliability, the methods for performing the tests are not standardized. In research, these assessments often use cross bars, pulley systems, and straps; however, these methods are often not clinically feasible. Additionally, there is little evidence available in the literature to indicate whether these tests are assessing the same construct (i.e., tightness) or if they are assessing...
another construct related to flexibility or joint excursion of the hip. Also it is unclear how to interpret the results of the various tests if collected simultaneously in order to assess and categorize patient function. Therefore, the purpose of this study was to investigate the relationships between four common clinical tests of apparent hamstring tightness. A secondary purpose was to compare the differences in correlations between sub-groups based on positive test findings.

**METHODS**

**Participants**

For this multi-site study, physically active, non-injured participants [N = 58 (24 female, 20.5 ± 1.4 years; 34 males, 20.8 ± 1.7 years)] were recruited from university athletic training clinics as well as the graduate and undergraduate student bodies at two NCAA Division I (Towson, University, University of Idaho), one NCAA Division II (Azusa Pacific University), one NCAA Division III (Waynesburg College), and one NAIA school (Northwestern College).

All participants had complaints of hamstring tightness and an AKE of more than 20°. The following exclusion criteria were applied: (1) lower extremity injury in the previous six weeks; (2) lumbar pathology including back injury in the previous six weeks, known lumbar spine pathology limiting ROM (dis-cogenic), prior lumbar spine surgical procedures, known lumbosacral spine physical impairments limiting ROM and function; (3) lower extremity surgery within last six months; major ligamentous surgery within last one year; (4) vestibulocochlear disturbances/concussion (5) joint hypermobility syndrome (Beighton Score of four or higher); (6) connective tissue disorders (e.g., Marfans, Ehlos Danlos); or (7) lower extremity neurovascular pathology, including numbness, tingling, and loss of sensation. The study was approved by the Institutional Review Board (IRB) of each data collection site; each participant provided informed consent and the participants' rights were protected.

**Reliability Testing**

Given the multi-site nature of the study, intra- and inter-rater reliability of the AKE, PSLR, FFD, and VSR were established prior to the start of the study (Table 1). A convenience sample of 24 participants (14 females, 30.2 ± 4.0 years; 10 males 33.5 ± 6.6 years) was recruited from the graduate population; these participants were not required to have complaints of hamstring tightness and were not included in the correlational analysis.

**Assessment Procedures**

All ROM measurements were collected by the primary investigators; The AKE and PSLR assessments utilized a digital inclinometer smartphone application (Clinometer, https://www.plaincode.com/products/clinometer/). While the Clinometer application has been identified as a valid measure for shoulder and ankle ROM, this is the first study to use the application for knee and hip measurements. Prior to each testing session, the Clinometer application was calibrated and the participant's leg was marked at the anterior tibia (7.62 cm below the tibial tuberosity) and on the anterior thigh (15.24 cm above the tibial tuberosity) to ensure accurate and consistent placement of the smartphone for use of the Clinometer app and a cloth tape measure was used for the FFD and VSR tests. For the AKE, PSLR, and FFD, the average of three measurements was reported; for the VSR, the third measure stood as the final score.

**Active Knee Extension (AKE) Measurement**

The AKE was measured with the participant in a supine position with one leg in a 90-90 position as an assistant stabilized the contralateral leg in extension. To maintain the 90-degree leg positioning, the clinician placed one hand on the hamstrings four inches superior to the knee while the other hand placed the smartphone inclinometer on the participant's quadriceps aligning the top of the phone with the marking on the participant's thigh. The participant was then instructed to actively extend the knee to the point of discomfort (i.e., an uncomfortable amount of tension), while maintaining 90 degrees of hip flexion (Figure 1). When the participant reached the point of discomfort the clinician relocated the smartphone inclinometer from the quadriceps to the mark at the mid-anterior tibia while maintaining 90 degrees of hip flexion with the other hand. Dysfunction on the AKE was defined a priori as more than 20 degrees.
Passive Straight Leg Raise (PSLR) Measurement
The PSLR was measured as the participant lay supine with the legs extended. While maintaining knee extension and monitoring pelvic rotation, the clinician slowly flexed the participant's hip until the point of discomfort was reached (Figure 2). An assistant stabilized the contralateral leg in an extended position during the procedure. The ROM measurement was recorded with the smartphone inclinometer placed at the mark on the thigh. Dysfunction on the PSLR was defined \textit{a priori} as less than 80 degrees.\cite{29}

V-Sit and Reach (VSR) Measurement
A cloth tape measure affixed to the floor was used to assess the participant's ROM. A piece of tape denoting the baseline “zero” point was placed at the 40 cm mark of the cloth tape measure. To denote the position of the participant's feet, on the baseline tape strip, two marks were placed 15 cm on either side of the tape measure (Figure 3). The participant was instructed to sit on the floor with the legs extended, the feet spaced 30 cm apart, and the plantar surface of each foot touching a box to keep the ankle joints in a neutral position.\cite{42} The legs were stabilized in an extended position by the clinician and assistant. To perform the VSR, the participant

<table>
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A KE = active knee extension test; FFD = finger-to-floor distance test; MDC = minimum detectable change; PSLR = passive straight leg raise test; SEM = standard error of mean; VSR = V-sit and reach test.

Figure 1. The AKE was measured with the participant in a supine position with clinician monitoring 90-90 position using the Clinometer smartphone application. Smartphone was aligned at a mark 15.24 cm above tibial tuberosity to ensure 90-90 positioning while patient actively performed knee extension. The smartphone inclinometer was relocated to a mark 7.62 cm below the tibial tuberosity to obtain the measurement.

Passive Straight Leg Raise (PSLR) Measurement
The PSLR was measured as the participant lay supine with the legs extended. While maintaining knee extension and monitoring pelvic rotation, the clinician slowly flexed the participant's hip until the point of discomfort was reached (Figure 2). An assistant stabilized the contralateral leg in an extended position during the procedure. The ROM measurement was recorded with the smartphone inclinometer placed at the mark on the thigh. Dysfunction on the PSLR was defined \textit{a priori} as less than 80 degrees.\cite{29}
placed one hand over the top of the other hand, flexed at the waist, and reached towards the toes to the point of discomfort. The motion was performed three times and the measurement was taken on the third attempt; the participant was required to hold the position while the measurement was obtained. The clinician measured from the edge of the baseline “zero” tape (located at the edge of the box) line to the tip of the middle finger. A measurement of “0” indicated the fingertip was in line with the edge of the baseline “zero” tape line. A negative number indicated that the fingers had not reached the edge of the line, while a positive number indicated the fingers were past the edge of the line. Measurements were rounded to the nearest half centimeter. Dysfunction on the VSR was defined a priori as an inability to reach to “zero” line on the tape.

**Finger to Floor Distance (FFD) Measurement**
The FFD test was performed with the participant standing feet together on a 20 cm box with toes positioned at the edge of the box. The participant flexed at the waist with hands on top of one another, reaching for the toes, and stopping at the point of discomfort. The clinician visually ensured the participant’s knees did not flex while performing the movement. The clinician measured from the top edge of the box to the tip of the middle finger of the top hand in centimeters (Figure 4). A measurement of “0” indicated the fingertip was in line with the edge of the box. A positive number indicated that the fingers had not reached the edge of the box, while a negative number indicated the fingers were past the edge of the box. Measurements were rounded to the nearest half centimeter. Dysfunction on the FFD was defined a priori as an inability to reach the edge of the box.

**Statistical Methods and Data Analysis**
Statistical analysis was performed using SPSS statistical software (version 23; SPSS Inc., Chicago, IL). Intraclass Correlation Coefficients (ICC) (3,1), with absolute agreement were performed to establish intra- and inter-rater reliability for each measure (Table 1). The standard error of measurement (SEM) and minimal detectable change (MDC) values were also calculated for each dependent variable from the reliability testing data performed prior to this study (Table 1). Standard measurement error was derived using the interrater ICC and the following formula: $\text{SEM} = SD \times \sqrt{(1-\text{ICC})}$. Minimum detectable change for this study was subsequently calculated using the formula $\text{MDC} = 1.96 \times \sqrt{2} \times \text{SEM}$ (Table 1).
Pearson’s correlations were conducted to determine the relationship between the measurements for all participants (N = 81), as well as for each dysfunctional group (Table 2). For example, the “dysfunctional PSLR group” included all participants who demonstrated dysfunction on the PSLR test. Correlation values were established a priori at 0-0.25 = little, if any, 0.26-0.49 = low, 0.5-0.69 = moderate, 0.70-0.89 = high, and 0.9-1.0 = very high.52

RESULTS

Reliability Measures
All measurements had high intra-rater and inter-rater reliability assessed with Intraclass Correlation Coefficients (ICC) (3,1), with absolute agreement (Table 1).51

Correlational Analysis for Dysfunctional

PSLR (N = 73)
Dysfunctional scores on the PSLR (N=73, mean = 56.1° ± 13.2°) have a strong correlation between the VSR (mean = -12.8 ± 8.8 cm) and FFD (mean = 7.2 ± 10.8 cm, r = -.785, r² = .616, p<0.001). Moderate correlations were found between the PSLR and FFD (r = -.520, r² = .27, p<0.001) and low correlations were identified for the PSLR and VSR (r = .464, r² = .215, p<0.001), the PSLR and AKE (mean = 42.3° ± 8.6°, r = -.291, r² = .085, p = .012), the AKE and VSR (r = -.316, r² = .01, p = .007), and the AKE and FFD (r = -.244, r² = .06, p = .038).

Correlational Analysis for Dysfunctional

VSR (N = 68)
Dysfunction on the VSR (N=68, mean = -14.7 ± 7.2 cm) also alters the correlations identified in this analysis. A strong correlation was identified between the VSR and FFD (mean =8.5 ± 10 cm, r = -.733, r² = .537, p<0.001). Weak correlations were found between the PSLR (mean = 55.8° ± 14.0°) and FFD (r = -.437, r² = .191, p<0.001), the PSLR and VSR (r = .303, r² = .092, p = .012), the PSLR and AKE (mean = 42.6° ± 8.5°, r = -.276, r² = .076, p = .023), AKE and VSR (r = -.266, r² = .071, p = .028), and the AKE and FFD (r = .194, r² = .038, p = .113).

Correlational Analysis for Dysfunctional

FFD (N = 51)
When the FFD was dysfunctional (N=51, mean = 12.7 ± 8.0 cm), the correlation between the VSR (mean = -16.8 ± 6.8 cm) and FFD became moderate (r=-0.572, r² = .327, p<0.001). Low correlations were identified between the PSLR (mean = 52.7° ± 12.7°) and VSR (r = 0.292, r² = .085, p = 0.038), the PSLR and AKE (mean = 43.7° ± 8.5°, r = -0.190, r² = .036, p = 0.183), AKE and VSR (r = -0.208, r² = .043, p = 0.143), and AKE and FFD (r = 0.101, r² = .01, p = 0.481).

Figure 4. The FFD test was performed with the participant standing feet together on a 20 cm box with toes positioned at the edge of the box. The participant flexed at the waist with hands on top of one another, reaching for the toes. The clinician measured from the top edge of the box to the tip of the middle finger of the top hand in centimeters using a cloth tape measure.
DISCUSSION

Hamstring tightness is frequently assessed in various populations including pediatrics, active young adults, and the elderly. The use of the AKE, PSLR, VSR, and FFD to assess hamstring tightness is widespread; however, each of these tests may be measuring the dysfunction utilizing different constructs. If true, this may suggest that the measurements are not able to be used interchangeably when assessing and treating apparent hamstring tightness in clinical practice. The current study is the first that the researchers are aware of to examine the relationships between all four of these assessments.

The strong correlation between the VSR and FFD in this study remained relatively consistent, with $r^2$ shared variance ranging from 34%-64% (Table 2), indicating a substantial portion of the variance in one test is associated with the other. A possible explanation is that both the VSR and FFD involve active trunk and hip flexion. Although the VSR utilizes a seated position (compared to the standing position of the FFD), both are closed kinetic chain assessments that require a patient to flex forward at the waist while also allowing for lumbar flexion. The similar movement pattern between the two tests may explain the shared variance, found between the VSR and FFD, while also explaining the low correlations with either of the “gold standard” AKE and PSLR tests. In weight bearing tests, such as the FFD, it is suggested that a dysfunctional motor control pattern of the postural muscles may present as apparent hamstring tightness.

Despite being unilateral, non-weight bearing, open kinetic chain assessments that do not have overt trunk flexion components, the AKE and PSLR did not have a similarly strong relationships, with consistently low (~8%) shared variance being found. The low correlation of $r = .284$ between the PSLR and AKE found in this study differs from the 0.53-0.72 range reported in previous studies, but is similar to the values reported by Gajdosik et al. A possible explanation may be the populations included in the different studies. The current study utilized a young adult population of at least recreationally

![Table 2. Correlation analysis results between hamstring tightness measures for all participants and for participants with dysfunctional measures.](https://example.com/table2.png)

**Table 2.** Correlation analysis results between hamstring tightness measures for all participants and for participants with dysfunctional measures.

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<th>VSR</th>
<th>FFD</th>
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<tr>
<td>PSLR</td>
<td>All (N=81)</td>
<td>$r = -.284^*$</td>
<td>$r^2 = .081$</td>
<td>$p = .01$</td>
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<td>Dysfunctional (N=73)</td>
<td>$r = -.291^*$</td>
<td>$r^2 = .085$</td>
<td>$p = .012$</td>
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<td>VSR</td>
<td>All (N=81)</td>
<td>$r = -.297^*$</td>
<td>$r^2 = .088$</td>
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<td>Dysfunctional (N=68)</td>
<td>$r = -.266^*$</td>
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<td>$r = .263^*$</td>
<td>$r^2 = .069$</td>
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<td>Dysfunctional (N=51)</td>
<td>$r = .101$</td>
<td>$r^2 = .010$</td>
<td>$p = .481$</td>
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AKE = active knee extension test; PSLR = passive straight leg raise test. VSR = V-sit and reach test. FFD = finger-to-floor distance test.

*Indicates statistically significance correlation at $p<0.05$.

$^*$ Dysfunction for each group was identified based on the a priori cut points based on the best available literature, as described above. For example, the “dysfunctional PSLR group” included all participants who demonstrated dysfunction on the PSLR test. A priori definitions for dysfunction were as follows: AKE greater than 20 degrees; PSLR less than 80 degrees; VSR inability to reach “zero” line; and FFD inability to reach edge of box.
active individuals as opposed to adolescents or young adults without activity requirements. While both the AKE and PSLR are purported to be the gold standards in the literature for measuring apparent hamstring length, the weak correlation and low shared variance demonstrated in the results of this study suggest that each test is may be measuring different underlying constructs of apparent hamstring tightness.

**FACTORS INFLUENCING APPARENT HAMSTRING TIGHTNESS**

**Sensory Theory**

Weippler and Magnusson proposed the sensory theory, suggesting that a patient’s complaint of “tightness” may be a perception of decreased ROM rather than actual tissue shortening or lack of elongation. Treatments for apparent hamstring tightness (e.g., stretching) focused on increasing tissue extensibility may demonstrate increases in ROM due to an increase in stretch tolerance.

**Quadriceps and Hamstrings Coactivation**

The active versus passive nature of the AKE and PSLR, respectively, may be another explanation for the low correlation between the two tests; active ROM is typically less than the passive movement available during the same maneuver (e.g., straight leg raise). The AKE requires active contraction of the quadriceps musculature to perform knee extension while maintaining hip flexion, while the PSLR involves passive hip flexion with the knee extended. Quadriceps “weakness” or active insufficiency in combination with a tight hamstring may make the AKE more challenging for patients than PSLR, thus contributing to the low correlation between the two tests.

**Lumbopelvic Control**

Researchers have suggested that hamstring activation may occur as a stabilizing strategy in individuals with poor lumbopelvic/core control. As one function of the hamstrings is to create movement at the hip, the use of the musculature to stabilize the lumbopelvic region would potentially decrease the flexibility of the muscles. While the authors were unable to identify any articles in which hamstring activation was examined in relation to lumbopelvic stabilization, some researchers have discovered a reduction in hamstring stiffness after participants completed exercises designed to improve the stability of the lumbopelvic complex. In contrast to the AKE and PSLR, the FFD is a test that requires motion at the lumbopelvic complex as the participant forward flexes the trunk. The weak correlation between the AKE and the FFD may represent a discrepancy between laboratory and clinical assessment.

**Clinical Application**

Interventions used to treat apparent hamstring tightness have had varied results, with some researchers identifying that stretching alone is successful and others suggesting that lumbopelvic stability is key to treatment. Additionally, researchers have also suggested that treatment using neurodynamics, in addition or contrast to, stretching or rehabilitation is effective for treating apparent hamstring tightness. While the AKE is frequently referred to as the “gold standard” in assessing apparent hamstring tightness, clinicians will commonly perform other assessments such as a “toe touch” test to identify whether a patient has “tight” hamstrings. As the AKE was not correlated strongly with any of the other tests, the researchers emphasize the questionable use of the test as the stand-alone gold standard for clinical diagnosis of apparent hamstring tightness as it likely measures different constructs than the other assessments. As indicated by the low correlations amongst the majority of these assessments, apparent hamstring tightness is likely a multi-factorial problem and the AKE may not assess all of the associated factors. Thus, there is a potential need for an algorithm to guide decisions on which assessment(s) to utilize. For example, if the clinician utilizes a single assessment for apparent hamstring tightness, other underlying factors (e.g., neural tension, lumbopelvic dysfunction) may go ignored and result in poor patient outcomes. The researchers of the current study suggest that clinicians utilize multiple assessments when evaluating apparent hamstring tightness in order to determine what underlying constructs (e.g., neural tension, lumbopelvic dysfunction) may be involved for each individual patient.

**Limitations**

All data was collected using a multi-site research approach at five clinical sites to improve study
external validity, however this methodology increases the potential for measurement error and reduced internal validity. Thus, intra- and inter-rater reliability was established to minimize variance between researchers.

CONCLUSIONS
The results of the current study indicate low correlation and a lack of shared variance amongst the majority of the assessments utilized, suggesting that each assessment may be measuring a different underlying construct of apparent hamstring tightness, such as hamstring muscle length, neural tension, and/or lumbopelvic stability, amongst others. In light of the findings described in this paper, clinicians may wish to consider including a battery of tests in the clinical evaluation of apparent hamstring tightness in order to discover the source of dysfunction and to guide treatment choices based on identified underlying factors.

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27. Davis DS, Quinn RO, Whiteman CT, Williams JD, Young CR. Concurrent validity of four clinical tests used to measure hamstring flexibility. *J Strength Cond Res.* 2008;22(2):583–588.


**ABSTRACT**

**Background:** A dynamic postural stability deficit has been suggested to be present in individuals with chronic ankle instability (CAI). Interventions to improve postural control in individuals with CAI have been reported, but they required a long period of compliance with interventions.

**Purpose:** To examine the effect of novel ankle-realigning socks on dynamic postural stability in individuals with CAI using the star excursion balance test (SEBT).

**Study Design:** Case-control study.

**Methods:** Twenty-eight control and 22 subjects with CAI (who were tested in both barefoot and with socks) were enrolled. The weight-bearing ankle dorsiflexion range of motion (DF-ROM) and SEBT were measured in the control group, the barefoot CAI group, and the CAI with socks group. In addition, subjective ankle instability during SEBT was measured using a visual analog scale (0 - 100).

**Results:** DF-ROM was 48.3 ± 7.4º in the control group, 43.3 ± 8.0º in the barefoot CAI group, and 45.7 ± 6.8º in the CAI with socks group. DF-ROM was significantly less in the barefoot CAI group than in the control group. The SEBT scores were significantly less in the barefoot CAI group than in the control group in all directions. The SEBT score was significantly larger in the CAI with socks group than in the barefoot CAI group in the posteromedial, posterior, and posterolateral directions. In addition, there were no significant differences between the control group and the CAI with socks group in six directions.

**Conclusion:** Wearing the novel ankle-realigning socks immediately improved dynamic postural stability as measured by the SEBT and subjective ankle instability in individuals with CAI.

**Level of Evidence:** Level 3b

**Keywords:** chronic ankle instability, dorsiflexion range of motion, lateral ankle sprain, star excursion balance test

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INTRODUCTION
Lateral ankle sprain is one of the most common injuries in competitive sports and recreational activities. Ankle injuries account for 10 to 30% of all athletic injuries and 40-56% of injuries in certain sports. The recurrence rates for lateral ankle sprains have been reported to be more than 50%, and repeated lateral ankle sprains potentially leading to chronic ankle instability (CAI). Thus, because of the economic and social costs of lateral ankle sprains, prevention of lateral ankle sprains and CAI is an important issue.

The postural control deficit in individuals with CAI has been extensively investigated, and the Star Excursion Balance Test (SEBT) has often been used to examine dynamic postural control. The SEBT involves having the subject maintain a single-leg stance while performing a maximal reach excursion with the contralateral limb in each of eight directions of a star on the floor. In a meta-analysis, individuals with CAI showed decreased dynamic postural control on the SEBT or time to stabilization by force plates, and balance training for the improvement of postural control for individuals with previous ankle sprains is important to prevent recurrent lateral ankle sprains. Some authors have reported the effects of interventions to improve postural control in individuals with CAI using a balance board or foot orthotics. showed improvement of maximal reach distances in individuals with CAI after 6 weeks of balance board training. Sesma et al. reported similar results after four weeks of foot orthotic use. However, these interventions had some issues because they required a long period and compliance.

Various factors such as joint kinematics and muscle activity have been shown to be related to the results of SEBT. In CAI, abnormal ankle joint alignment and kinematics can occur, which may contribute to decreased postural stability. Researchers have reported that talocrural joint mobilization for joints with CAI improved dynamic postural stability. The improvement is believed to be attributed to posterior gliding of the talus relative to the tibia during the SEBT, which can be achieved by taping to induce posterior gliding of the talus. To avoid using technique-dependent taping in this study, a novel functional soft brace in the form of socks (novel ankle-realigning socks) was used as a new intervention for CAI (Realine socks®, GLAB Corp, Hiroshima, Japan, Figure 1). These novel ankle-realigning socks are designed to normalize talocrural joint kinematics by inducing posterior gliding of the talus without restricting joint mobility by using a material with high and low elasticity in parts, as with taping as reported in the past. Wearing the socks is very simple and does not require any special technique as is required in taping. This novel intervention may induce normal kinematics of the talocrural joint and improve postural stability.

Thus, the objective of this study was to examine the effect of novel ankle-realigning socks on dynamic postural stability in individuals with CAI using the star excursion balance test (SEBT).

The authors hypothesized that the ankle-realigning socks would immediately improve dynamic postural stability in individuals with CAI.

METHODS
Participants
The protocol of this case-control study was approved by the Institutional Review Board at Hokkaido Chitose College of Rehabilitation, and the purpose of this study was to compare dynamic postural stability in individuals with CAI wearing a novel device and healthy individuals. The subjects were recruited by
questionnaires of medical college students in January 2015. Informed consent was obtained from all subjects prior to participation. Inclusion criteria and exclusion criteria for the CAI group conformed to the criteria proposed by the International Ankle Consortium (IAC). In addition, Identification of Functional Ankle Instability (IdFAI) was used to assess subjective ankle instability as recommended in the IAC criteria. The inclusion criterion for the control group was no ankle sprain history. Exclusion criteria for the control group were as follows: (a) history of surgery or fractures of the lower extremity; (b) pain in the lower extremity; (c) history of cerebrovascular disorders or neuropathy that affects balance; or (d) use of any medications that could affect balance.

Twenty-eight control (28 feet; male 16/female 12; mean ± SD age: 20.8 ± 2.3 years) and 22 CAI (26 feet; male 12/female 10, mean ± SD age: 20.8 ± 2.4 years) subjects participated in this study. There were no significant differences in their general characteristics (Table 1). The measurement limbs were the right in 21 and the left in 7 in the control group, and the right in 18 and the left in 8 in the CAI group. The average value of the IdFAI score of the CAI group was 18.1 (11-30).

**Ankle Realigning Socks**

The ankle-realigning socks were designed to control talocrural joint motion, including posterior gliding of the talus during dorsiflexion and anterior gliding during plantar flexion, while preventing inversion (Figure 1). The structure of the socks was designed based on the author’s original taping structure often used for athletes to accelerate return to play after ankle injury. It includes two bands medially and two bands laterally. Medially, the first band pulls the sole of the foot at the medial arch toward the medial malleolus, located posterior to the talocrural dorsiflexion/plantar-flexion joint axis. Therefore, it is in greater tension with ankle dorsiflexion, which helps posterior gliding. The second band pulls the medial heel to the medial malleolus, inducing calcaneal external rotation to balance the first band in the horizontal plane. By combining the two bands, the dorsiflexion/plantar-flexion joint axis is stabilized medially. Laterally, the third band pulls the lateral calcaneus to the lateral malleolus to prevent calcaneal inversion. The fourth band connects the 5th metatarsal to the region 10 cm proximal to the inferior tip of the lateral malleolus, preventing inversion during plantar flexion. The four bands together are thought to increase the range of motion in the neutral ankle position and improve stability at maximal dorsiflexion due to bony conformity. Patients with previous injuries of the anterior talofibular ligament experience an immediate reduction of pain, which suggests that the socks help reduce the tension of the ligament by realigning the talus posteriorly. A kinematic study is currently underway to support these speculations and observations.

**Protocol**

The measurements were performed in the order of (1) trochanter malleolar distance (TMD), (2) weight-bearing ankle dorsiflexion range of motion (DF-ROM), and (3) SEBT. The CAI group underwent the SEBT barefoot on the affected ankle (barefoot CAI group), and the control group was tested barefoot on the randomly selected side (control group). Then, subjects with CAI underwent the DF-ROM and SEBT the next day wearing the ankle-realigning socks (CAI with socks group). After putting on the socks, all subjects walked for five minutes to fit the socks to the feet. In order to eliminate the

| Table 1. General characteristics of the participants, reported as means ± SD. |
|-----------------|-----------------|-----------------|
| Variable        | Control (n = 28) | CAI (n = 22)    | 95% CI          |
| Age (y)         | 20.8 ± 2.3      | 20.8 ± 2.6      | -1.3, 1.4       |
| Height (cm)     | 165.1 ± 6.7     | 165.6 ± 6.9     | -4.4, 3.4       |
| Mass (kg)       | 58.3 ± 8.1      | 62.6 ± 10.0     | -9.4, 0.9       |
influence of walking, all subjects walked for the same amount of time even before barefoot measurements. The TMD was measured three times in the supine position, and the average value was calculated. The DF-ROM was measured according to the technique reported by Kobayashi et al. Each subject was asked to place the foot perpendicular to a wall in a lunge position and bend the forward knee toward the wall, without lifting the heel, until the maximum range of ankle dorsiflexion was reached. During the testing, the subject was instructed to align and maintain the orientation of the forward knee and toe. The examiner measured the ankle dorsiflexion angle three times using an inclinometer tightly pressed against the anterior aspect of the tibia, and the average value was calculated. The SEBT was measured according to the previous study (Figure 2). Measurements were performed three times after four practice times in each direction to avoid learning effects. The average value of three times was then calculated. After the measurements were completed, subjective ankle instability was measured with a visual analog scale (VAS, 0-100). At that time, subjects were instructed to self-evaluate the “fear of twisting the ankle" and the “feeling of ankle instability" of the pivot foot. The value obtained by dividing the average distance in each direction by the TMD was defined as the SEBT score. The first measurement direction of the SEBT was set randomly, and then subsequent measurements were performed counterclockwise.

**Statistical analysis**

All data were confirmed to be normally distributed by the Shapiro-Wilk test. The general characteristics of the subjects were compared using the independent t-test. For comparisons among the three groups (control/barefoot CAI/CAI with socks) of the DF-ROM and SEBT score, one-way analysis of variance was performed. Similarly, one-way analysis of variance was used to compare the VAS in each direction of SEBT in the control group. Two-way repeated measures analysis of variance (direction × socks) was used to compare the VAS of the subjects with CAI. Tukey’s HSD test was used as a post hoc test. To assess the clinical significance of the data, effect sizes (η) were calculated and interpreted according to Cohen (small, < .01; medium, 0.02 to 0.13; large, ≥ .14). The minimum effect size of the SEBT score in CAI was 0.67 in a similar previous study. Statistical power analysis based on this value showed that nine or more subjects were required in each group (α = .05, β = .20). All data were analyzed using the Statistical Software Package for the Social Sciences (SPSS ver.19, SPSS Inc., Chicago, IL, USA). Differences were considered significant at p < .05.

**RESULTS**

**DF ROM**

DF-ROM was 48.3 ± 7.4º in the control group, 43.3 ± 8.0º in the barefoot CAI group, and 45.7 ± 6.8º in the CAI with socks group. DF-ROM was significantly smaller in the barefoot CAI group than in the control group (p = .033). The effect size for DF-ROM was 0.11 or medium (Table 2).

**SEBT score**

The SEBT score was significantly smaller in the barefoot CAI group than in the control group in all
directions (p < .05). The scores in the posteromedial (PM), posterior (Post), and posterolateral (PL) directions were significantly larger in the CAI with socks group than in the barefoot CAI group. In addition, there were no significant differences between the control group and the CAI with socks group in six directions (anterolateral (AL), medial (Med), PM, Post, PL, lateral (Lat)). The effect size for the SEBT score was medium to large (AL; 0.11, Ant; 0.14, AM; 0.16, Med; 0.15, PM; 0.18, Post; 0.21, PL; 0.21, Lat; 0.10) (Table 3).

**Subjective ankle instability**
There was no significant difference in subjective ankle instability among SEBT directions in the control group (Table 4). In contrast, interaction was observed in the comparison of the barefoot CAI group and the CAI with socks group (p = .028). The VAS scores in all directions in the subjects with CAI were significantly decreased by wearing socks (Table 5). PL was significantly greater than Med, PM, and Post (Med p < .001, PM p = .003, Post p = .002), Lat was significantly greater than Med (p = .001), and AL was significantly greater than Med (p = .001) in the barefoot CAI group (Table 5). In the CAI with socks group, PL was significantly greater than Med (p = .002), and Lat was significantly greater than Med and PM (Med p = .009, PM p = .042) (Table 5). The effect size (η) for the main

### Table 2. Weight-bearing DF-ROM (Mean ± SD)

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Barefoot CAI</th>
<th>CAI with socks</th>
<th>Effect size (η)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF-ROM (°)</td>
<td>48.3 ± 7.4</td>
<td>43.3 ± 8.0 *</td>
<td>45.7 ± 6.8</td>
<td>0.11</td>
</tr>
</tbody>
</table>

* DF-ROM is significantly smaller in the barefoot CAI group than in the control group (p = 0.033).

DF= dorsiflexion; ROM= range of motion; CAI= chronic ankle instability

### Table 3. SEBT Scores, percentage to trochanter malleolar distance (Mean ± SD)

<table>
<thead>
<tr>
<th>Direction</th>
<th>Control</th>
<th>Barefoot CAI</th>
<th>CAI with socks</th>
<th>Effect size (η)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>68.6 ± 7.4</td>
<td>62.9 ± 7.4 *</td>
<td>64.7 ± 7.2</td>
<td>0.11</td>
</tr>
<tr>
<td>Ant</td>
<td>72.8 ± 6.4</td>
<td>67.5 ± 7.0 *</td>
<td>67.9 ± 6.3 *</td>
<td>0.14</td>
</tr>
<tr>
<td>AM</td>
<td>81.5 ± 6.1</td>
<td>75.7 ± 6.5 *</td>
<td>77.1 ± 6.2 *</td>
<td>0.16</td>
</tr>
<tr>
<td>Med</td>
<td>94.2 ± 7.5</td>
<td>87.4 ± 7.6 *</td>
<td>89.4 ± 7.4</td>
<td>0.15</td>
</tr>
<tr>
<td>PM</td>
<td>109.7 ± 9.1</td>
<td>101.2 ± 8.2 †</td>
<td>105.2 ± 8.4</td>
<td>0.18</td>
</tr>
<tr>
<td>Post</td>
<td>117.1 ± 11.3</td>
<td>105.7 ± 11.3 †</td>
<td>111.7 ± 10.7</td>
<td>0.21</td>
</tr>
<tr>
<td>PL</td>
<td>105.7 ± 12.6</td>
<td>92.0 ± 12.8 †</td>
<td>99.5 ± 11.3</td>
<td>0.21</td>
</tr>
<tr>
<td>Lat</td>
<td>67.0 ± 8.3</td>
<td>60.2 ± 8.6 *</td>
<td>61.4 ± 9.4</td>
<td>0.10</td>
</tr>
</tbody>
</table>

* The SEBT score is significantly smaller than in the control group (p < 0.05).
† The SEBT scores is significantly less in the barefoot CAI group than in the control group and the CAI with socks groups (p < 0.05).

SEBT= Star Excursion Balance Test; CAI= chronic ankle instability; AL= anterolateral; Ant= anterior; AM= anteromedial; Med= medial; PM= posteromedial; Post= posterior; PL= posterolateral; Lat= lateral
The objective of this study was to examine the effect of ankle-realigning socks on dynamic postural stability in subjects with CAI. The results of this study demonstrated that DF-ROM and the SEBT scores were significantly less in the barefoot CAI group than in barefoot control subjects. When using socks, the SEBT score improved instantly in the PM, Post, and PL directions, and the subjective ankle instability during SEBT was also significantly improved.

Dynamic postural stability in individuals with CAI has been considered in several studies. Gribble et al. reported decreased SEBT scores in the Ant, Med, and Post directions in individuals with CAI.

**DISCUSSION**

**Table 4. VAS for subjective ankle instability of the control group during SEBT (Mean ± SD).**

<table>
<thead>
<tr>
<th>Direction</th>
<th>VAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>22.2 ± 21.6</td>
</tr>
<tr>
<td>Ant</td>
<td>18.7 ± 21.7</td>
</tr>
<tr>
<td>AM</td>
<td>16.6 ± 18.3</td>
</tr>
<tr>
<td>Med</td>
<td>12.5 ± 13.0</td>
</tr>
<tr>
<td>PM</td>
<td>13.1 ± 14.8</td>
</tr>
<tr>
<td>Post</td>
<td>13.3 ± 15.1</td>
</tr>
<tr>
<td>PL</td>
<td>20.1 ± 20.1</td>
</tr>
<tr>
<td>Lat</td>
<td>21.1 ± 23.7</td>
</tr>
</tbody>
</table>

There was no significant difference among the SEBT directions.

**Table 5. VAS for subjective ankle instability of CAI groups during SEBT (Mean ± SD).**

<table>
<thead>
<tr>
<th>Direction</th>
<th>Barefoot CAI (Mean ± SD)</th>
<th>CAI with socks (Mean ± SD)</th>
<th>Socks (p-value)</th>
<th>Direction</th>
<th>CAI with socks (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>43.5 ± 27.2</td>
<td>29.7 ± 19.1</td>
<td>0.002</td>
<td>&gt; Med 0.012</td>
<td></td>
</tr>
<tr>
<td>Ant</td>
<td>35.5 ± 23.3</td>
<td>23.9 ± 16.2</td>
<td>0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM</td>
<td>36.3 ± 21.3</td>
<td>25.3 ± 17.5</td>
<td>0.006</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Med</td>
<td>27.7 ± 19.5</td>
<td>19.0 ± 13.2</td>
<td>0.001</td>
<td>&lt; AL 0.012 &lt; PL 0.000 &lt; Lat 0.001 &lt; PL 0.002 &lt; Lat 0.009</td>
<td></td>
</tr>
<tr>
<td>PM</td>
<td>30.8 ± 23.5</td>
<td>22.1 ± 12.7</td>
<td>0.026</td>
<td>&lt; PL 0.003 &lt; Lat 0.042</td>
<td></td>
</tr>
<tr>
<td>Post</td>
<td>33.3 ± 23.0</td>
<td>25.0 ± 17.2</td>
<td>0.037</td>
<td>&lt; PL 0.002</td>
<td></td>
</tr>
<tr>
<td>PL</td>
<td>50.8 ± 22.8</td>
<td>29.8 ± 17.0</td>
<td>&lt; 0.000</td>
<td>&gt; Med 0.000 &gt; PM 0.003 &gt; Post 0.002 &gt; Med 0.002</td>
<td></td>
</tr>
<tr>
<td>Lat</td>
<td>49.0 ± 25.5</td>
<td>32.0 ± 17.6</td>
<td>&lt; 0.000</td>
<td>&gt; Med 0.001 &gt; Med 0.009 &gt; PM 0.042</td>
<td></td>
</tr>
</tbody>
</table>

VAS= visual analog scale; CAI= chronic ankle instability; SEBT= Star Excursion Balance Test; AL= anterolateral; Ant= anterior; AM= anteromedial; Med= medial; PM= posteromedial; Post= posterior; PL= posterolateral; Lat= lateral
Similarly, decreases in the SEBT scores in the AM, Med, PM, and PL directions were reported by other previous studies. However, these studies differed in the selection criteria for CAI. The present study met IAC criteria and all individuals with CAI demonstrated decreased SEBT scores.

The effects of interventions aimed at improving dynamic postural stability in individuals with CAI have been verified by other authors (Table 6). These authors reported significant improvements in SEBT scores after four to six week interventions. Although the results of the present study supported these previous results, the present study included only short-term follow-up. This suggests that the novel ankle-realigning socks have the effect of improving immediate and short-term dynamic postural stability in individuals with CAI within a short period of time. Meanwhile, in the present study, there was no significant improvement in the anterior SEBT direction, despite significant improvement in previous studies. This may be because no significant improvement was observed in ankle DF-ROM, which was positively correlated with the anterior SEBT direction. Earl and Hertel reported that the muscle activity of the vastus medialis was related to the anterior SEBT direction. However, this study did not measure muscle activity anywhere in the lower extremity, thus, the effect of muscle activity is unknown. It is unknown whether after a longer period, of sock wearing there may be a significant change in the anterior SEBT direction, and, therefore, further study is necessary.

Some researchers have shown that DF-ROM and hip/knee joint kinematics affect the SEBT score. In the present study, the barefoot CAI group had significantly decreased DF-ROM compared to the control group, and this may have affected the results of the SEBT score. In addition, subjective ankle instability increased in the PL, Lat, and AL directions in the barefoot CAI group, which may be due to increased inversion necessary to increase these tasks. When individuals with CAI wore the ankle-realigning socks, subjective ankle instability was significantly decreased. Although subjective ankle instability was decreased, there was no limitation on DF-ROM by wearing the socks, but rather a slight improvement was observed (barefoot CAI, 43.3 ± 8.0°; CAI with socks, 45.7 ± 6.8°). This may suggest that ankle-realigning socks changed not only talocrural joint kinematics, but sensory awareness, proprioception, or muscle activity. The authors need to verify detailed mechanisms of action of the novel socks, by

Table 6. Intervention intended to increase dynamic postural stability (SEBT) in CAI.

<table>
<thead>
<tr>
<th>Study</th>
<th>Number of subjects</th>
<th>Intervention</th>
<th>Frequency Duration</th>
<th>Results (SEBT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sesma, 2008</td>
<td>34</td>
<td>foot orthotics</td>
<td>4-8 hours/day</td>
<td>significantly improved (all 8 directions)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 weeks</td>
<td></td>
</tr>
<tr>
<td>Sefton, 2011</td>
<td>12</td>
<td>balance training</td>
<td>3 sessions/week</td>
<td>significantly improved (Ant / AM / PM)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6 weeks</td>
<td></td>
</tr>
<tr>
<td>Schaefer, 2012</td>
<td>36</td>
<td>balance training, soft-tissue mobilization</td>
<td>2 sessions/week</td>
<td>significantly improved (Ant / PM / PL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 weeks</td>
<td></td>
</tr>
<tr>
<td>Cruz-Diaz, 2015</td>
<td>70</td>
<td>multi-station balance training</td>
<td>-</td>
<td>significantly improved (Ant / PM / PL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6 weeks</td>
<td></td>
</tr>
<tr>
<td>Current study</td>
<td>22</td>
<td>novel ankle-realigning socks</td>
<td>-</td>
<td>significantly improved (PM / Post / PL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 minutes</td>
<td></td>
</tr>
</tbody>
</table>

CAI= Chronic ankle instability; Ant= anterior; AM= anteromedial; PM= posteromedial; Post= posterior; PL= posterolateral; SEBT= star excursion balance test
analysis of joint kinematics (e.g. 3D-to-2D analysis technique) or electromyography to explore this possibility. This reduction of subjective ankle instability induced by the ankle-realigning socks may have increased dynamic stability and mobility of the lower limb joints and led to an improved SEBT score.

The subjects in the present study were recruited according to IAC criteria. In addition, the SEBT and DF-ROM measurements were performed according to methods proven highly reliable in previous studies. Accordingly, this study was carried out with high internal validity. As for external validity, since this study included only young college students, these results may not be applicable to athletes, adolescents, or elderly persons.

This study had some limitations. This study did not investigate muscle activity or joint kinematics that may affect the SEBT score. In addition, the effects of the ankle-realigning socks on ankle kinematics, sensory awareness, and lower leg muscle activity are unknown, and the mechanism of the effect of the socks remains speculative. Accordingly, it is necessary to determine the mechanism of action. Moreover, this study considered only the immediate effect; the sustainability of the effect is unknown.

CONCLUSION
The results of the current study indicate that in individuals with CAI meeting IAC criteria, DF-ROM and the SEBT scores of all eight directions were significantly decreased compared to healthy subjects. In addition, subjective ankle instability was increased during lateral reach in those with CAI. The results indicate that wearing the ankle-realigning socks immediately significantly improved dynamic postural stability and subjective ankle instability in subjects with CAI in the short term. A future study may focus on the mechanism of the effect of the ankle-realigning socks with a larger sample size for appropriate power.

REFERENCES


ABSTRACT

Background: While researchers have investigated low back pain (LBP) and its association with the thickness of trunk muscles in the general population, few articles have studied this relationship in athletes.

Hypothesis/Purpose: To compare the lateral abdominal muscle thickness and other possible functional risk factors in young soccer players with and without LBP.

Study Design: Cross-sectional study

Methods: Thirty young male soccer players, with and without LBP, from the Premier League participated in this study. The thicknesses of the external oblique, internal oblique and transversus abdominis muscles were measured via musculoskeletal ultrasound imaging, bilaterally. In addition, hamstring flexibility, lumbar spine flexion range of motion, and trunk extensor muscle endurance were measured and were compared in those with and without the history of LBP.

Results: The mean age of the subjects was 17.4 (+/- 1.1) years. There was no statistically significant difference between groups (p > 0.05). Subjects with a history of LBP during their lifetime of sports participation (sports life), within the prior year, and within the prior month had statistically significant lower external oblique muscle thickness bilaterally (p<0.05). Subjects with a sports life history of LBP had lower internal oblique muscle thickness on both sides (p<0.05). Moreover, those with a sports life history of LBP had significantly less hamstring flexibility than the non-LBP group on the dominant limb (p <0.05).

Conclusion: In this sample group of young soccer players, abdominal muscle ultrasound measurements were different between players with and without LBP. Further longitudinal studies are needed to evaluate the role of these muscles as LBP risk factor for soccer players.

Levels of Evidence: 3a

Key Words: External oblique; Internal oblique; Low back pain; Soccer; Transversus abdominis; youth athletes
INTRODUCTION

Low back pain (LBP) has become a common complaint amongst athletes. It is reported that the prevalence of LBP is between 1.3% and 6.5% in elite male soccer players, and reported LBP odds ratio is about 1.6 (CI: 1.3-2.2) in soccer players. Several risk factors such as height, weight, high levels of physical activity, muscle endurance, and flexibility have been proposed as the risk factors for LBP in young athletes. However, there may be other unknown risk factors.

Researchers have suggested that unilateral or bilateral abdominal muscles’ with altered motor control, including internal oblique (IO), external oblique (EO), and transverse abdominis (TrA) muscles, may have a role in LBP. In addition, alteration in the ability of these muscles during drawing in maneuver has been found in subjects with LBP in comparison with normal subjects. Regarding the role of these muscles in the athletes’ LBP, Hides et al. showed that cricketers with LBP had less activity of TrA muscle in the draw in maneuver during MRI assessment, and elite Australian Football League players with LBP showed lower recruitment during abdominal drawing in maneuver also measured via MRI. Additionally, Rostami et al. revealed that off-road cyclists who suffered from LBP had thinner TrA and smaller cross-sectional area of lumbar multifidi muscles in comparison with cyclists without LBP, when assessed using musculoskeletal (MSK) ultrasound. It could be hypothesized that changes in EO, IO, TrA thickness and their activation might have a role in soccer players’ LBP, and that stabilizing exercises that focus on coordination and strengthening of these muscles could help reduce the risk of spinal injury and may be useful in the treatment of LBP in soccer players.

No study has investigated the status of EO, IO, and TrA muscles thickness in young soccer players with and without LBP, while there are several studies on this topic for other sports. The purpose of this study was to compare the lateral abdominal muscle thickness, and other possible functional risk factors (including hamstring flexibility, trunk extensor muscles endurance, leg length discrepancy and lumbar spine flexion range of motion) in young soccer players with and without LBP.

METHODS

Study population

A cross-sectional study was conducted in the Sports Medicine Research Center. This study was in accordance with the principles of the Declaration of Helsinki and the study design and protocol were approved by the institutional review board and ethics committee of Tehran University of Medical Sciences.

Fifty-five young male players between the ages of 16-20 years were enrolled in the study. They were playing at the youth soccer league in three soccer clubs (all members of clubs). A written informed consent was obtained from all subjects and/or their parents. A trained interviewer attended the training camp and asked the players to complete the questionnaire (Appendix 1). LBP was defined as “a pain between the last rib and lower gluteal fold as you can see in the following mannequin (labeled with a gray area on the questionnaire), which is bad enough to limit or change an athletes’ daily routine or sports activities for more than one day” according to a previous study by Noormohammadpour et al. Exclusion criteria were considered as those with history of direct trauma to the lumbar area, those who had leg pain or paresthesia in addition to back pain, musculoskeletal deformity (i.e. scoliosis or kyphosis), history of lumbar or abdominal surgery, systemic disease which may have influence on abdominal muscle thickness, and those subjects who had participated in exercises which dominantly activate EO, IO, and TrA muscles during the prior six months. Subjects were divided into different subgroups according to their history of LBP: lifetime LBP (experience of LBP at any time at their life), sports life LBP (experience of LBP at any time after beginning sports participation), prior year LBP (experience of LBP in the past year), prior month LBP (experience of LBP in the past month), and no history of LBP (no experience of LBP in any time at their life).

Measurements

Subjects were asked to visit the Sports Medicine Research Center for all measurements and examinations. In addition, age, LBP VAS (visual analog scale from 0 to 10) during last episode, training sessions or competition absence, and care-seeking behaviors due to LBP were asked in the questionnaire (Appendix 1).
**Height**: Height of the subjects was measured by asking the subjects to stand straight without shoes, place their heels together, look straight ahead and take a deep breath and hold it.\(^{17}\)

**Weight**: Weight was measured by asking the subjects to wear light sportswear (a T-shirt and shorts) and stand on a digital scale with the accuracy of 0.1 kilograms.\(^{17}\)

**Muscle thickness**: A SonoSite sonography device (FUJIFILM SonoSite Inc., Bothell, WA, USA) with a 6 to 13 MHz linear transducer was used to measure the thickness of the abdominal muscles (EO, IO, and TrA) at rest in the B-mode format, bilaterally. Because of known effect of food consumption on abdominal muscle thickness,\(^{18,19}\) subjects were asked to attend without having consumed breakfast. A point 25 mm anteromedial to the midpoint between the inferior rib and the iliac crest to the mid-axillary line was used as the standardized position to measure EO, IO, and TrA thickness where their fascial margins were parallel.\(^{20}\) Subjects assumed a hook-lying position and the measurement of muscle thickness was performed by the transducer in transverse plane position at the center point of the image using the caliper feature of the device. The subjects could not view the process and the measurements were taken when they were at the end of the normal exhalation. Adequate gel was applied between the transducer and the skin to increase the contact area and reduce the need for the excess pressure of probe on the skin (which could lead to measurement errors). For more precise measurement, the depth of the image was manipulated so that the EO, IO, and TrA thickness filled approximately 40–50% of the ultrasound display.\(^{21}\) The distance between the top of the inferior fascial layer and bottom of the superior fascial layer of each muscle was considered as EO, IO, and TrA thickness, respectively.\(^{20}\) The EO, IO, and TrA thickness bilaterally was measured twice in a one-hour interval by the same assessor for the assessment of reliability and mean of the two measurements for each muscle on each side was used for analysis.

**Trunk extensor muscle endurance**: In order to assess the trunk extensor muscles endurance, the Sorensen test was used. Subjects laid prone on the examination table, with the upper edge of the iliac crest at the edge of the table. To fix subjects’ lower limbs on the examination table, three straps were used at hip, knee, and ankles. Subjects were asked to cross their hands across the front of their chest and hold their upper trunk in an isometric horizontal position, while the amount of time that the subject could maintain this position was recorded.\(^{22}\) An inclinometer was applied gently between the two scapulae, and when the trunk was tilted down more than 5 to 10° the test was stopped.

**Lumbar spine flexion range of motion (ROM)**: The amount of forward flexion of the subjects was assessed by using a tape measure to record the linear distance between the spinous processes of the 12th thoracic and the 1st sacral vertebrae in standing, at rest position and also while performing as much active forward flexion as possible.\(^{23}\) A SonoSite sonography device with a 2 to 5 MHz curved transducer was used to find spinous processes. Difference between the two measurements was used for analysis.

**Leg length measurement**: Previous studies have shown that difference in leg length can be a risk factor for LBP in school children and young athletes;\(^{14,24}\) therefore, leg length was measured with the subject in supine position. The distance between the anterior superior iliac spine and medial malleolus was recorded by using a tape measure to find the length of both limbs.\(^{25}\)

**Hamstring muscle flexibility**: Subjects were asked to lie down in the supine position and flex their hip joint to 90 degrees. The examiner then passively extended the knee, while preventing rotation and abduction of the subjects’ knee until pain or tightness of muscles limited the extension of the knee joint. The center of a standard goniometer was placed on the surface of lateral epicondyle of the femur, then its proximal arm was placed on the femur towards the greater trochanter and its distal arm was placed on the fibula toward lateral malleolus. The difference between measured data at this angle and 180 degrees was used for analysis.\(^{26}\)

**Statistical Analysis**
Data analysis was performed using Statistical Package for Social Sciences (SPSS, version 16, Chicago, Inc., US) and \(p < 0.05\) was considered statistically significant. Quantitative and categorical variables
were described as mean (SD) and number (percent), respectively. The Kolmogorov-Smirnov test was applied to assess the normal distribution of the data. To evaluate the association between LBP presence, and EO, IO, TrA thickness and other variables, a multiple linear regression model was used with adjustment for age and body mass(weight) of the participants as the potential confounders of outcomes. Intraclass correlation coefficient (ICC) and standard error of measurement (SEM) were calculated to evaluate within-subject reliability.

RESULTS
Fifty-five young male players between 16-20 years old were recruited to participate in the study from three soccer clubs. However, twenty-five were excluded because seven subjects had the history of radicular leg pain symptoms, and eighteen subjects participated in a routine core stability program. Therefore, thirty subjects participated in the study. Table 1 displays the demographic characteristics of the study subjects. Mean (SD) age, and BMI of the subjects who reported sports life LBP were 17.2(1.1) years, and 20.7(2.7), respectively. Subjects participated in their first competition at a mean age of 13.4(2.3) years and their mean training time was 9.8(1.4) hours per week. The LBP features of the subjects are summarized in Table 2. The mean VAS was 4.9(1.4) out of 10. Demographic and clinical measurements for the subjects with and without the history of LBP are displayed in Table 3. There were no statistically significant differences regarding age, BMI, weekly training hours, and age of starting to compete between the different groups in the study population (p > 0.05).

In comparison with subjects with no history of LBP, the forward flexibility of lumbar spine was not different in subjects with any of the groups with LBP (p > 0.05). Subjects with sports life and prior year history of LBP had less right and left hamstring flexibility in comparison with those without a history of LBP, although the differences were not statistically significant.

Subjects with sports life, prior year, and prior month history of LBP had significantly lower EO muscle thickness bilaterally (p<0.05). In addition, subjects with sports life history of LBP had significantly lower IO muscle thickness bilaterally (p<0.05). Subjects without history of LBP had higher TrA muscle thickness but the results were not statistically significantly different. The ranges of ICC and SEM were from 0.75 to 0.89 and from 0.07 to 0.6, respectively; which indicate within-subject reliability of ultrasound measurements.

In total, 66.7% (n=20) of subjects were right leg dominant. Comparison of the clinical measurements

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>16.0</td>
<td>20.0</td>
<td>17.4</td>
<td>1.1</td>
</tr>
<tr>
<td>Weight (Kg)</td>
<td>49</td>
<td>100</td>
<td>65.6</td>
<td>11.3</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>164</td>
<td>192</td>
<td>176.2</td>
<td>6.2</td>
</tr>
<tr>
<td>BMI (Kg/m2)</td>
<td>17.0</td>
<td>26.3</td>
<td>21.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Training/week (hours)</td>
<td>5.0</td>
<td>15.0</td>
<td>9.8</td>
<td>1.7</td>
</tr>
<tr>
<td>Age of starting to compete (years)</td>
<td>9.0</td>
<td>17.0</td>
<td>13.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

SD: Standard deviation, BMI: body mass index

Table 1. The demographic characteristics of the study subjects.

Table 2. The characteristics of the population under study.

<table>
<thead>
<tr>
<th>Variable</th>
<th>% (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBP</td>
<td></td>
</tr>
<tr>
<td>Lifetime prevalence</td>
<td>50.0(15)</td>
</tr>
<tr>
<td>Sports life prevalence</td>
<td>50.0(15)</td>
</tr>
<tr>
<td>Prior year prevalence</td>
<td>30.0(9)</td>
</tr>
<tr>
<td>Prior month prevalence</td>
<td>16.7(6)</td>
</tr>
<tr>
<td>Point (recent) prevalence</td>
<td>10.0(3)</td>
</tr>
<tr>
<td>Care-seeking behaviors</td>
<td></td>
</tr>
<tr>
<td>Visit to LBP specialist</td>
<td>10.0(3)</td>
</tr>
<tr>
<td>Use of medication</td>
<td>16.7(5)</td>
</tr>
<tr>
<td>Plain radiography</td>
<td>3.3(1)</td>
</tr>
<tr>
<td>MRI</td>
<td>3.3(1)</td>
</tr>
<tr>
<td>Absent due to LBP</td>
<td></td>
</tr>
<tr>
<td>From training session</td>
<td>43.3(13)</td>
</tr>
<tr>
<td>From competition</td>
<td>16.7(5)</td>
</tr>
<tr>
<td>Dominant leg</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>66.7(20)</td>
</tr>
<tr>
<td>Left</td>
<td>33.3(10)</td>
</tr>
</tbody>
</table>

N: Number
LBP, Low back pain; MRI, Magnetic resonance imaging

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between the subjects with and without the history of LBP according to the dominant or non-dominant leg is shown in Table 4. Subjects with sports life history of LBP had statistically significant lower hamstring flexibility in their dominant limb. In addition, they had significantly lower IO and EO muscles thickness on both dominant and non-dominant sides (p<0.05).

**DISCUSSION**

The results of the current study indicate that young male soccer players with sports life LBP had thinner EO and IO muscles in comparison with subjects without LBP. Subjects with sports life and prior month history of LBP had thinner TrA muscles in comparison with subjects without the history of LBP but this difference was not statistically significant. This is the first study that shows such a difference in this population. In addition, these players had significantly lower hamstring flexibility in their dominant leg.

There are several studies in the literature indicating that the TrA muscle plays an essential role in
the biomechanical stability of the lumbar spine; however, regarding athletes with or without LBP, there is a controversy among different studies which have investigated lateral abdominal muscle thickness.8,10,12 Similarly, Rostami et al. found that the thickness of lateral abdominal muscles was lower in adult male off-road cyclists with LBP in the cycling position.10 Gray et al. demonstrated that the total thickness of lateral abdominal muscles is greater in cricket fast bowlers without LBP on the non-dominant side, and the IO thickness was less in bowlers with LBP than those without LBP (p=0.02).12 Gildea et al. showed that thickness of IO and TrA at rest and during abdominal drawing-in maneuver did not differ between ballet dancers with and without LBP via MRI.8 Additionally, Gill et al. found no significant difference in relative thickness of the TrA based on the history of back pain in collegiate single sided rowers (p: 0.075).29 The controversy between studies could be explained by various sports physical demands and activation of these muscles in different sport-specific positions which could not be detected in resting measurements.

Previous researchers have shown the role of lateral abdominal muscles contributes to core stability and strength of trunk, which can indirectly impact athletes’ performance and allow them to train with fewer injuries.30-32 These muscles’ role in stability is attributed to their ability to produce concordant forward flexion, lateral flexion, and rotational movements. Additionally, they can control external forces which are imparted in the opposite direction of these movements. Also, they are responsible for maintaining posture and distribution of muscle forces in the trunk for rapid movements and power generation.30-32 Soccer players have shown shorter reflex latencies for trunk muscles in comparison with non-players against sagittal plane perturbations.33 It could be that in soccer players, the activation of EO, IO, and TrA during cutting maneuvers which require trunk side flexion and rotation, play a role in the spinal injury prevention. Therefore, investigation of EO, IO, and TrA muscles’ thickness and their recruitment in functional and sports-related positions is important in soccer players and other athletes.

Differences in these muscles’ activation in sport-related positions and movements may explain the controversy in the results of different studies.8,10,12,28,29 As Rostami et al. showed the difference between groups in the cycling position, applying other sports specific positions could be helpful for future assessments instead of resting position/status. The role of trunk muscles in the different sports and dominant side of the body during sports may affect the interpretation of findings, also different LBP definitions8,10,12 in studies make it difficult to draw firm conclusions.

<table>
<thead>
<tr>
<th>Variables</th>
<th>History of LBP</th>
<th>p-value</th>
<th>History of LBP</th>
<th>p-value</th>
<th>History of LBP</th>
<th>p-value</th>
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</thead>
<tbody>
<tr>
<td><strong>hamstring flexibility (degrees)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>LBP + 8.2(6.2)</td>
<td>0.04*</td>
<td>LBP - 4.0(4.2)</td>
<td>0.75</td>
<td>LBP + 8.3(8.4)</td>
<td>0.04*</td>
</tr>
<tr>
<td>Non-dominant</td>
<td>LBP + 7.0(5.8)</td>
<td>0.04*</td>
<td>LBP + 10.7(2.4)</td>
<td>0.04*</td>
<td>LBP - 7.5(1.5)</td>
<td>0.04*</td>
</tr>
<tr>
<td><strong>EO (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>LBP + 7.2(1.7)</td>
<td>0.001*</td>
<td>LBP + 7.3(1.8)</td>
<td>0.04*</td>
<td>LBP + 7.7(1.7)</td>
<td>0.04*</td>
</tr>
<tr>
<td>Non-dominant</td>
<td>LBP + 11.1(2.1)</td>
<td>0.001*</td>
<td>LBP - 9.8(2.8)</td>
<td>0.04*</td>
<td>LBP + 9.2(2.6)</td>
<td>0.04*</td>
</tr>
<tr>
<td><strong>IO (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>LBP + 9.3(2.0)</td>
<td>0.03*</td>
<td>LBP + 9.8(2.4)</td>
<td>0.72</td>
<td>LBP + 9.1(2.1)</td>
<td>0.37</td>
</tr>
<tr>
<td>Non-dominant</td>
<td>LBP + 10.9(2.3)</td>
<td>0.03*</td>
<td>LBP + 10.2(2.2)</td>
<td>0.84</td>
<td>LBP + 10.8(2.2)</td>
<td>0.80</td>
</tr>
<tr>
<td><strong>TrA (mm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dominant</td>
<td>LBP + 3.4(0.8)</td>
<td>0.34</td>
<td>LBP + 3.8(0.9)</td>
<td>0.63</td>
<td>LBP + 3.8(0.9)</td>
<td>0.37</td>
</tr>
<tr>
<td>Non-dominant</td>
<td>LBP - 4.0(1.2)</td>
<td>0.34</td>
<td>LBP + 3.8(1.1)</td>
<td>0.63</td>
<td>LBP + 3.8(1.1)</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
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</tbody>
</table>
| SD: Standard deviation; LBP+: had history of low back pain; LBP-: did not have history of low back pain; EO: External Oblique, IO: Internal Oblique, TrA: Transversus Abdominis.

*Statistically Significant: (p-value<0.05)
Therefore, further studies with a unique definition of LBP and functional measurements of lateral abdominal muscles may be helpful in this field.

The results of the current study did not show any association between LBP and the number of training hours or LBP and the age when players started to compete. This finding is in accordance with Tunas et al. who did not find any association between history of LBP in the previous year and number of seasons playing soccer at the top level and also annual training volume. In a study by van Hilst et al. no relation between LBP and years of experience was reported for young soccer players.

These results did not show a significant association between the difference in length of the limbs and LBP or VAS score. This finding is in accordance with a previous study by Biering-Sorensen that reported leg length discrepancies could not predict LBP in subjects during the prior year. Similar to Biering-Sorensen’s findings this study found a significant association between lower hamstring muscles flexibility of the dominant limb and history of sports life LBP, while Stutchfield et al. showed that there was no association between LBP and hamstring flexibility in young male rowers (mean age was 20 years). Although Biering-Sorensen reported that increased endurance of back muscles can prevent LBP, the current findings did not show a significant association between trunk extensor muscles endurance and LBP. This finding could be due to differences between LBP definitions.

**Study Limitations**
The first limitation is the retrospective nature of the study in which subjects were asked about their history of LBP in past 12 months or throughout their lifetime of sports participation which is prone to recall bias and memory lapses. Second, this study is cross-sectional, thus findings could not evaluate cause and effect relationship between muscle thickness or other factors and LBP. Another limitation is that muscle thickness was measured at rest; while there are reports that indicate muscles thickness measured during drawing-in maneuver (ADIM) or active straight leg raise test may be more precise for assessing lateral abdominal muscular recruitment. Finally, the sample size was not large. Authors suggest further studies with a uniform protocol for these muscles’ contraction such as active straight leg raise test.

**CONCLUSIONS**
The results of the current study indicate that young soccer players with the history of sports life LBP had thinner EO and IO muscles and less hamstring flexibility in comparison with players without LBP. There was no significant difference in the TrA thickness between groups. No significant association was detected between LBP and age, height, weight, weekly training hours, the age of starting to compete and endurance of trunk extensor muscles in young athletes. Further studies with assessments conducted in sports specific positions and during functional tasks could be helpful to evaluate the association between LBP and thickness of the TrA muscle.

**REFERENCES**
Appendix 1. Low Back Questionnaire

This is a questionnaire for low back pain study in female athletes. Please answer each question as best as you can. All of your data will remain confidential.

**Basic characteristics:**

First name/Last name:  
Age:  
Hours of training per week:  
Age when you had your first competition:  
What is your playing role in the field? Goalkeeper Defender Midfielder Forward

**Low back pain questions:**

Low back pain (LBP) is defined as a pain between the last rib and lower gluteal fold as you can see in the following mannequin (gray area), which is bad enough to limit or change your daily routine or sports activities for more than one day.

Did you have low back pain within the last 48 hours?  
Yes  
No

Did you have low back pain within the last month?  
Yes  
No

Did you have low back pain within the past 12 months?  
Yes  
No

Did you have low back pain during your sports participation period?  
Yes  
No

Have you ever had low back pain?  
Yes  
No

Has your low back pain gotten worse since your sports participation?  
Yes  
No

**Care seeking behaviors questions:**

Did you visit a general practitioner for your low back pain within the last year?  
Yes  
No

Did you visit a low back pain specialist for your low back pain within the last year?  
Yes  
No

Did you take medication for your low back pain within the last year?  
Yes  
No

Did you have any plain radiography tests (Xrays) for your low back pain within the last year?  
Yes  
No

Did you have a MRI check for your low back pain within the last year?  
Yes  
No

**Absence due to low back pain:**

Were you absent from training sessions due to LBP within the last year?  
Yes  
No

Were you absent from competitions due to LBP within the last year?  
Yes  
No

**Please mark, on the line below, the intensity of your pain during last episode of LBP:**

0=No pain  
10=Worst possible pain

Thanks for your participation in this study.
ABSTRACT

**Background:** Patients with concussion may present with cervical spine impairments, therefore accurate characterization of cervical post-concussion impairments is needed to develop targeted physical therapy interventions.

**Purpose:** To characterize the type, frequency and severity of cervical impairments in children and adolescents referred for physical therapy after concussion.

**Study design:** Retrospective, descriptive study

**Methods:** A retrospective analysis was conducted for 73 consecutive children and adolescents who received cervical physical therapy following a concussion. Data was classified into six broad categories. The frequency and intensity of cervical impairments within and across the categories was reported.

**Results:** Ninety percent of patients demonstrated impairments in at least three out of five assessment categories whereas 55% demonstrated impairments in at least four out five assessment categories. Of the five assessment categories, posture (99%) and myofascial impairment (98%) demonstrated highest impairment frequency followed by joint mobility (86%) and muscle strength (62%). Cervical joint proprioception was the least commonly evaluated assessment category.

**Conclusion:** High prevalence of cervical spine impairments was observed in the subjects included in this study with muscle tension, joint mobility, and muscle strength being most commonly affected. The categories of impairments examined in this cohort were consistent with the recommendations of the most recent clinical practice guidelines for neck pain. This study provides preliminary data to support the framework for a cervical spine evaluation tool in children and adolescents following concussion.

**Level of evidence:** Level 4

**Key words:** Cervicogenic, movement system, traumatic brain injury, youth

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**Declaration of Conflict of Interest:** The authors report no conflicts of interest.

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INTRODUCTION

Concussion is defined as a complex pathophysiological process affecting the brain which is induced by biomechanical forces.\(^1\) Concussion is one of the most common athletic injuries in the United States and is a growing concern among children and young adults. In any given year, 43,200 to 67,200 of the 1.2 million total high school football players in the U.S. sustain concussions, with adolescents 15-19 years being most susceptible.\(^2,4\) Of the 502,000 children and adolescents diagnosed with concussion between years 2001 and 2005, 35% were estimated to fall between the ages of 8-13 years.\(^5\) Prevalence of post-concussion symptoms has been reported in previous studies with 90-92.2% of athletes experiencing headaches, 90% experiencing neck pain, and 68.9% experiencing dizziness.\(^6,8\)

Cervical musculoskeletal attributes such as neck strength may represent a modifiable risk factor for concussion\(^9,10\) and biomechanical similarities exist between concussion and whiplash injuries. Previous researchers have suggested a need for a structured cervical spine examination following a concussion.\(^11,12,13\) This recommendation is further supported by the overlap between concussion symptoms and symptoms associated with whiplash injuries.\(^1,12-14\) The transmission of forces to the head during a concussion may result in trauma to the cervical spine.\(^1,15\) Axial loading, hyperflexion and hyperextension of cervical spine are the most frequently reported mechanisms of injury to the cervical spine associated with various sports such as football, hockey and wrestling.\(^1,15\)

In previous studies, children demonstrated less cervical strength and greater head to body ratio than adults.\(^16-18\) Therefore, children may not be able to generate sufficient tensile stiffness to control the head’s response to impulsive loads,\(^19\) and may experience greater head acceleration as compared to adults.\(^20\) Moreover, it has been postulated that children exhibit reduced ability to efficiently dissipate energy from a head impact primarily due to underdevelopment of the neck and shoulder musculature.\(^11\) Smaller and weaker cervical muscle attributes in children may predispose them to greater cervical impairments after a concussive event, and warrant a thorough characterization of cervical post-concussion impairments in adolescents.

Prior authors have acknowledged that patients may often experience post-concussion symptoms pertinent to the cervical spine.\(^21-24\) Signs and symptoms such as decreased range of motion, muscle tenderness, headaches, stiffness and radicular symptoms have been reported to occur post-concussion.\(^22\) In previous studies more than 50% of patients continue to demonstrate symptoms such as headache, fatigue and dizziness even after the expected recovery time-frame post-concussion.\(^23,25\)

A comprehensive multifaceted approach to evaluation and treatment of post-concussion impairments must acknowledge heterogeneity of impairments including central and autonomic nervous system impairments, cervical and thoracic spine impairments, and vestibular and oculomotor impairments. A variable combination of impairments across these categories contributes to the overall constellation of symptom.\(^12,23,26\) For the best possible outcomes, physical therapy interventions must be directed toward specific impairments that are found during evaluation.\(^23\) Developing impairment-directed therapeutic interventions would result in supporting progression to subsequent clinical trials to establish efficacy and enhance practice patterns.\(^23,27\)

Despite the consensus that a thorough cervical examination is needed in patients with concussion,\(^12,26\) the evidence for characterization of common cervical impairments after concussion in children and adolescents (i.e. ≤18 y) is sparse.\(^28,29\) Although the most recent Clinical Practice Guidelines (CPG) for neck pain thoroughly reviewed the literature surrounding neck pain and associated cervical impairments, studies including children (i.e. < 18 years) were excluded from the CPG.\(^30\) Moreover, authors of the CPG recommend further research into treatment of patients with neck pain because of a concussion.\(^30\) Accurate characterization of the type, number and severity of cervical post-concussion impairments is needed for the development of targeted interventions.\(^12,21\) The purpose of this study was to characterize the type, frequency and severity of cervical post-concussion impairments in children and adolescents after concussion. This study will provide valuable insights into the extent and nature of cervical spine impairments post-concussion that may provide a foundation to develop targeted physical therapy interventions.
METHODS

Setting
The data for this study was retrospectively collected from the electronic medical records of a tertiary center specializing in comprehensive interdisciplinary management of patients with concussion. The study was approved by the Institutional Review Board at the University of Michigan.

Design and participants
A retrospective chart review was conducted of 73 children and adolescents between the ages of 8 to 18 years who received cervical physical therapy following a concussion from January 1, 2017 to August 31, 2017. The patients were referred from emergency and athletic departments to the tertiary interdisciplinary concussion clinic by care providers. In the clinic, a physician performed symptom-based examination that included a brief cervical spine screening in patients complaining of neck pain at the time of their visit. A brief cervical screen included tests for ligamentous stability, followed by range of motion testing, palpation, or segmental mobility testing. Following examination, the patients were referred for physical therapy for treatment of the cervical spine if indicated. Seven physical therapists performed examinations on patients, and recorded their findings. Upon inception of the concussion management program in this tertiary clinic, all seven treating therapists were trained to standardize administration of the tests and used standardized assessment forms as a measure of quality assurance. Demographic and clinical information was retrieved from electronic medical records.

Procedures
A data extraction sheet was developed by two investigators (DT and BA). The investigators independently extracted data for five random patients and the extracted data was compared to ensure consistency in data extraction. After ensuring quality of the extracted data, the primary investigator (DT) completed the remaining data collection. Assessment data from the first physical therapy visit was extracted. In the event that a full assessment was not completed due to excessive increase in patient's symptoms, the subsequent two visits were screened to extract additional assessment data.

Demographic, injury and care process data:
Demographic and injury characteristics were retrieved from electronic medical records. These characteristics included age, gender, primary sport(s), prior history of migraine or prior learning disabilities, date of sustaining concussion and mechanism of injury. In addition, the date of first medical visit, date of first physical therapy visit, total number of physician visits and total number of physical therapy visits were also collected.

Self-reported symptoms and disability:
Sports Concussion Assessment Tool 3rd edition (SCAT-III) symptom evaluation checklist: SCAT-III is a concussion evaluation tool that was developed from the original SCAT to make decisions regarding return to play. This study utilized the symptom evaluation checklist of the SCAT-III. The data on symptom severity score was collected on 22 concussion related symptoms including cognitive, physical, sleep and affect related symptoms using a Likert scale (0 = none, 6 = severe), where higher scores indicated greater symptom severity (maximum possible score = 132).

Neck disability index (NDI): The NDI is a self-reported measure with 10 items that is used to record perceived disability in patients with neck pain. The NDI scores were interpreted as described by Vernon and Mior where score of 0-4 indicated no disability, 5-14 mild disability, 15-24 moderate disability, 25-34 severe disability and scores above 35 indicated complete disability with a maximum possible score of 50.

Screening for ligamentous instability:
Results of special tests for upper cervical ligamentous instability including tests for alar ligament and transverse ligament were collected.

Test for alar ligament: The test for alar ligament was performed with patient in a seated position. The examiner's palm was placed on the forehead and index finger of the other hand was placed on the tip of spinous process of second cervical vertebra. The examiner then side bends and rotates the patient's head to the left or right while stabilizing C2. The test is considered positive for instability if movement between head and neck is observed. This test
demonstrates high specificity (0.88-1) and moderate to high sensitivity (0.54-0.84) to detect ligamentous instability in patients with whiplash disorder.37,38

Test for transverse ligament: The test for transverse ligament was performed with the patient in supine position with examiner supporting the head. Examiner’s index finger was placed between the occiput and spinous process of C2 vertebra. The head and C1 vertebra was then lifted anteriorly, not allowing either flexion or extension and the position was maintained for approximately 15 seconds. The test was considered positive if the patient exhibited nausea/vomiting, reported lip paresthesia, lump in the throat sensation, dizziness, headache or muscle spasm.39 This test demonstrates high specificity (0.96-1) and moderate to high sensitivity (0.51-0.79) for patients with whiplash disorder.37,38

Cervical Physical Therapy Examination

Cervical physical therapy assessment data were classified into six broad assessment categories. These assessment categories included posture, movement quality and generalized joint hypermobility (GJH), myofascial tension to palpation, joint mobility, muscle strength and endurance, proprioception, special tests for upper extremity radicular symptoms. (Figure 1)

![Figure 1. Assessment categories included in cervical examination.](image)

Posture, movement quality, Generalized Joint Hypermobility (GJH):

Posture: Forward head posture, scapular anterior tilt and increase in thoracic kyphosis were the dysfunctions assessed by observation using an ordinal scale (no/mild/moderate/severe). Posture was classified as impaired if a patient has one or more of these dysfunctions. As a part of continuous quality assurance initiative in our clinic, the treating therapists underwent a training to standardize the evaluation procedure and to ensure inter-rater reliability using standardized patients. For assessment of posture, treating therapists demonstrated high reliability as indicated by 100% percent agreement in their assessment of postural abnormalities.

Scapulohumeral rhythm: Scapulohumeral rhythm is defined as the ratio of glenohumeral movement to scapulothoracic movement during arm elevation.40 Scapulohumeral rhythm was assessed by observation using an ordinal scale of good (symmetric, full motion), fair (symmetric, not full motion) and poor (asymmetric, not full motion). In this study, scapulohumeral rhythm was considered abnormal if it was rated as fair or poor.

Beighton Scale: Greater than normal joint laxity across joints has been associated with a range of connective tissue disorders. Evidence suggests that children with generalized joint hypermobility (GJH) experience greater pain as compared to those without hypermobility. Morris and colleagues reported that adolescents with GJH had higher odds of musculoskeletal pain after participating in sports as compared to children who did not have GJH (Odds ratio = 2.51 (1.48-4.26)).41 Also, GJH has been reported to contribute to chronic pain, fatigue and impaired proprioception in children thereby limiting their activity and participation.42 Beighton test is a measure to evaluate GJH in children.43 The scale assesses items including passive dorsiflexion of 5th metacarpophalangeal joint, passive elbow hyperextension, passive knee hyperextension (all three bilaterally measured by goniometry), bilateral passive opposition of the thumb to the flexor side of forearm and forward flexion of the trunk with knees straight.43,44 It is scored on a 0-9 scale where a score of 5 or greater indicates GJH.35,45

Test results were interpreted as presence (a score of ≥ 5) or absence (a score of < 5) of GJH. The Beighton Scale demonstrates good intra-rater (ICC = 0.96-0.98)
and fair inter-rater (ICC = 0.73) reliability and has been documented as a valid measure to assess GJH in healthy children and adolescents.44,45

**Myofascial tension to palpation:**

**Tension to palpation:** For this study, muscle tension to palpation was defined as a persistent painful contraction that could not be completely relaxed by voluntary effort.46 Data on myofascial tension to palpation (no, mild, moderate, severe) for specific cervical muscle groups and individual muscles (paraspinals, suboccipitals, upper trapezius, levator scapulae, sternocleidomastoid and scalenes) was collected for both right and left sides. Presence or absence of tension to palpation was assessed on a 0-3 Likert scale (0 = No tension, 3 = severe tension). If tension was present, then the data was further categorized as unilateral or bilateral presence of tension to palpation for each muscle group. Palpation of muscle has previously been shown to demonstrate discriminant validity and acceptable reliability (ICC = 0.40 – 0.84) using different Likert scales.47-49 Additionally, the pilot data indicated that treating therapists demonstrated good agreement between their scoring of palpation tests. (Percent agreement = 83.33%).

**Joint mobility:**

**Range of motion (ROM) and pain:** Data on active range of motion for cervical spine for flexion, extension, side bending and rotation (right and left) were recorded using cervical range of motion assessment device (CROM). Data was classified using previously published percentile values.50 Consistent with previous studies that used a median split to define high and low performers, scores less than the median (i.e. < 50th percentile) in each direction were considered abnormal.50,51 The frequency of abnormalities was reported for each direction. Additionally, the total number of abnormal directions was reported for each patient. Neck pain associated with cervical spine movements was recorded as presence or absence of pain (yes/no) with movement. The frequency of pain was reported for each movement, and the total number of painful directions was reported for each patient.

**Segmental mobility testing:** Segmental mobility of the cervical spine was assessed in prone position using posterior to anterior glide.52,53 Each segment was classified as hypomobile, hypermobile, or normal). The data for cervical spine was further classified according for the upper cervical (C0- C2) and the lower cervical spine (C3-C7). Based on these scores, the overall mobility was rated as hypomobile (hypomobile for one or more segments), normal (normal for all segments), or hypermobile (hypermobile for one or more segments).54 Patients that presented with hypermobility in some segments but hypomobility in others were reported as mixed findings. Previous studies have reported variable reliability for segmental mobility tests.55-57 To ensure consistency, reliability among treating therapists was calculated and acceptable reliability for segmental mobility tests (percent agreement = 66-100%) was found.

**Rib mobility:** While the patient lay in supine position, the rib mobility was tested. The therapist was feeling for the anteroposterior movement of the ribs as the patient inhaled and exhaled. The therapist quantified any restriction or asymmetry in rib motion.38

**Muscle strength and endurance:**

**Manual Muscle Test (MMT):** This consisted of manual muscle testing of upper, middle and lower trapezius, rhomboids and cervical flexors (i.e. Longus Colli and Sternocleidomastoid) on a 0-5 point scale (0 = no perceptible muscle contraction & 5 = muscle holds test position against “full pressure”).59,60 The data were classified as normal (5/5) or abnormal strength (<5/5). Muscle strength was considered impaired if deficits were observed on MMT.60

**Neck flexor endurance test (NFET):** NFET is a timed test that is used to evaluate muscle endurance of cervical flexors. In this test, the patient maintained a chin tuck position in supine lying while holding the head 2.5 cm above the supporting surface.61,62 The test was considered normal if the patient was able to maintain the required position for 38 seconds or more.63 The NFET demonstrates moderate to good intra-rater (ICC = 0.67-0.93) and inter-rater (ICC = 0.69-0.96) reliability.61,64

**Cranio-cervical flexor test (CCFT):** The test consisted of five, 2-mm Hg progressive pressure increases from a baseline of 20-mm Hg to a maximum of 30-mm Hg. The patient was required to maintain isometric contraction for more than 10 seconds at each pressure level without substituting with superficial neck muscles.65 The CCFT is a reliable test (ICC = 0.98-0.99).
used to assess progressive activation and endurance of deep cervical flexors.65

**Proprioceptive testing**

Joint position error test (JPET): This test measures the neck reposition sense reflecting afferent input from the neck joint and muscle receptors. The test was performed with patient in a seated position. The examiner established the neutral head position by focusing a laser pointer on the target. The patient received visual feedback for the neutral head position. The patient then performed active head rotation on one side with eyes closed and attempted to return to neutral head position. Final position of the laser point indicated error related to the center of the target.66 The test was performed for right and left rotation. An error of more than 4.5 degrees or 7 centimeters was considered as clinically significant.67 The test was considered normal if the patient could return to the neutral head position with an error < 4.5 degrees or 7 cm in at least 2 out of 3 trials. The JPET demonstrates fair to excellent reliability (ICC = 0.35-0.9) in evaluating cervico-cephalic kinesthesia.68

**Special tests for upper extremity radicular symptoms**

Spurling test: Spurling test was used to evaluate radicular symptoms. The patient performed lateral flexion and extension of the cervical spine. This was followed by application of axial pressure on the spine by the examiner. The test was considered positive if symptoms such as pain or tingling were reproduced.69 Spurling test demonstrates acceptable reliability (Kappa = 0.60 (0.25-0.99))70 and diagnostic accuracy (sensitivity = 52.9%, specificity = 93.8%) to evaluate radicular symptoms.71

**Statistical analysis**

The demographic, injury and process of care data were expressed using descriptive statistics. All calculations were performed using Statistical Package for Social Sciences (SPSS) version 24.0 (SPSS Inc., Armonk, NY). The frequency of patients with a specific impairment as well as the number of impairments exhibited by each patient was presented using descriptive statistics i.e. frequency and percentages. Spinal and rib mobility impairments, muscle strength and muscle guarding impairments were described as frequencies and percentages. Active range of motion were expressed as percentiles compared to normative data.50,51 Joint position error test was reported as normal or abnormal whereas Beighton test was reported according to the presence or absence of GJH. The distribution of myofascial tension, cervical and thoracic segmental mobility, and results on Spurling test were reported as percentages.

**RESULTS**

**Demographics, mechanism of injury and process of care**

Data from 73 patients was collected in this study. The average age of patients was 14.6±2.5 years (44% males). Thirty percent of patients sustained concussion after contacting the playing surface, 21% of the injuries were resulted from contact with another player whereas 18% of patients sustained injury from coming into contact with sporting equipment. Mechanism of injury was not sport-related for 29% of patients. Data on injury mechanism was not available for 3% of patients (Table 1).

Thirty-eight percent of patients had a history of migraine; more specifically, 51% of female patients (21/42) and 22% of male patients (7/32) had a history of migraine, 14% had attention deficit, 12% had a known learning disability, and 10% of patients had attention deficit hyperactivity disorder.

The median time to first physician visit following injury was 16 days and the median time taken for physical therapy evaluation following their first physician visit was six days (Table 1).

**Self-reported symptom, cervical symptom disability, and screening for ligamentous instability:**

The average score on SCAT-III was 34 with scores ranging from 0- to 119) out of a possible score of 132. Patients reported an average of 14 individual symptoms (Range: 0-22) symptoms at initial physician visit. On NDI, 70% of patients reported disability attributed to neck pain (29% mild, 32% moderate, 8% severe and 1% complete) whereas only 15% of patients reported no disability. The NDI was not tested in 15% of the patients. All patients demonstrated intact cervical ligamentous integrity as
Cervical physical therapy assessments

Posture (99%) and myofascial impairment (98%) demonstrated highest impairment frequency. Joint mobility was impaired in 86% of patients and muscle strength were impaired in 62% of patients (Table 2). Cervical joint proprioception was quantified only 29% of participants. Because proprioception was not examined in 71% of patients, it was not included in the aggregated results quantifying the frequency of patients exhibiting impairments across the remaining five categories. Of the remaining five assessment categories, 90% of patients demonstrated impairments in at least three out of five categories whereas 55% demonstrated impairments in at least four out of five categories.

Posture, movement quality, and GJH assessment

Posture abnormality was the most common impairment observed in this study. Forward head posture was observed in 99% of patients, 86% of patients demonstrated increased thoracic kyphosis, and scapular anterior tilt was observed in 74% of patients (Table 3). Forty-eight percent of patients demonstrated abnormal scapulo-humeral rhythm (Table 3). GJH was the least common impairment as only 14% of patients demonstrated hypermobility as indicated by the findings of Beighton test (Table 3).

Myofascial tension to palpation

Data on myofascial assessment revealed that 98% of patients demonstrated increased muscle tension. Upper trapezius (86%) and suboccipitals (83%) demonstrated highest percentage of patients with bilateral muscle tension followed by paraspinals, scalenes, levator scapulae and sternocleidomastoid (70-79%) (Table 4).

Joint/Rib mobility

Cervical spine extension was found to be the most limited (i.e. <50 percentile) movement (77%) followed by side bending (L = 55; R = 59%), flexion (45%) and finally rotation (L = 41; R = 42%). Overall, 90% of patients demonstrated impaired cervical AROM in one or more direction of movement (six directions = 15%, five directions = 12%, four directions = 18%, three directions = 19 %, two directions = 12%, one direction = 14%). Percentile scores for all AROM movements are reported in Table 5.

Twenty-three percent of patients reported neck pain with cervical flexion, closely followed by extension (22%) whereas up to 18% of patients reported pain with side bending or rotation (Table 5). Twelve percent of patients demonstrated pain with movement in one direction, 11% demonstrated pain with

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<table>
<thead>
<tr>
<th>Table 1.</th>
<th>Demographic, injury and care characteristics of participants.</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (% males)</td>
<td>73 (44)</td>
</tr>
<tr>
<td>Age in years, mean (SD)</td>
<td>14.6 (2.5)</td>
</tr>
<tr>
<td>Attention deficit, n (%)</td>
<td>10 (14)</td>
</tr>
<tr>
<td>Attention deficit hyperactivity disorder, n (%)</td>
<td>7 (10)</td>
</tr>
<tr>
<td>Learning disability, n (%)</td>
<td>9 (12)</td>
</tr>
<tr>
<td>History of migraine, n (%)</td>
<td>28 (38)</td>
</tr>
<tr>
<td>Mechanism of injury N (%)</td>
<td>Contact with another player 15 (21)</td>
</tr>
<tr>
<td>Contact with playing surface</td>
<td>22 (30)</td>
</tr>
<tr>
<td>Contact with sporting equipment</td>
<td>13 (18)</td>
</tr>
<tr>
<td>Others (Non-sport related)</td>
<td>21 (29)</td>
</tr>
<tr>
<td>Not specified</td>
<td>2 (3)</td>
</tr>
<tr>
<td>Process of care, Median (Min – Max)</td>
<td>Days to first physician visit following concussion 16 (1-237)</td>
</tr>
<tr>
<td>Days to first PT visit following physician visit</td>
<td>6 (0-380)</td>
</tr>
<tr>
<td>Number of physician visits</td>
<td>4 (1-11)</td>
</tr>
<tr>
<td>Number of physical therapy visits</td>
<td>3 (1-14)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2.</th>
<th>Frequency of patients exhibiting with impairments in the six assessment categories.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impairment</td>
<td>Abnormal</td>
</tr>
<tr>
<td>Posture, movement quality &amp; generalized joint hypermobility</td>
<td>72 (99)</td>
</tr>
<tr>
<td>Joint mobility</td>
<td>63 (86)</td>
</tr>
<tr>
<td>Myofascial tension to palpation</td>
<td>71 (98)</td>
</tr>
<tr>
<td>Muscle strength and endurance</td>
<td>45 (62)</td>
</tr>
<tr>
<td>Proprioception</td>
<td>14 (19)</td>
</tr>
<tr>
<td>Special tests for upper extremity radicular symptoms</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>
movement in two directions whereas 17% demonstrated pain in more than two directions of movement. Fifty-six percent of patients demonstrated no pain with cervical spine movements.

Seventy-one percent of patients demonstrated hypomobility exclusively in upper cervical spine segments (C0- C2), 52% demonstrated hypomobility in more than two spinal segments and 4% demonstrated hypomobility only in lower cervical spine segments (C3-C7). In terms of thoracic mobility, T1-T4 segments were most commonly evaluated and demonstrated hypomobility in 60% of patients. Similarly, first rib was most commonly evaluated

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### Table 3. Impairment frequencies in posture, movement quality & generalized joint hypermobility.

<table>
<thead>
<tr>
<th>Test</th>
<th>N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Posture</td>
<td></td>
</tr>
<tr>
<td>Forward head</td>
<td>29 (40)</td>
</tr>
<tr>
<td>Scapular anterior tilt</td>
<td>34 (47)</td>
</tr>
<tr>
<td>Increased thoracic kyphosis</td>
<td>34 (47)</td>
</tr>
<tr>
<td>Scapulothoracic Rhythm</td>
<td></td>
</tr>
<tr>
<td>Abnormal</td>
<td>35 (48)</td>
</tr>
<tr>
<td>Hypermobile</td>
<td>10 (14)</td>
</tr>
</tbody>
</table>

### Table 4. Myofascial tension to palpation (N = 73).

<table>
<thead>
<tr>
<th>Muscle groups</th>
<th>Bilateral TTP N (%)</th>
<th>Unilateral TTP N (%)</th>
<th>No TTP N (%)</th>
<th>Not tested N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraspinals</td>
<td>57 (79)</td>
<td>4 (5)</td>
<td>8 (11)</td>
<td>4 (5)</td>
</tr>
<tr>
<td>Suboccipitals</td>
<td>60 (83)</td>
<td>3 (4)</td>
<td>6 (8)</td>
<td>4 (5)</td>
</tr>
<tr>
<td>Upper trapezius</td>
<td>63 (86)</td>
<td>2 (3)</td>
<td>5 (7)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>Levator scapulae</td>
<td>52 (72)</td>
<td>3 (4)</td>
<td>12 (16)</td>
<td>6 (8)</td>
</tr>
<tr>
<td>Sternocephaloid</td>
<td>51 (70)</td>
<td>3 (4)</td>
<td>12 (16)</td>
<td>7 (10)</td>
</tr>
<tr>
<td>Scalene</td>
<td>53 (73)</td>
<td>4 (5)</td>
<td>13 (18)</td>
<td>3 (4)</td>
</tr>
</tbody>
</table>

TTP = Tension to palpation

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### Table 5. Percentile distribution for cervical active range of motion and pain with range of motion testing.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>&lt;2.5</th>
<th>2.5</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>95</th>
<th>97.5</th>
<th>Missing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>0 (0)</td>
<td>6 (8)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>8 (11)</td>
<td>6 (8)</td>
<td>13 (18)</td>
<td>1 (1)</td>
<td>4 (6)</td>
<td>12 (16)</td>
<td>4 (6)</td>
<td>3 (4)</td>
<td>5 (7)</td>
<td>6 (8)</td>
<td>5 (7)</td>
</tr>
<tr>
<td>Extension</td>
<td>14 (19)</td>
<td>11 (15)</td>
<td>3 (4)</td>
<td>15 (21)</td>
<td>1 (1)</td>
<td>3 (4)</td>
<td>9 (12)</td>
<td>2 (3)</td>
<td>0 (0)</td>
<td>7 (10)</td>
<td>2 (3)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>1 (1)</td>
<td>5 (7)</td>
</tr>
<tr>
<td>Left SB</td>
<td>10 (14)</td>
<td>3 (4)</td>
<td>5 (7)</td>
<td>16 (22)</td>
<td>3 (4)</td>
<td>0 (0)</td>
<td>3 (4)</td>
<td>1 (1)</td>
<td>2 (3)</td>
<td>12 (16)</td>
<td>6 (8)</td>
<td>1 (1)</td>
<td>4 (6)</td>
<td>2 (3)</td>
<td>5 (7)</td>
</tr>
<tr>
<td>Right SB</td>
<td>12 (16)</td>
<td>6 (8)</td>
<td>4 (6)</td>
<td>2 (3)</td>
<td>17 (23)</td>
<td>2 (3)</td>
<td>0 (0)</td>
<td>2 (3)</td>
<td>1 (1)</td>
<td>12 (16)</td>
<td>5 (7)</td>
<td>1 (1)</td>
<td>3 (4)</td>
<td>1 (1)</td>
<td>5 (7)</td>
</tr>
<tr>
<td>Left Rot.</td>
<td>7 (10)</td>
<td>1 (1)</td>
<td>15 (21)</td>
<td>1 (1)</td>
<td>0 (0)</td>
<td>6 (8)</td>
<td>0 (0)</td>
<td>17 (23)</td>
<td>3 (4)</td>
<td>3 (4)</td>
<td>4 (6)</td>
<td>7 (10)</td>
<td>3 (4)</td>
<td>0 (0)</td>
<td>6 (8)</td>
</tr>
<tr>
<td>Right Rot.</td>
<td>8 (11)</td>
<td>2 (3)</td>
<td>2 (3)</td>
<td>13 (18)</td>
<td>1 (1)</td>
<td>5 (7)</td>
<td>0 (0)</td>
<td>2 (3)</td>
<td>18 (24)</td>
<td>3 (4)</td>
<td>2 (3)</td>
<td>8 (11)</td>
<td>0 (0)</td>
<td>3 (4)</td>
<td>6 (8)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pain with movement</th>
<th>Yes</th>
<th>No</th>
<th>Not tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>17 (23)</td>
<td>53 (73)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>Extension</td>
<td>16 (22)</td>
<td>54 (74)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>Rotation (Right)</td>
<td>12 (16)</td>
<td>58 (80)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>Rotation (Left)</td>
<td>10 (14)</td>
<td>60 (82)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>Side bending (Right)</td>
<td>13 (18)</td>
<td>57 (78)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>Side bending (Left)</td>
<td>11 (15)</td>
<td>59 (81)</td>
<td>3 (4)</td>
</tr>
</tbody>
</table>

SB = Side bending, Rot. = Rotation
and 41% of patients demonstrated hypomobility (Table 6).

**Muscle strength and endurance:**  
Manual muscle testing data revealed that rhomboids were the most common muscles to demonstrate weakness i.e. muscle strength < grade 5 (35%) followed closely by middle (30%) and lower trapezius (31%) whereas upper trapezius was found to be the muscle group that demonstrated weakness in least number of patients (3%) (Table 7). The neck flexor endurance was abnormal in 40% of patients indicating poor endurance (Table 7). Since CCFT was the least common of the strength measures used (performed in only 4% of patients), the data was not considered adequate to draw meaningful inferences and hence not reported.

**Upper extremity radicular symptoms:**  
None of the patients demonstrated upper extremity radicular symptoms on Spurling test.

**DISCUSSION**  
High prevalence of cervical spine impairments was observed in this study of young patients post-concussion, with over 90% of patients demonstrating impairments in three or more categories. Most commonly observed impairments were noted in muscle tension, joint mobility, and muscle strength. The categories of impairments examined in this cohort are consistent with the impairments reported in the most recent clinical practice guidelines for neck pain.30

Cervical spine injuries may independently contribute to many concussion symptoms including headaches, dizziness, neck pain, disturbance of concentration or memory, irritability, sleep disturbance, and fatigue.13 The findings of this study revealed that over 70% of the patients had upper cervical spine mobility impairments. Similar findings were noted

### Table 6. Segmental spine and rib mobility results.

<table>
<thead>
<tr>
<th></th>
<th>All cervical segments</th>
<th>Upper cervical spine only (C0-C1 &amp; C1-C2)</th>
<th>Lower cervical spine only (C3-C7)</th>
<th>More than two spinal segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypomobility</td>
<td>19 (26)</td>
<td>52 (71)</td>
<td>3 (4)</td>
<td>38 (52)</td>
</tr>
<tr>
<td>Hypermobility</td>
<td>1 (1)</td>
<td>2 (3)</td>
<td>3 (4)</td>
<td>3 (4)</td>
</tr>
<tr>
<td>Normal</td>
<td>8 (11)</td>
<td>14 (19)</td>
<td>34 (47)</td>
<td>NA</td>
</tr>
<tr>
<td>Not tested</td>
<td>2 (3)</td>
<td>5 (7)</td>
<td>4 (5)</td>
<td>4 (5)</td>
</tr>
<tr>
<td>Mixed findings</td>
<td>43 (59)</td>
<td>NA</td>
<td>29 (40)</td>
<td>28 (39)</td>
</tr>
</tbody>
</table>

NA = Not applicable

### Table 7. Muscle strength and endurance results.

<table>
<thead>
<tr>
<th></th>
<th>N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength</td>
</tr>
<tr>
<td>Muscle group</td>
<td>Abnormal</td>
</tr>
<tr>
<td>Upper trapezius</td>
<td>2 (3)</td>
</tr>
<tr>
<td>Middle trapezius</td>
<td>22 (30)</td>
</tr>
<tr>
<td>Lower trapezius</td>
<td>23 (31)</td>
</tr>
<tr>
<td>Rhomboids</td>
<td>26 (35)</td>
</tr>
<tr>
<td>Longissimus coli</td>
<td>8 (11)</td>
</tr>
<tr>
<td>Sternocleidomastoid</td>
<td>9 (12)</td>
</tr>
</tbody>
</table>

**Endurance**

| Neck flexor endurance test | 29 (40) | 12 (16) | 32 (44) | NA      |

NA = Not applicable
in a recent preliminary report that observed range of motion and segmental mobility impairments primarily affecting the upper cervical spine. Upper cervical spine (C1- C3) has previously been reported to contribute to most of the cervicogenic symptoms observed following trauma including cervicogenic headaches, dizziness and unsteadiness. Factors including cervical zygapophyseal joint mobility impairments and abnormal somatosensory inputs from upper cervical and trigeminal sensory afferents may explain headaches and dizziness following cervical spine injury. High occurrence of headaches (84%) and dizziness (57%) among the patients in this study warrants detailed examination of upper cervical spine mobility in this population.

High pain intensity and high NDI scores have been identified as risk factors for having persistent symptoms if present after acute whiplash. Pain associated with cervical spine movement could be attributed to altered axio-skeletal muscle activity and dysfunction in scapular mobility as reported by Helgadottir and colleagues in young adults with whiplash injury. Moderate to high level evidence exists for evaluation of neck pain intensity and collecting NDI scores to establish prognosis following whiplash. In this study, 40% of patients demonstrated moderate to severe disability on NDI thereby indicating the lasting perception of disability following concussion. However, it is important to note that NDI has not been validated in individuals younger than 18 years of age and may not capture the true extent of cervical disability perceived by adolescents.

Daenen and colleagues reported that alterations in muscle activity continue to exist over time following whiplash trauma, indicating the need of strength and endurance evaluation for treatment and prevention of re-injury. In this sample, muscle strength and endurance deficits were observed among 40% of the patients. Although the clinical practice guidelines on neck pain recommended the use of cranial-cervical flexion and neck flexor muscle endurance test in patients with all types of neck pain and movement-coordination impairments, these tests were not frequently performed by the treating therapists. CCFT and NFET were not commonly tested due to the acute nature of the injury, increased pain level and increased muscle guarding upon testing.

Of the patients that were tested for JPET (n = 21) in this study, 14 were found to have impaired position sense. The control of head position has been reported to be affected when neck proprioceptive information is inaccurate, which has been observed in patients with chronic non-traumatic neck pain as well as with whiplash-type injuries. Impairments in position sense may contribute to dizziness, disequilibrium and impaired postural control. The high percentage (66%) of abnormal joint position sense in those participants that were tested may warrant consideration for including this test in evaluation of this population. However, completion of JPET in the first visit may have not been feasible, especially in patients with other various documented impairments.

Additionally, active range of motion at the cervical spine has been associated with both proprioception and oculomotor performance in adults with whiplash-type injuries, thereby indicating a role of zygapophyseal joints in proprioceptive dysfunction. Increased muscle tension of the cervical spine musculature, may also result in impaired proprioceptive signals. This close association of cervical proprioceptive inputs to the contribution of head position and equilibrium reinforces the need for detection of cervical joint position error to determine the source of balance problems and initiate appropriate intervention strategies (cervical or vestibular).

Previous literature has indicated that children and adolescents have lesser cervical spine mobility as compared to young adults. Similar findings were observed in this study with over 70% of participants demonstrating hypomobility. However, the lack of a perfect relationship between range of motion deficit and the results of segmental mobility testing can be explained by various reasons. First, many patients presented with hypomobility in some segments and hypermobility in others, which may have not affected the overall ROM measurement results. Cervical spine segments adjacent to hypomobile segments may become hypermobile, creating an unimpaired active range of motion. Second, range of motion can be influenced by factors other than segmental mobility. These factors can include pain, altered posture, and limited cervical muscle extensibility and motor control deficits.
It was also noteworthy that none of the patients tested positive for alar or transverse ligament instability and/or radicular symptoms during physical therapy evaluation in this study. Tests for ligamentous integrity have been reported to have sufficient specificity but demonstrate high variability in sensitivity, and therefore need to be interpreted with caution.\(^{38}\)

Several limitations were associated with this study. Many of the tests employed in this study are subjective and may not demonstrate ideal reliability. Although the therapists underwent training to standardize administration of tests for quality assurance and to improve inter-rater reliability, it is possible that the inherently subjective nature of these tests influenced the findings of this study. Variations in the choice of tests and in grading and interpretation of the tests administered at initial evaluation could have influenced the prevalence of impairments found in this study. Additionally, pain associated with segmental mobility could not be documented in this study due to inconsistencies with documentation. Since reproduction of symptoms is important for localizing impaired segments,\(^{56,57}\) future studies should focus on pain assessment with segmental mobility.

The cervical physical therapy examination was impairment-guided and was often dictated by injury acuity and patient's tolerance to testing. Since patients varied in injury acuity, tolerance to assessment, and in exhibited impairments, not all tests were conducted on all patients. This may have biased the reported prevalence of the impairments by over-representing impairments on tests that were administered more often and under-representing the prevalence of impairments identified in tests that were done less often. Additionally, assessment of radiculopathy using only the Spurling test instead of utilizing the Wainner's test item cluster\(^7,12\) may have led to underrepresentation of the prevalence of radiculopathy in the sample. This study reported the percentage of patients in which a particular test was not administered. Therefore, clinicians are encouraged to take that in consideration when interpreting the prevalence of cervical impairments in patients with concussion.

Impairments identified in this study are subjected to sample bias and may not represent the prevalence of cervical impairments in the wide spectrum of concussion patients. Nonetheless, given the clear link between common concussion symptoms and cervical impairments,\(^7,12\) findings of this study can provide a foundation for clinicians aiming to identify cervical impairments in patients with concussion.

**CONCLUSIONS**

High prevalence of cervical spine impairments was observed in the subjects included in this study with muscle tension, joint mobility, and muscle strength being most commonly affected post-concussion. The findings of this study provide preliminary data to support the framework for a cervical spine evaluation tool in children and adolescents following concussion.

**REFERENCES**


57. Aartun E, Degerfalk A, Kentsdotter L, Hestbaek L. Screening of the spine in adolescents: inter- and


ABSTRACT

Introduction: Impairments in postural stability have been identified following sports-related concussion. CaneSense™ is a recently developed mobile lower limb motion capture system and mobile application for movement assessment which provides an objective measure of postural stability. One of the components within CaneSense™ is the Post-Concussive Excursion Index (PCEI), a measure of postural stability expressed as a percentage of symmetry between lower limbs.

Purpose: The purpose of this case series is to examine pre- and post-concussion differences using two separate measures, CaneSense™, and a known test, the Balance Error Scoring System (BESS), in Division I collegiate football players.

Methods: A convenience sample of eight football players diagnosed with a concussion, were the subjects in this case series. All subjects underwent baseline testing prior to the start of pre-season camp consisting of the single limb stance (SLS) test with CaneSense™ and the BESS test. Twenty-four to 72 hours following their concussion, SLS with CaneSense™ test and the BESS test, were administered. Segmental excursions for the thigh and shank segments for each lower limb were combined into the Post-Concussion Excursion Profile (PCEP), which represents each segment’s maximum excursion in the medial-lateral and anterior-posterior direction. The PCEI is a single metric generated to quantify differences within subjects by comparing the PCEP value between lower limbs during SLS where 100% suggests absolute symmetry.

Results: The PCEI value decreased significantly post-concussion (41.43 ± 15.53% vs. 87.41 ± 6.05%, p < 0.001) demonstrating a 52.6% decrease in inter-limb symmetry when compared to baseline values. There was an unanticipated 36.36% improvement in composite BESS performance post-concussion (10.5 ± 4.87 errors vs. 16.5 ± 8.49 errors, p = 0.10).

Conclusions: Differences in inter-limb postural stability were found in subjects post-concussion. By assessing postural stability in both lower limbs individually, using the PCEI, impairments were detected that otherwise would have likely gone undiagnosed using the BESS test alone.

Levels of Evidence: Therapy, Level 4

Key Words: Balance Error Scoring System, CaneSense™, Concussion, Performance-based measure, Postural Stability
INTRODUCTION
Management of sport-related concussions have become a serious concern in recent years because of the substantial increase in awareness of, education regarding, and reported incidence of concussion.1,2 Concussions are often considered a transient injury and monitoring recovery by using appropriate clinical assessments, prescribing treatment, and determining clearance for return to sport is challenging, as overt impairments may resolve in a relatively short timeframe (7-10 days).3-5 Short-term sequelae of concussions include functional disturbances and axonal injuries rather than grossly detectable structural brain damage and may present with a wide range of clinical signs and symptoms.2,9,11-15

Despite the transient nature of concussion, cortical and postural impairments can be present for a significant period of time before returning to baseline.2 In part, neuropathological evaluations have shown that concussion-induced axonopathy may persist for years.2 Moreover, researchers have identified intracortical facilitation, motor-evoked potential (MEP) amplitude, and maximal voluntary muscle contractions to be negatively affected in the post-concussed population.16-20 Increased MEP latencies and the associated decreased amplitude post-concussion suggest that the brain may be unable to effectively coordinate movement, which may be associated with impaired postural stability, increased reaction times, and the risk of acute lower extremity musculoskeletal (MSK) injury.20

Impairments in postural control, postural stability, and neural activation patterns have been identified from months to years' post-concussion despite apparent clinical recovery.21-28 Concussions produce greater changes in balance and postural stability than has been previously believed.14,20,28-44 Postural control under static conditions is typically referred to as “postural steadiness,” whereas the dynamic postural response to applied or volitional perturbations is called “postural stability.”45 Postural stability is defined as the ability to maintain the position of the body, and specifically, the center of mass, within specific boundaries of space, referred to as stability limits.46 Postural stability has been described as an essential component in assessing the efficacy of balance interventions.47-49

The assessment of postural stability can provide an indirect means of identifying concussion-related neurophysiological abnormality.27,50 The central nervous system (CNS) combines information from three pathways (i.e., visual, vestibular, and somatosensory systems) to maintain postural stability.51 The resultant efferent motor output that maintains postural stability travels down the descending tracts of the spinal cord and can either progress ipsilateral or contralateral (decussation) from the site of origin.52 Therefore, clinical presentation may produce bilateral, unilateral, or contralateral impairments to the potential site(s) of the injury(s).

Disrupted cortical pathways alter neural activation patterns resulting in impairments to postural stability, potentially explaining the increased risk of acute lower limb MSK injury post-concussion.16-20,27,33,41-42,53-59 The disruption in neural activation patterns can present as the inability to integrate and/or process sensory information quickly (slower reaction times) and/or efficiently between the visual, vestibular, and somatosensory systems.33,41,42,55-59 Disintegration of the cortical pathways to the MSK system, have the potential to impair movement when performing high-level mobility skills.20,27,53,54

The assessment of impaired postural stability has been performed during static and dynamic movement tasks.36,39 Postural stability tests include a combination of single-limb stance (SLS) or double-limb stance, alterations in base of support, stressing of sensory system(s), use of different equipment and surfaces, and inclusion of dual-task conditions, such as level walking while undergoing a cognitive distractor task.29,34,35,38-40 Optimal timeframes for initial and repeated postural stability assessments is also unclear, as impairments post-concussion can linger beyond return to play.37

Two common clinical tests for assessing postural stability post-concussion are the Balance Error Scoring System (BESS) and a dynamic posturography test known as the Sensory Organization Test (SOT).5,55-58 The BESS consists of three different stance positions on non-compliant and compliant surfaces: double-limb stance with narrow base of support, non-dominant limb SLS, and tandem stance with non-dominant foot as the posterior limb.27,28,57,59
Recent literature suggests the use of the modified BESS (mBESS) for post-concussion testing. The SOT objectively identifies postural control by assessing integration and weighting of visual, vestibular, and proprioceptive information during a specific task. Yet, Cavanaugh et al. has suggested that SOT equilibrium scores may not be capable of detecting subtle changes in postural control. Not all clinics are able to administer the SOT because of the time to administer testing, clinical space restraints, advanced training requirements, and potentially cost-prohibitive equipment (NeuroCom® Balance Master Equitest® or NeuroCom® Smart Equitest® [NeuroCom International, Inc., Clackamas, OR]).

The emergence of mobile health (mHealth) and the use of wearable sensor technology have increased in popularity across healthcare disciplines because of the potential to reduce the limitations traditionally associated with performance testing and sports medicine. The use of inertial measurement unit (IMU) sensors provides clinicians with the ability to use instrumented, objective measures that are reproducible in a variety of sports-related environments or in combination with performance-based assessment measures. This case series used CaneSense™ (University of Miami, Department of Physical Therapy, Coral Gables, FL, USA), a mobile wireless sensor system and application for assessing human movement consisting of four IMUs secured in two elastic knee sleeves which communicates via Bluetooth low energy (BLE) to a mobile tablet. The IMU sensors were custom made at the University of Miami Functional Outcomes Research Evaluation Center and validated for estimating human kinematics against the gold-standard optical motion capture systems.

Demographic information including injury history and lower-limb kinematics during testing were obtained and analyzed via an iPad Air 2® (Apple®, Cupertino, USA) for all enrolled subjects using the CaneSense™ mobile app. The mobile app provides cues for the verbal instructions, and an instructive drawing to guide the progression of the testing. CaneSense™ IMU sensors are quick to don (< 30 sec) and testing is also quick (< 2 min). A component of CaneSense™ is the Post-Concussive Excursion Index (PCEI), a measure of postural stability expressed as a percentage of symmetry between lower limbs. A decrease in PCEI post-concussion is indicative of altered postural stability and greater asymmetry.

The purpose of this case series is to examine pre- and post-concussion differences using two separate measures, CaneSense™, and a known test, the Balance Error Scoring System (BESS), in Division I collegiate football players.

CASE DESCRIPTIONS
A convenience sample of eight Division I collegiate football players diagnosed with an in-season concussion was included in this case series. Prior to the start of fall football practice, the whole team completed the informed consent process and were baseline tested. At the time of pre-season testing, subjects were informed that their baseline data and any subsequent post-injury testing results for their cases could be potentially submitted for publication. The subjects' confidentiality was protected according to the U.S. Health Insurance Portability and Accountability Act (HIPPA) and IRB approval for this case series was granted. The inclusion criteria for subjects was an in-season concussion diagnoses. Subjects were excluded from the case series if they were unable to follow commands post-concussion.

Baseline Testing
The subjects performed baseline testing solely with the tester in a quiet, well-lit indoor gymnasium. Baseline testing of postural stability consisted of the SLS test with CaneSense™ and the BESS test, respectively. Prior to pre-season testing, all the subjects reported to be right foot dominant as per the BESS testing script, therefore SLS testing during the BESS was performed with the left lower limb. During tandem standing, the left lower limb was positioned posteriorly.

History
The eight subjects who were enrolled in this case series sustained a concussion during either a practice or game. Once diagnosed with a concussion, none of the subjects were allowed to return to play as a safety precaution and were immediately placed in the University's concussion protocol which includes neurocognitive testing, neurological status assessment, and symptom severity measurement.
The on-site clinician(s) noted that none of the subjects demonstrated signs indicative of gross motor impairment (e.g., step, stumble, fall, loss of coordination), nor alterations in mental status (e.g., dazed, stunned, confused) at the time of injury or during testing. Additionally, none of the subjects were taken to the hospital nor underwent any diagnostic imaging following the concussion. Table 1 provides a description of mechanism of injury and post-concussion clinical presentation for each subject.

### POST-CONCUSSIVE ASSESSMENT

Twenty-four to 72 hours following the diagnosis of concussion by the team physician, the subjects performed the CaneSense™ and BESS test in the same testing environment used during baseline testing. All subjects were symptomatic at the time of testing, however, were able to complete all static postural stability testing and were able to stand on each lower limb for 30 seconds. Dynamic postural stability tests in the early phase of recovery post-concussion were not included, as the authors recognize that the neurophysiologic demand for more complex movements should be assessed once the static elements of balance meet the threshold of time described above.

### Single Limb Stance

The SLS test is often used as a measure of static postural stability and a threshold test for determining readiness to begin high-level exercise programs, such as plyometrics. The ability to maintain SLS can be used to detect differences between lower limbs and assist clinicians to determine if impairment is present. Standing with arms crossed over their chest, subjects were asked to raise one foot over a 15cm cone placed on the floor directly in front of that foot. The stopwatch started when the foot was lifted off the floor and stopped when the foot returned to the floor, the foot fell below the cone, they hopped, arms became uncrossed, or 30 second(s) was achieved. A maximum of two trials were permitted for each lower limb to successfully achieved 30s. Subjects were given a 30s rest period between each trial. Testers used the App to record all IMU data for the PCEI and SLS times to the nearest 0.02s.

### Post-Concussive Excursion Index (PCEI)

To quantitatively assess postural stability, the CaneSense™ system generates a metric called Region of Limb Stability (ROLS). Lower limb stability is defined by both thigh and shank movements of the supporting limb during SLS. Specifically, ROLS quantifies the area of excursion of the thigh and shank using acceleration data from the two IMUs imbedded in the elastic sleeve worn over the knee joint.

The segmental excursions for the thigh and shank segments for each lower limb can be seen in Table 1.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanism of Injury</td>
<td>Tackled</td>
<td>Collision</td>
<td>Collision</td>
<td>Tackled</td>
<td>Collision</td>
<td>Collision</td>
<td>Collision</td>
<td>Tackled</td>
</tr>
<tr>
<td>Collision Location</td>
<td>Helmet</td>
<td>Helmet</td>
<td>Body</td>
<td>Helmet</td>
<td>Body</td>
<td>Helmet</td>
<td>Helmet</td>
<td>Helmet</td>
</tr>
<tr>
<td>Impact of Location of Collision</td>
<td>Left</td>
<td>Right</td>
<td>Right</td>
<td>Left</td>
<td>Front</td>
<td>Right</td>
<td>Left</td>
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</tr>
<tr>
<td>Delayed Onset of Symptoms</td>
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<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>Alteration in Mental Status</td>
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<td>Yes</td>
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<td>Yes</td>
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<tr>
<td>Retrograde Amnesia</td>
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<td>No</td>
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<td>No</td>
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<tr>
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</tbody>
</table>
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Concurrent validity has been established for the CaneSense™ ROLS values in assessing for area of excursion of the lower limbs. Kim et al. compared excursion using the CaneSense™ to a three-dimensional optical motion analysis system (Vicon Motion Systems Ltd., UK) in a group of healthy adults. There were high correlations (0.82-0.93) and no significant difference (p > 0.05) in the tested parameters between the optical- and IMU-based systems.64

**Balance Error Scoring System**

The three BESS stances were performed consecutively on a non-compliant firm surface and on a compliant medium-density foam square (Airex®, Sins, Switzerland; 50 cm × 41 cm × 6 cm thick). The subjects were asked to close their eyes while holding these stance positions. The tester counted the number of errors the individual demonstrated during each 20s trial. Each error was considered a measure of postural instability. An error was defined as opening eyes, lifting hands off hips, stepping, stumbling or falling out of position, lifting forefoot or heel, abducting the hip by more than 30°, or failing to return to the test position > 5s. Scores were determined by calculating the number of errors committed during each of the 20s trials, with an absolute 5s maintenance of balance required for testing. Each error counted as one point and the total score was the sum of all the errors, with the best performance being a score of 0 errors. Ten errors is the maximum number allowed per trial. BESS composite scores were calculated and used for analysis.

**Statistical Analysis**

Statistical analysis was performed using IBM® SPSS version 22. Descriptive statistics were used to characterize pre-post-concussion CaneSense™ and BESS composite scores. Paired samples t-test was used to examine the pre-post-concussion differences in PCEI and BESS composite scores. Significance was set at p ≤ 0.05. Effect sizes were calculated for change in PCEP, PCEI, Left SLS No Foam BESS (NFBE), Left SLS Foam BESS (FBE), and Composite BESS Errors (CBE) post-concussion.

**OUTCOMES**

The mean, standard deviation (SD) and range for pre-season baseline and post-concussion PCEP, PCEI, and BESS values are described in (Table 2) for the eight subjects. Pre-season baseline dominant and non-dominant PCEP (5.13 ± 1.71 cm² and 5.92 ± 1.64 cm²)
and PCEI values (87.41 ± 6.05%) are consistent with pre-season baseline values on healthy non-injured athletes PCEP (6.70 ± 3.47 cm² and 6.03 ± 3.30 cm²) and PCEI (89.7 ± 6.03%). Pre-season BESS composite scores are consistent with published ranges for subjects collected at pre-season. Post-concussion changes in PCEP values for the dominant (13.05 ± 13.87 cm², 154.39% increase) and non-dominant (9.73 ± 8.21 cm², 64.36% increase) limbs were found. However, changes in PCEP for the dominant (p = 0.14) and non-dominant limb (p = 0.23) were not statistically significantly different. The PCEI value decreased significantly post-concussion (41.43 ± 15.53% vs. 87.41 ± 6.05%, p < 0.001) demonstrating a 52.6% decrease when compared to pre-season baseline values. The effect sizes for concussion on PCEP for the dominant and non-dominant limb (4.63 and 2.32) and PCEI (-7.07) were all considered very large. The effect sizes of concussion on left SLS NFBE (-0.58), left SLS FBE (-0.72), and CBE (-0.71) were moderate. Interestingly, BESS left SLS performance not on foam (p = 0.11), on foam (p = 0.17), and BESS composite scores (p = 0.10) had generally lower error scores post-concussion, however, they did not reach statistically significant differences.

Table 3 presents the changes in PCEP, PCEI, and BESS values for each subject. Interestingly, a trend was found that the PCEP values for one lower limb remained the same while the other limb was worse than baseline values. Specifically, change in dominant limb PCEP values ranged from 5% – 794% and change in non-dominant limb PCEP values ranged from 12% – 306%, respectively. The PCEI post-concussion were all under 75%, with a range from 14.48% – 74.37%, indicating there to be a significant imbalance. Figure 2 graphically depicts ROLS segmental excursion and PCEP as an example (from Subject 1) of the left lower limb or non-dominant ROLS and PCEP values. The pre- and post-concussion values were different with an increase of 35 cm and a change of 452%.

DISCUSSION

Assessment of postural stability post-concussion appears to be a valuable tool for screening and has the potential to guide clinical decision making. The results of this case series suggest that testing SLS with both lower limbs using the CaneSense™ to assess changes in postural stability in subjects after...
sustaining a concussion may be an effective measure to quantify the extent of injury. Although the p-values demonstrated no difference between baseline and post-concussion PCEP values, the effect size of concussion on postural stability values as measured by the CaneSense™ of the dominant and non-dominant limb were very large. In addition, when examining the symmetry of postural stability between both limbs (PCEI), the effect size was even greater, suggesting that lower limb excursion was an effective method of assessing change in postural stability post-concussion.

The ability to perform complex movements depends upon the activation of networks of neurons in the motor cortex and brainstem. Motor areas of the cerebral cortex direct purposeful, voluntary movement, while neurons located in brainstem nuclei direct automatic movements such as postural control that are both ipsilateral and contralateral. Consequently, injuries to the motor cortex and brainstem can present with disruptions in movement and alterations of balance strategies. When considering the neuroanatomy of the CNS and the potential variations in motor and sensory impairments that may

---

Table 3. Pre-season baseline and Post-Concussion Excursion Index values and Balance Error Scoring System errors.

<table>
<thead>
<tr>
<th>Sub</th>
<th>1</th>
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<td>Pre</td>
<td>Post</td>
<td>%</td>
<td>Pre</td>
<td>Post</td>
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<td>8.14</td>
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<td>PCEI (%)</td>
<td>94.26</td>
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<td>28.43</td>
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<td>Right SSFBE (a)</td>
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**BOLD** = percentage values that are negative; **Sub** = Subjects; **GM** = Outcome Measures; **DL** = Dominant limb, **NDL** = Non-dominant limb, **NFBE** = No foam BESS errors, **FBE** = Foam BESS errors, **CBE** = Cumulative BESS errors, **%** = Percent change between pre-season baseline and post-concussion outcome results.

* DS: Dominant side, NDS: Non-dominant side, NFBE: No foam BESS errors, FBE: Foam BESS errors, CBE: Cumulative BESS errors.

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Figure 2. A graphical depiction of an example (Subject 1) Region of Limb Stability (ROLS) segmental excursion and Post-Concussion Excursion Profile (PCEP) for the left lower limb (non-dominant) displayed as ROLS and PCEP values. The pre- and post-concussion values are similar, with an increase in excursion of 4 cm and a change of 60%.
present clinically, testing of both lower limbs should be strongly considered. Therefore, using ROLS and PCEP to assess postural stability for each lower limb may be beneficial.

Improvements were noted in post-concussion BESS test performance in this case series. Five of the eight subjects demonstrated better BESS scores post-concussion, with a mean improvement of 11.8 points which could be attributed to problems with the assessment. The remaining three subjects had higher BESS composite scores, with a mean improvement of 3.67 points. The BESS test has several limitations which include low inter and intrarater reliability, heavy reliability on rater interpretation of errors, practice and learning effect, and setting differences during testing (training room vs. sideline during a competition). The BESS has also been reported to have a low sensitivity statistic (0.34) and an inability to detect balance dysfunction seven days after initial concussion.

Researchers have identified a potential risk of MSK injury post-concussion that extends beyond the acute stage of injury. Two factors that may contribute to the increased risk include undetected impairments and decreased postural stability. Through the use of ROLS PCEI results, clinicians could prescribe a more targeted rehabilitation program based on the identification of specific deficits. Postural stability requires numerous resources for balance and postural control including: biomechanical constraints, sensory strategies, dynamic controls, orientation to space, movement strategies, and cognitive processing. Each of these resources has several components that can be addressed with rehabilitation but must be properly identified before the appropriate treatment may be prescribed. Moreover, impairments to balance and postural control, especially in previously concussed athletes, may contribute to the risk of subsequent lower limb MSK injury.

ROLS, PCEP, and PCEI values can help to provide insight into impairment of postural stability. The clinical benefits of ROLS, PCEP, and PCEI versus BESS includes: 1) assessment of symmetry in SLS for both limbs, 2) objective numeric comparison of limb excursion with respect to area and direction, 3) identification of impairments in postural stability in multiple planes, 4) objective measure of change over time, 5) potential for targeted treatment prescription, and 6) immediate, objective performance feedback.

The present study involved several limitations that should be considered in future works. First, the population was small, only eight subjects, which may prohibit extrapolating these findings to the general population. Next, considerations on expanding the use of PCEP bilateral assessments of postural stability with a greater number of athletes, across ages...
and genders, type of sport playing when injured, and accounting for past medical history. Likewise, the ability to use repeated measures to longitudinally track change over time may prove useful in establishing post-concussive return to play criteria. Continued use of the PCEP and PCEI will assist sports medicine clinicians to accurately determine sensorimotor and postural control deficits that may have otherwise gone unrecognized.

**CONCLUSIONS**

The results of this case series indicate that significant differences in lower limb postural stability were found post-concussion as measured by the CaneSense™. The PCEP and PCEI afford reproducible data that can determine differences between lower limbs and document changes over time in postural stability. Of note, the BESS test was unable to identify dominant limb postural stability deficits with these subjects. The use of mobile, wireless technologies provides a practical form of objective testing for concussion injuries. The use of CaneSense™ with the PCEP and PCEI metrics provides sports medicine clinicians with an objective measure of postural stability for both lower limbs that can be administered in a variety of environments. Future work will be required to determine the utility of the PCEP and PCEI with respect to assessment of athletes who sustain a concussion and return to sport criteria.

**REFERENCES**


ABSTRACT

Background and Purpose: Distal biceps rupture is less common than injury to the proximal biceps; however, injury distally has profound functional implications on activities which rely on power during elbow flexion and forearm supination. The majority of distal biceps ruptures can be treated with surgical repair of the distal biceps utilizing either a single or two-incision technique; both of which achieve comparable improved outcomes and reported minimal pain and disability at two years. Safe and effective rehabilitation following distal biceps repair is accomplished through a phased progression, with avoidance of premature stress to the healing soft tissue repair.

The purpose of this clinical commentary is to provide a concise review of distal biceps tendon injury, including relevant anatomy, etiology, diagnosis, and operative intervention as well as post-operative factors influencing the pursuit of a criterion based, progressive rehabilitation program after distal biceps tendon repair. This commentary seeks to provide an update on current treatment strategies used in distal biceps rehabilitation with accompanying scientific rationale.

Level of Evidence: 5

Key words: Distal biceps tendon rupture, distal biceps tendon surgical repair, rehabilitation
INTRODUCTION
Distal biceps tendon ruptures are rare injuries that may have significant functional sequelae. Debate continues regarding optimal treatment as historical reports comparing operative and conservative treatment outcomes suggest acceptable function following non-operative treatment. As knowledge of native anatomy and fixation methods have progressed, results following operative fixation have improved when compared to non-operative fixation, particularly in the high-demand patient population. Currently, operative fixation is recommended in the majority of cases, and operative management of distal biceps pathology mandates a working knowledge of native anatomy and biomechanical factors for appropriate repair and rehabilitation. The purpose of this clinical commentary is to provide a concise review of distal biceps tendon injury, including relevant anatomy, etiology, diagnosis, and operative intervention as well as post-operative factors influencing the pursuit of a criterion based, progressive rehabilitation program after distal biceps tendon repair. This commentary seeks to provide an update on current treatment strategies used in distal biceps rehabilitation with accompanying scientific rationale.

EPIDEMIOLOGY
Distal biceps tendon ruptures are reported as occurring on the dominant arm of male patients between the third and sixth decades of life. Safran et al projected an incidence of 1.2 distal biceps tendon ruptures per 100,000 patients per year. They found that the injury occurs in the dominant extremity 86% of the time and smokers have a 7.5 fold greater risk of injury than nonsmokers. Anabolic steroid use and local corticosteroid injection have also been proposed as risk factors for distal tendon rupture.

ANATOMY
The biceps brachii muscle and tendon is comprised of two heads. The long head of the biceps tendon originates from the supraglenoid tubercle on the scapula. The long head of the biceps receives its proximal blood supply from the ascending branches of the anterior humeral circumflex artery and from the brachial and deep brachial arteries distally. The short head originates from the coracoid process of the scapula. The two heads merge into a single unit at the level of the deltoid tuberosity and insert distally onto the bicpital tuberosity on the proximal radius with the long head contribution extending over the distal aspect of the tuberosity. The proximal tendon is stabilized by soft tissue constraints collectively known as the biceps pulley, a complex comprised of a portion of the rotator cuff (supraspinatus and subscapularis tendons), coracohumeral ligament, and pectoralis major insertion. Distally, the lacertus fibrosus originates from the distal tendon and expands ulnarly in three distinct layers superficially, forming a distal biceps aponeurosis with the fascia of the forearm, which acts as a stabilizer to the distal tendon.

Several publications have emphasized the anatomic footprint and functional anatomy of the distal biceps insertion, including the predictable orientation of fibers rotated in the coronal plane —clockwise in left elbows and counterclockwise in right. Anatomic research on the dimensions of the biceps insertion and the orientation of the radial tuberosity have developed the surgeon's understanding of native anatomy and fine-tuned goals of anatomic fixation during repair.

ETIOLOGY
The etiology of distal biceps ruptures remains an area of active investigation. Current theories posit both anatomic and mechanical causes for rupture. Seiler et al examined these proposed mechanisms in a study involving both radiographic and anatomic components. Twenty-seven cadavers received vascular injections into the blood supply of the distal biceps tendon, revealing a zone of hypovascular tissue measuring approximately 2.14 cm in diameter between the musculotendinous junction and the attachment to the tuberosity. This hypovascular zone corresponded to areas of focal degeneration on light microscopy. The radiographic portion of the same study included computed tomography (CT) comparisons scans of forearm in positions of maximal supination, neutral, and maximal pronation. With the forearm fully pronated, the space for the distal biceps tendon insertion and its course is 48% less than the space available with the forearm in full supination. Accordingly, mechanical impingement...
on the tendon with the forearm in a pronated position is suggested as another contributing factor of distal biceps tendon rupture.

**DIAGNOSIS/IMAGING**

Patients often report a sudden “pop” during time of injury following an unexpected extension force to the flexed elbow, often with the forearm pronated. There is subsequent eccentric contraction of the biceps and a sharp tearing pain in the antecubital fossa. After the immediate pain resolves, the patient may complain of continued subtle weakness with elbow flexion and a marked decrease in supination strength, highlighting the biceps role as the forearm’s primary supinator. An early and accurate diagnosis is essential, as delayed diagnosis may preclude primary repair and lead to chronic weakness. The biceps squeeze test described by Ruland et al is analogous to the Thompson test for the Achilles tendon, and is performed by squeezing the biceps brachii when the elbow is flexed to 90 degrees to elicit forearm supination if the distal tendon is intact.

The hook test developed by O’Driscoll et al is also useful for the diagnosis of complete biceps tendon disruptions. O’Driscoll describes inserting the clinician’s finger under the lateral edge of the biceps tendon and hooking the cord-like prominence in the antecubital fossa with the patient’s elbow flexed at 90 degrees. This test had 100% sensitivity and specificity in the original cohort of forty-five patients with patients found to have a complete tendon rupture, confirmed during surgical exploration of the tendon and compared to the contralateral, intact upper extremity. It is important to emphasize probing the lateral edge of the biceps tendon, as an intact laceratus fibrosis encountered during a medial approach may be mistaken for an intact tendon. The 100% sensitivity and specificity of the O’Driscoll hook test was higher than the 92% sensitivity and 85% specificity of magnetic resonance imaging (MRI) in the same cohort. Plain radiographs are only occasionally helpful as distal biceps tendon rupture is primarily a soft tissue structure, although occasionally an avulsion fragment may be visible from the radial tuberosity. Suspected incomplete ruptures or chronic tears can be further elucidated with MRI. Giuffre’ and Moss describe the flexed abducted supinated (FABS) position for MRI of the distal biceps tendon. This position was described as 90 degrees of elbow flexion, 180 degrees of shoulder abduction, and relative forearm supination.

**SURGICAL MANAGEMENT**

Surgical repair is ideally performed within a few weeks from injury. A delay in surgical management may necessitate a more extensive surgical approach with reconstruction due to chronic tendon retraction and formation of scar tissue. Surgical approaches for distal biceps tendons repair include single-incision and two-incision techniques. Single-incision approaches are performed at or immediately distal to the transverse elbow crease in the antecubital fossa. Incisions may be transverse, longitudinal, or L-shaped depending on surgeon preference. The incision may be extended proximally if needed to ensure adequate exposure in delayed surgical repair or in revision cases. The single-incision technique is associated with lateral antebrachial cutaneous nerve (LACN) neuropaxia due to a more extensive dissection and longer duration of deep anterior retractor placement. The two-incision approach has a similarly placed, albeit smaller, anterior incision as well as a posterolateral incision to expose the radial tuberosity with subperiosteal elevation of the common extensor muscle mass off the ulna. Although there are several modifications to the two-incision approach, it is reported to be associated with posterior interosseous nerve (PIN) injury and heterotopic ossification which may lead to proximal radioulnar synostosis. There are a variety of techniques to repair the distal biceps to the radial tuberosity. Using the single incision approach, fixation may be performed using suture anchors, an interference screw, a cortical button, or a combination of these methods. If the two-incision method is used, the tendon is generally secured to the biceps tuberosity with high-strength sutures through multiple bone tunnels. The cortical button has been shown to be have the highest load to failure, but is associated with undesired tendon motion at the insertion site with cyclic loading. This may predispose the repair to gap formation at the insertion site, especially with early motion. Sethi et al reported good outcomes on the use of a cortical button in combination with an interference
screw; this augmented construct benefits from the strength of the cortical button while the interference screw prevents tendon motion and gap formation at the insertion. Use of this type of dual fixation may allow for a more aggressive post-operative rehabilitation protocol.\(^{23}\)

In patients with chronic distal biceps injuries and tendon retraction, primary fixation to the radial tuberosity may not be possible. In this situation, the use of autograft or allograft should be considered to lengthen the distal end of the biceps tendon and permit anatomic fixation to the radial tuberosity. Due to harvest site morbidity associated with autografts, allografts (anterior tibialis, achilles or semitendinosus tendon) are more commonly used.

Watson et al,\(^{24}\) in a systematic review of 22 studies summing 494 patients (498 elbows) who underwent distal biceps repair, reported an overall surgical complication rate of 24.5%. There was no significant difference in complication rates between the single and two-incision techniques. LACN neuropraxia occurred in 11.6% of patients who underwent repair via the single-incision approach, whereas only 5.8% of the two-incision group experienced LACN neuropraxia. Heterotopic ossification occurred in 7% of patients who had the two-incision approach, and only 3.1% in the single incision group. A lower rate of complications was associated with cortical button fixation (0 of 18) when compared with intrasosseous screw fixation and suture anchor fixation. Re-rupture occurred in 1.6% of cases overall, and there was no difference in re-rupture rates between the single and two-incision groups.

Grewal et al\(^{25}\) reported in a randomized prospective study that patients in her single-incision group had 10% better final isometric flexion strength (104%) compared to the two-incision group (94%), although there were no differences in the rate of strength recovery, ASES, DASH, or PREE scores. Both the single and two-incision groups achieved comparable improved outcomes and reported minimal pain and disability at two years.

**REHABILITATION**

**Progression of Rehabilitation Phases**

The post-operative rehabilitation protocol for distal biceps repair utilized at the senior author's (MTP) institution has been provided (Appendix 1). A standard therapy program progresses through sequential phases of rehabilitation, including an acute recovery phase, an intermediate phase featuring motion progression and onset of light isotonics, an advanced strengthening phase, and lastly, a phase focused on return to preferred activity. Each phase must be tailored to the individual patient's needs and restrictions. Temporal phase progressions are provided for guidance; however, the treating therapist should evaluate the patient's readiness to advance at each phase change. Progression of the protocol should be performed under the careful supervision of a rehabilitation team, with strong communication between treating providers. A complaint of persistent or recurrent pain and/or swelling indicate inappropriate phase progression. The overall principles guiding rehabilitation of the distal biceps tendon repair include protection of the tendon from excess load, followed by the safe and step-wise return to activities of daily living and sport.

**Bracing and Early Range of Motion**

Bracing is implemented post-operatively to protect the soft tissue repair (Appendix 1). Range of motion parameters are established intra-operatively. In the case of a retracted distal biceps tendon, the surgeon may initially limit extension range of motion and progress to full extension based on the amount of tension present in the repaired tendon over four to six weeks. In these cases of restricted extension range of motion, a hinged elbow brace may be implemented to help the patient maintain these parameters.

**Phase I: Early Recovery (Weeks 0 to 6)**

Early goals include pain and effusion reduction, protection of the surgical repair, and optimization of the tissue healing environment. Cryotherapy should be used and may be incorporated via multiple mediums, including ice massage, ice packs, cold whirlpool, or the Cryo-Cuff, for durations of 5 to 20 minutes with careful attention to avoid skin irritation.\(^{19}\) Hand and wrist range of motion and gripping exercises should begin immediately, and may include rubber ball squeezing or simple daily tasks such as using a smart phone. Shoulder girdle range of motion is also encouraged to avoid shoulder
pain and stiffness and allow hygiene, including glenohumeral and scapulothoracic passive and active motion. Patients may perform computer work/typing; but must refrain from any lifting with their operative extremity. No active elbow flexion or supination is permitted, including tasks such as drinking coffee or feeding. Gravity-assisted flexion and extension may begin at two weeks post-operatively; with restriction in the full arc of motion if an extension limitation has been determined necessary. Contraindication to progression to phase II of the rehabilitation protocol includes persistent or recurrent pain and/or swelling.

Cardiovascular fitness training, such as using a treadmill or elliptical, also be introduced as early as week one post-operatively and is recommended to enable continued overall health; however, the treating therapist must place emphasis on safety and balance in order to avoid a fall onto the operative extremity.

Phase II: Weeks 6 to 12

Isometric triceps exercises (Figure 1) may begin at six weeks post-operative with isotonics beginning at week 8. Strengthening of wrist flexion and extension and the shoulder girdle may also commence at week 8. In addition to traditional isotonics, correction of underlying scapulothoracic dyskinesia to promote proper biomechanics of the shoulder girdle during upper extremity elevation should be incorporated. Postural control exercise (Figure 2) is an essential foundation prior to the strengthening progression included in Phase III.

Phase III: Weeks 12 to 16

At the start of Phase III, biceps isometrics begin, followed by light biceps isotonics at week 16 (Figure 3). Continuation of rotator cuff and periscapular stabilization exercises enable maintenance of overall upper extremity and postural health and promote proper mechanics as the patient advances to more complex exercises and activities. Inclusion of both open and closed kinetic chain exercises is essential, as activity of shoulder girdle musculature demonstrates significant electromyographic (EMG) differences when activated in exercises performed in an open versus closed kinetic chain.19,20

Phase IV: Week 16+

Biceps strengthening is advanced to include side curls (Figure 4). Upon attainment of full upper extremity strength, readiness to return to sport may be assessed on a sport-specific basis. No specific

Figure 1. Triceps Isometric
Begin in a seated position with the forearm on an adjacent table with palm down. While keeping the ipsilateral shoulder girdle relaxed, push the entire forearm and palm into the table. Hold for 10 seconds and repeat for 10-15 repetitions, 3-5 sets.

Figure 2. Postural Control
Begin prone on the ball as pictured. While maintaining a neutral spine and a relaxed cervical spine, abduct and externally rotate the shoulder. Pinch the scapulae together and hold for 3 seconds. Repeat 10-15 repetitions, 3-5 sets.
test for return to sport following distal biceps repair exists; instead therapists must assess the quality and strength of movements specific to the preferred sport. At this stage, therapists are encouraged to employ creativity in designing a gym program focused on functional movement patterns that include the upper body, lower body and trunk prepare the individual for return to their preferred activity. Criteria for return to activity include full and painless range of motion, strength within 10% of the contralateral upper extremity and pain-free participation in activity-specific movement patterns.

**SUMMARY**

The purpose of this clinical commentary was to present a detailed rehabilitation protocol following distal biceps repair. Distal biceps rupture is a debilitating injury and restoration of function can be successfully achieved with proper surgical technique, followed by a criterion based, progressive rehabilitation. This rehabilitation program progresses through phases with objective criterion requirements being met prior to advancement. The ultimate goal of rehabilitation of a distal biceps repair is to optimize the patient’s function and their ability to return to their desired work and recreational activities.

**Figure 3. Traditional Biceps Curls, Hammer Biceps Curls and Reverse Biceps Curls**

3A: Begin in standing with palms facing outward. While keeping the shoulders relaxed, bend the elbows and perform traditional biceps curls. Repeat 10-15 repetitions, 3-5 sets.

3B: Begin in standing with palms facing toward the body. While keeping the shoulders relaxed, bend the elbows and perform hammer biceps curls. Repeat 10-15 repetitions, 3-5 sets.

3C: Begin in standing with palms facing backward. While keeping the shoulders relaxed, bend the elbows and perform reverse biceps curls. Repeat 10-15 repetitions, 3-5 sets.
REFERENCES


**Figure 4. Figure Biceps Side Curls, position 1 and 2**

4A: Begin in standing, begin with the arms at 90 degrees of flexion and 90 degrees of abduction with palms facing upward.

4B: Maintain a relaxed shoulder girdle and cervical spine while flexing the elbows as shown in 4b. Repeat 10-12 repetitions, 3-5 sets.


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<td>• Brace for protection until 6 weeks with progressive allowance of ROM</td>
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<td>• No active elbow flexion or supination</td>
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<td><strong>Goals:</strong></td>
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<td>• Full, pain-free range of motion by week 6</td>
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<td><strong>Therapeutic Exercises:</strong></td>
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<td>• Elbow range of motion as prescribed</td>
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<td>• Hand/wrist range of motion and edema control</td>
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<tr>
<td>• Scapular retraction/protraction/elevation/depression</td>
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<td>• Gravity-assisted flexion and extension (begin at week 2)</td>
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<tr>
<td><strong>Criteria for Progression</strong></td>
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<tr>
<td><strong>Goals:</strong></td>
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<td>• Initiation of upper extremity strengthening</td>
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<tr>
<td><strong>Therapeutic Exercises</strong></td>
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<td>• Isometric triceps exercises (Figure 1)</td>
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<tr>
<td>• Strengthening of wrist flexors and extensors (begin week 8)</td>
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<td>• Cardiovascular fitness (treadmill walking, elliptical without arm use, bike)</td>
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<tr>
<td><strong>Criteria for Progression</strong></td>
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<tr>
<td>• Full, painless range of motion of the shoulder, elbow, wrist and hand.</td>
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<tr>
<td>• Proper scapulothoracic mechanics (no dyskinesia).</td>
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### Appendix 1. Distal Biceps Repair Protocol. (continued)

#### Phase III

**12 to 16 weeks after surgery**

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<td>Goals:</td>
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**Therapeutic Exercises**

- Isometric biceps exercises
- Light isotonic biceps exercises (begin at week 16) (Figures 3A-C)
  - Hammer
  - Traditional
  - Reverse grip
- Rotator cuff and periscapular stabilization exercises
  - Open and Closed Kinetic Chain
- Cardiovascular fitness (treadmill walking, elliptical with or without arms, bike)

**Criteria for Progression**

- Full, painless range of motion of the shoulder, elbow, wrist and hand.
- Proper scapulothoracic mechanics (no dyskinesia).
- Full biceps strength against gravity (5/5 manual muscle test)

#### Phase IV

**16+**

<table>
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<th>Precautions:</th>
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| Goals:       | Continue to increase strength of upper extremities
  - Return to preferred sport and/or activity |

**Therapeutic Exercises**

- Biceps curls
  - Hammer
  - Traditional
  - Reverse
  - Side Curls (Figures 4A,B)

- Triceps extensions
- Rotator cuff and periscapular strengthening exercises
- Sport-specific exercises
- Cardiovascular fitness (treadmill walking, elliptical with or without arms, bike)

**Criteria for Progression**

- Functional / Sport Testing for discharge to maintenance program
ABSTRACT

Subscapularis (SSC) tendon tears are less common than tears of the remaining rotator cuff tendons, but one with serious consequences given its function as one of the main internal rotators and anterior stabilizers. Mild fraying involving the upper third of the tendon can be treated non-operatively; however, more substantial tears usually require repair in cases of pain or functional impairment. Given the importance of the subscapularis tendon in maintaining stability of the glenohumeral joint and performing internal rotation of the arm, surgical intervention with emphasis on repair may be recommended to eliminate pain and restore strength. Postoperative rehabilitation through phased progression is utilized to avoid premature stress on the healing tissue while enabling early return to daily activities. The purpose of this clinical commentary is to provide an evidence-based description of postoperative rehabilitation following SSC tendon repair with guidance for safe and effective return to activity and sports.

Level of Evidence: 5

Key words: Repair, Return to sport, Shoulder, Subscapularis tear
INTRODUCTION
The subscapularis (SSC) tendon forms the anterior section of the rotator cuff (RC) and its muscle is the largest and most powerful rotator cuff muscle. The upper 60% of the insertion is tendinous and the lower 40% consists of muscle. The SSC is one of the most important anterior stabilizers of the glenohumeral joint. It balances the force couple in the horizontal and frontal planes. Moreover, SSC functions mainly as an internal rotator, whereas its superior fibers assist in abducting the arm and its inferior fibers help in adducting it. Tears of the SSC tendon are less common than tears of the remaining rotator cuff tendons. The prevalence of SSC tears was reported to range from 31.4% to 37% in patients who underwent arthroscopic rotator cuff surgery. The majority of subscapularis tendon tears are degenerative in origin, however some result from trauma following an anterior shoulder dislocation or more commonly following violent external rotation force such as in a motor vehicle accident. Tears and dislocation of the long head of the biceps is very common in conjunction with subscapularis tendon rupture because of the loss of its medial constraint as the pulley tears. Classification of SSC tendon lesions has been described by Fox and Romeo along with Lafosse et al. Surgical repair is often advocated for full-thickness tendon lesions. The size of the tear, tendon tissue quality, muscle fatty degeneration and chronicity of the condition can have drastic effects on the outcome of these repairs. Moreover, subcoracoid impingement can cause a “roller-wringer effect” on the SSC tendon and contribute to the pathogenesis of SSC tears. Thus, the senior author performs a subcoracoid decompression simultaneously with SSC repair.

Biomechanics
As the most powerful rotator cuff muscle, the SSC contributes to 53% of the cuff moment. The force-generating capacity is equal to that of the other three muscles combined. A tear or rupture of the subscapularis muscle may manifest as pain, weakness with internal rotation (IR) and increased passive motion with external rotation (ER) or anterior glenohumeral instability. Superior and midsuperior portions of the SSC were shown to have significantly higher stiffness compared to the inferior region both in hanging arm and 60° of abduction. They concluded that higher stiffness and ultimate load in the superior tendon region may explain the extension of rotator cuff tears into the SSC tendon.

Clinical examination
The integrity of the SSC can be assessed with the belly-press, lift-off, modified lift-off, bear-hug tests and belly off sign. The belly-press test was described by Gerber et al. and is performed with the arm at the side with elbow flexed to 90° and the palm held against the stomach. Next, the patient is asked to push their palm toward their abdomen while the examiner pulls in the opposite direction. A positive test is denoted by an inability of the patient to resist or by compensation through wrist flexion and/or arm extension. Moreover, a combination of shoulder extension and adduction due to compensation through latissimus and pectoralis major activation may be seen. The lift-off test is performed with the dorsal surface of the hand being positioned on the lumbar spine. The patient is asked to internally rotate the shoulder by lifting their hand off the lumbar spine. A positive test is denoted by inability to lift the dorsum of the hand or by compensation through elbow and/or shoulder extension. The modified lift-off test is performed with the patient’s arm maximally internally rotated and extended behind the back with the hand 5 to 10 cm from the skin, followed by the release of the arm. The test is considered positive when the hand lands on the back. This is also considered the IR lag sign. The bear-hug test utilizes resisted IR as the palm is held on the opposite shoulder while the elbow is held in a position of maximal anterior translation. With the belly off sign, the arm of the patient is passively brought into flexion and maximum IR with 90° of elbow flexion. The belly off...
sign occurs if the patient cannot maintain this position and flexes the wrist or a lag occurs.9

Surgical Management
The repair of the torn SSC tendon involves reattachment to the anatomical footprint on the lesser tuberosity with suture anchors, which can be done arthroscopically or via an open surgical approach. The technique utilized by the senior author has been previously published by Katthagen et al.14 All procedures are performed with the patient in the beach-chair position under general anesthesia with an interscalene nerve block. Following standard diagnostic arthroscopy and confirming the size of the SSC tear, subcoracoid soft tissue decompression is performed along with release of any adhesions around the torn tendon. For partial tears, a knotless repair technique is preferred. To facilitate this, a spinal needle is placed percutaneously through the tear and a polydioxanone suture (PDS) is shuttled out through an anterior-superior portal. Next, a suture tape (FiberTape, Arthrex) is passed through the tear. After preparing the anatomic SSC footprint with a shaver to create a bleeding bone bed and tapping, the suture tape is passed through a bioabsorbable anchor (4.75 Bio SwiveLock, Arthrex). The anchor is then inserted in the lesser tuberosity and the tendon is secured back to the bone.14

In full-thickness SSC tears that involve the tendinous portion, the senior author prefers to perform an arthroscopic repair in a double-row, linked, knotless, bridging technique (SpeedBridge, Arthrex, Naples, FL). The SSC is visualized arthroscopically after a subcoracoid decompression. After mobilization of the tendon stump and debridement of the tendon footprint on the humerus to a bleeding surface, medial anchors are placed approximately 1 mm from the articular margin. The suture tapes are then passed through the SSC tendon. The SSC tendon is compressed onto the footprint and the lateral anchors are secured.14 The arm is then taken through a range of motion to confirm that the SSC is secure and stable, and has appropriate tension. For massive tears that involve the direct muscular insertion or for chronic retracted tears, an open deltopectoral approach can be used.

In all cases of SSC tear and whenever the biceps pulley is disrupted, a biceps tenodesis is performed. The biceps is released arthroscopically and a subpectoral biceps tenodesis is performed with an interference screw.15 Concomitant pathology of the long head of the biceps (LHB) is common in SSC tendon lesions.16 Tahal et al. demonstrated that subpectoral biceps tenodesis is an excellent treatment option for active patients with LHB tenosynovitis and chronic anterior shoulder pain, resulting in decreased pain, improved function, high satisfaction, and improved quality of life.17 Thus this is our preferred treatment option for LHB pathology. Immediately after the operation, the shoulder is immobilized in a sling. Early passive ROM is started with a limitation of 30° ER. Since a concomitant LHB tenodesis is performed whenever the SSC is repaired, resisted elbow flexion should be avoided for 6 weeks.15 Moreover, resisted supination should also be avoided to minimize overall stress to the biceps.

Clinical outcome
Seppel et al. investigated the long-term results of arthroscopic repair of isolated SSC tears, reporting significant clinical improvements and enduring tendon integrity. The SSC strength remains reduced in the long term, however, 88.2% of patients were “very satisfied” or “satisfied” with their results.18 In an earlier study, Adams and colleagues reported results of arthroscopic SSC repairs at a median follow-up of five years, finding 80% (32 of 40) of patients had a good or excellent result after an arthroscopic STR.19 Recently, Katthagen et al. reviewed the senior author’s (PJM) patient outcomes and demonstrated improved outcomes with high patient satisfaction following arthroscopic single-anchor repair of upper third SSC tears in 31 patients with a mean follow-up of 4.1 years. They reported more favorable outcomes following repair of full-thickness upper third SSC tears compared with high grade partial-thickness upper third SSC tears.14

GUIDELINES FOR REHABILITATION
A successful outcome following SSC repair surgery is a pain-free and stable shoulder that has sufficient mobility, stability and strength for a patient’s desired level of activity and participation. Postoperative rehabilitation is tailored to the individual according to a criteria and functional based progression taking into account healing time lines, the attainment of
specific clinical goals and in conjunction with the recommendations of the referring physician. Healing phases include the inflammatory phase, proliferation (repair) phase and remodeling phase. The overall aim of rehabilitation is centered on the principle of gradual application of controlled stresses to the shoulder with consideration of the healing phases in order to optimize patient outcome.20

Literature to support the efficacy of a specific rehabilitation protocol for SSC repair is limited. Rehabilitation following SSC repair is dependent on the extent of the lesion and will vary regarding whether the repair involves a full-thickness tear of the upper 1/3 of the tendon versus repair of the entire tendon all the way down to the direct muscular insertion. Clinicians, surgeons and physical therapists must have a working knowledge of the anatomy and kinematics of the shoulder complex, underlying pathophysiology, principles of tendon healing and the specific attributes and limitations of selected treatment interventions and need to select treatment strategies accordingly to achieve an optimal outcome. Time-based and performance-based criterions need to be united, with milestones for each being met prior to progression to the next phase. Millett et al. emphasized the importance of an evaluation-based rehabilitation protocol which takes into account not only healing time times but also the attainment of specific clinical goals.21,22 Criterion to progress through each phase of rehabilitation are proposed by merging time-based and performance-based principles. This respects the biology and temporal aspects of healing while at the same time necessitate that functional goals be accomplished prior to progression to the next phase of rehabilitation. Such a program allows the patient to achieve a strong foundation in mobility, endurance and strength before returning to unrestricted activity or sport performance. Suggested guidelines for rehabilitation following repair of full-thickness upper 1/3 and extensive SSC tears were developed based on the current literature, best available evidence and professional expertise. This should provide clinicians who treat these injuries with guidelines to enhance rehabilitation following surgery.

The rehabilitation program is divided into five phases. The underlying pathology, integrity of the repair and the biology of healing along with the desired level of activity will determine the speed of progression through all five phases.

Phase I is the maximal protection phase involving immobilization with only passive exercises that minimize loads across the repair. The muscular endurance phase, Phase II, consists of the introduction of active exercises, which gradually apply load to the repair and begin to transfer loads back onto the healing tissues. Phase III focuses on muscular strength, incorporating resistive exercises to further apply controlled stress to the tissues. If the individual does not require advanced or power movements for their activities of daily living (ADL), occupational or sport preferences, meeting Phase III goals could result in the completion of rehabilitation. If the individual has high physical demands from their occupational or sport needs progressing through the power Phase IV and/or Phase V return to sport may be necessary.

PHASE I: PROTECTION PHASE
The goals of this phase of rehabilitation are to maximally protect the surgical reconstruction, optimize the environment for tissue healing, decrease pain and inflammation, restore passive mobility to minimize stiffness (being mindful to not exceed ER limits), and pain free restricted ADL with use of a sling. These goals must be addressed without causing inappropriate stress to the healing structures.

Good communication between the physical therapist, patient, and surgeon is essential at this phase and helps direct the course of rehabilitation. Patient related factors, such as prior surgery, smoking and comorbidities negatively influence tendon healing, rehabilitation and ultimately clinical outcomes. Each variable should be considered when formulating a postoperative therapy plan, which should be tailored to each individual case. Patient education to convey the rationale of the outlined rehabilitation protocol and the importance of protecting the healing tissues from excessive stress is critical to ensure compliance.

Protection
In order to reduce strain on the repair, the shoulder is protected for four weeks. This is achieved by using
an abduction sling during the day and at night. The authors suggest protecting the arm in slight abduction to promote optimal blood flow and minimize tension to the repair. Patients are allowed waist level activity in the sling (i.e. keyboarding) as tolerated. Gurney et al. evaluated electromyographic (EMG) activity of the shoulder during commonly performed tasks such as ambulation, donning/doffing a sling and other movements. The authors demonstrated that rehabilitation tasks such as pendulum exercises, passive range of motion performed by a physical therapist, and self-ranging motion with a dowel showed low EMG activity, whereas ambulation without a sling, donning/doffing a sling and pulleys in the sagittal and scapular plane showed greater activity. These findings indicate caution is needed following STR when donning/doffing a sling and highlights the importance of wearing the sling during ambulation.

Cryotherapy
Continuous cryotherapy has been shown to cause a significant reduction of both glenohumeral joint and subacromial space temperatures in the shoulder at variable times during the first 23 postoperative hours. Cryotherapy should be used during this phase to control pain, decrease swelling and muscle spasm, suppress the inflammatory response and improve sleep patterns.

Range of motion
Active hand, wrist and elbow range of motion should be part of a home exercise program. The authors encourage early passive ROM exercises for the glenohumeral joint. Keener et al. could not show an apparent advantage or disadvantage of early passive range of motion (PROM) compared with immobilization in a prospective randomized trial following arthroscopic rotator cuff repair. It has been shown that continuous passive motion properly applied (at the knee and elbow) during the first two stages of stiffness (bleeding and edema) following surgery acts to pump blood and edema fluid away from the joint and periarticular tissues. This allows maintenance of normal periarticular soft tissue compliance. Early ROM prevents adhesions and when the repair is secure and tissue quality is good, early PROM is allowed. ER is typically limited to avoid undue loading on the nascent SSC repair.

Immediately following surgery, the repair is reliant on the mechanical strength of the sutures and anchors. Therefore, active motion of the shoulder joint at this time would overly stress the healing tissues. In these cases, a gradual progression of PROM over four weeks is recommended. However, with the shoulder at 0° abduction, passive glenohumeral ER movement past 30° stresses the anterior capsule as well as the SSC muscle and is not recommended following repair of a SSC tendon tear for three weeks. For a massive tear, with very poor quality tissue or undue tension on the repair, the authors sometimes limit ER to neutral for several weeks to avoid stressing the repair. Following SSC repair, passive internal rotation should be restricted to belt line for the first four weeks.

Scapula
For the first two weeks following repair of a large full thickness tear of the SSC, excessive scapular mobility can stress the repair and should be avoided. After two weeks or initially following upper 1/3 SSC repairs, scapular mobility exercises can be incorporated. Normal active scapular movement (protraction, retraction, elevation and depression) helps to facilitate early neuromuscular control of the scapula. The side-lying scapular clock exercise is a great starting point for this with progression to sitting or standing with the sling on.

Isometrics
To protect the repair from shear or compressive forces, no isometric exercises should be performed during weeks 0-3 following repair of extensive SSC tears and weeks 0-2 following upper 1/3 SSC repair. After this time isometric exercises of the muscles surrounding the shoulder girdle can be initiated. These should be submaximal and non-painful, with the shoulder in a neutral position. Rhythmic stabilization, involving gentle manual resistance to the proximal forearm using oscillating perturbation in a neutral shoulder position, is appropriate to facilitate low contraction of the scapular and rotator cuff musculature and can be beneficial for early neuromuscular re-education.
Manual therapy
Manual therapy during this phase should consist of soft-tissue techniques and PROM. Soft tissue techniques initially include lymphatic drainage to assist with swelling reduction and later include myofascial release techniques of the upper quarter and portal scar mobilization techniques. Glenohumeral mobility is not assessed due to healing structures and post-surgical precautions since anterior humeral glide could put excessive strain on the repaired SSC.

Kinetic chain exercises
Addressing the kinetic chain early in rehabilitation will benefit the patient long term, therefore breathing and basic core exercises should be incorporated at this stage of rehabilitation. Core exercises in a hook-lying position with the sling on, with focus on lower extremity movement will ensure the surgical reconstruction is safe and not stressed. Stationary recumbent bike should be encouraged in order for the patient to maintain cardiovascular conditioning, enhance blood flow to healing tissues and for mental health benefits.27

The criterion to progress to the next phase of rehabilitation is outlined in Table 1. The Disabilities of the Arm, Shoulder and Hand (DASH) questionnaire may be used as a criterion to progression as well.28 In addition to this, it is important to work with the individual surgeon to elicit their preferred time frames for progression and to understand their rationale in deciding ROM restrictions.

Table 1. Subscapularis Tendon Repair Progression Criteria Algorithm.
PHASE II: MUSCULAR ENDURANCE
The primary goals of this phase are careful progression to full active ROM (AROM), improvement of muscular endurance and neuromuscular control of the shoulder complex. In addition, normal use of the involved extremity for ADLs should be achieved by the end of this phase with the exception of no overhead lifting, fast-jerking motions or repetitive activities.

During this phase the sling is discontinued and ROM progressed to include active-assisted ROM (AAROM) and AROM. PROM and light stretching should be continued as needed until full PROM is achieved. If deficits remain, low load, long duration stretching and joint mobilization can be utilized at 5-6 weeks postoperatively. Isotonic exercises should focus on high repetitions with low to no resistance. Gravity alone for resistance is often sufficient at this time. Individuals following repairs of smaller upper 1/3 SSC tears will usually move into this phase a week sooner than those with larger or more extensive tears due to the earlier timeframe for initiating AROM.

AAROM is initiated one week prior to commencing AROM, as it is important to gradually apply load without overstressing the healing structures during this phase. Equipment such as a foam roller and stability ball can be utilized to allow patient to progress AAROM, as maintaining low muscle activation of the SSC following repair is important. Previous literature have used EMG studies to guide postoperative rehabilitation progression in the RC following surgery with 15% MVIC considered as an upper limit of a safe loading range during exercises in the early motion stages following repair. Table slides, pulley-assisted elevation, seated row, wall-assisted ER have all been shown to have a MVIC of 15% or less. Patients may have significant deficits in ER mobility due to post-operative restrictions; utilizing a bar to progress ER AAROM in supine is encouraged.

Once the patient exhibits effective isometric muscle contraction as well as fair muscle activation with AAROM, the initiation of AROM can commence. ROM can be performed in supine, side-lying or prone positions to reduce the effects of gravity, progressing to a standing position as endurance improves. For example, progression of shoulder abduction would commence with supine, slide board AAROM with a bar (Figure 1), to side-lying shoulder abduction adding rhythmic stabilization to aid with neuromuscular control (Figure 2), advancing to prone T’s (horizontal abduction) (Figure 3) and standing abduction/adduction against a wall with a focus on scapular control.

It is vital to incorporate ROM exercises that enhance scapular control during this phase. A synchronized contribution from scapular musculature is essential for optimal positioning, stability and functioning of the shoulder complex. The upper (UT), middle (MT) and lower trapezius (LT) muscles and the serratus anterior muscle are the greatest contributors to scapular stability and mobility. It is clinically important to enhance the LT/UT and MT/UT activation ratios as a dominant UT has been linked to shoulder pathologies due to contributions of poor posture and muscle imbalances. Particular exercises which have been shown via EMG studies to accentuate periscapular control while minimizing UT muscle activation are side-lying ER, side-lying...
forward flexion, prone horizontal abduction with ER, prone flexion and prone extension. These activate key scapular stabilizing muscles without placing high demands on the shoulder joint.

Functional stability of the shoulder is accomplished through passive and active mechanisms. The passive mechanisms include the joint’s geometric configuration and the integrated functions of the joint capsule, ligaments and the glenoid labrum. The active mechanisms include the dynamic stabilization of the surrounding musculature and the innervation of those muscles, particularly the rotator cuff musculature. Additionally, the dynamic stabilizers provide stability through an active mechanism referred to as neuromuscular control. Dynamic stability is accomplished through proprioceptive and kinesthetic awareness and efficient muscular activity, which is achieved through the efficiency of several muscular force couples of the shoulder. The SSC and pectoralis musculature work in conjunction with the external rotators to establish the internal/external rotator force couple that functions in concert with the deltoid. Dynamic glenohumeral stability is accomplished by these force couples through joint compression, ligament tension and proficient neuromuscular control. An essential goal of therapeutic exercise should be directed towards enhancing neuromuscular control and thus improving dynamic functional stability of the glenohumeral joint.

As ROM targets are met, the focus of rehabilitation can shift to neuromuscular retraining. The neuromuscular training must provide a stepwise increase in muscular demand in order to protect the healing structures and also prevent abnormal movement.
patterns from developing. Rhythmic stabilization at various angles and diagonal proprioceptive neuromuscular facilitation patterns can be initiated to help gain stability and control into functional patterns. Open chain scapular exercises, such as supine serratus punch/plus can help establish proper scapula-thoracic force couples and improve neuromuscular endurance with AROM. Loaded closed chain exercises are not appropriate during this phase as these can create too much compressive joint stress and negatively affect the surgical repair.36 Unloaded closed kinetic chain scapular exercises such as wall slides (Figure 4) or wall plus, can be initiated cautiously at this time. Loaded closed chain scapular exercises should be initiated in Phase III in order to allow sufficient time to develop proper dynamic stability prior to initiation of compressive forces of the glenohumeral joint.

This phase of rehabilitation can potentially require a significant amount of time to properly retrain the rotator cuff and periscapular musculature. Before progressing into Phase III of rehabilitation the patient needs to achieve adequate PROM as well as non-compensated shoulder and scapulothoracic AROM (see Table 1).

**PHASE III: MUSCULAR STRENGTH**

Following establishment of good muscle activation and endurance in Phase II, the main goal of Phase III is to improve strength by increasing resistance and reducing repetitions, to advance muscular endurance and dynamic stability exercises. This can be done through a periodization format to load the repair and stimulate healthy remodeling. It is recommended initial strengthening does not commence prior to 6 weeks postoperatively and advanced strengthening is delayed until 10 weeks postoperatively. Iannotti et al. could show in a prospective imaging study that re-tears primarily occurred between six and twenty-six weeks after arthroscopic rotator cuff repair thus underlining the importance of this recovery phase.37 As this is a criterion-based progression, individuals should not start this phase until Phase II goals are met, therefore a significant variability between when individuals start strengthening may exist.

A strengthening program for the entire shoulder girdle is employed, with focus on rotator cuff and periscapular musculature. Initially the non-resisted exercises previously described in Phase II are implemented with the addition of resistance. Dumbbells, elastic cords (Figure 5), cable machines, barbell weights and manual resistance including perturbation can be incorporated to these exercises to make them more challenging. The focus should be on controlled concentric and eccentric contractions. Initial strengthening exercises should be chosen which have been shown to have EMG activation of 21-50% MVIC. Specifically for the SSC this includes upright bar assisted elevation, forward punch and IR at 0° abduction.29 During the late strengthening phase EMG activation of >50% MVIC can be initiated. These include IR at 45° abduction, ER at 0° and 90° abduction; dynamic hug; diagonal; IR at 90° abduction; low row, high row, resisted shoulder extension; resisted active elevation/flexion.29 (Figure 6)
Initially, closed chain body weight exercises are performed as isometric or static exercises, which can be progressed to increase weight bearing through the upper extremities. Advancing from wall to tabletop or to quadruped position creates a gradual increase in loading and is excellent for scapular control. Some examples include push up with a plus, which has demonstrated high EMG activity for SSC; and quadruped upper extremity and lower extremity reaches, which additionally challenges core stability. Placing an unstable base under the upper limbs such as a stability ball or BOSU®, enhances neuromuscular control at a reflex level while the altering perturbation will challenge proprioception and improves joint position sense. Light impact activities (jogging) can be included at the end of this phase.

Strength testing periodically throughout this phase is important in order to identify specific muscular deficits and focus exercise prescription accordingly. Handheld dynamometry (HHD) offers an accurate measurement of strength. The balance between external and internal rotation (ER/IR) strength is important to normal glenohumeral joint function. An adequate external-internal rotator muscle strength ratio has been emphasized in the literature with a minimum of 65% and optimally between 66% and 75%. Increased EMG activity of the SSC with internal rotation at 90° abduction (IR90) has been reported compared to 0° abduction (IR0). Previous studies have recommended SSC strengthening exercises in adducted positions; conversely Alizadehkhaiyat et al. found significantly higher activation of SSC along with low-to-moderate activation of pectoralis major, latissimus dorsi and teres major in IR90, indicating a preference of this exercise for selective SSC activation. This finding is in line with Decker et al. who demonstrated higher levels of pectoralis major and latissimus dorsi activation at IR0 compared to IR90, and suggested IR90 would be more beneficial in strengthening SSC due to minimizing the contributions of larger muscle groups.41

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**Figure 5.** Internal rotation at 45° with elbow supported on table using sport cord.

**Figure 6.** Dynamic hug with sport cord.
The belly-press test was found to activate the upper SSC muscle significantly more than the lift-off test, whereas the lift-off test was found to pose a significantly greater challenge to the lower SSC muscle than the belly-press test. In addition to strength goals, individuals should have active ROM of >90% of contralateral side and achieve three out of the five tasks described in Table 1. If the individual has occupational or athletic demands that require power movements or overhead strength, they will advance to Phase IV of the rehabilitation program. Otherwise once these goals are achieved they can be discharged from therapy with a home exercise program.

PHASE IV: POWER PHASE

The main goals for this phase are to incorporate speed, explosive strength and introduce patterns of movement biased towards the individuals' specific sporting or occupational demands. It is the role of the physical therapist to continue to develop and individualize the patient's program. Repetition, speed and load may be varied in relation to the desired task, facilitating feed forward processing.45

Plyometric exercises are an excellent, functional method for an individual to increase power, endurance and stability of the RC and activation of the periscapular musculature.46 Plyometric exercises should focus on the SSC muscle combined with trunk stabilization. Starting with double upper extremity plyometric exercises, such as slams to the ground, overhead throws against a wall and side throws against a wall (Figure 9). Progressing to single upper extremity plyometric exercises as power, strength and ability permit. These exercises can be performed with 90° of glenohumeral joint abduction which prepares the athlete for a return to the demands of overhead function and has been shown to improve IR/ER strength and throwing performance after 8 weeks of training.47 During the cocking phase of throwing, the SSC contracts eccentrically to decelerate ER and protects the anterior and inferior structures of the glenohumeral joint. The acceleration phase is very explosive and requires the SSC to concentrically contract. Single arm plyometric exercises include IR wall dribbles, IR throws against a trampoline and supine 90/90 IR ball toss using a light handheld medicine ball).
compensation, risk of re-injury or dysfunctional movement patterns. Loading is progressed towards normal participation levels by increasing volume and intensity.

It is advised that clinical testing and sport-specific testing are undertaken prior to releasing athlete to full play. This includes meeting all mobility and strength based criteria in addition to sport specific tests, such as simulated sporting activity, performing in sport practice, playing at a lower level and the player feeling ready and confident.52 Moreover, it should be considered that the SSC plays an important role during the late cocking and acceleration phase of throwing.53 Thus, special attention should be paid to this phase of throwing during sport-specific rehabilitation. A slow re-introduction back into the sport, using irritability as a guide to his or her progression is also recommended.

CONCLUSION
The purpose of this clinical commentary was to present a detailed rehabilitation protocol for use following SSC repair. The success of SSC repair depends on appropriate rehabilitation, proper surgical technique
and consideration of other procedures performed. The graded application of stress to the healing tissues guides the therapy. This rehabilitation program advances through five phases with objective criterion requirements in order to progress to the next phase. Phase I focuses on protection of the repair and initiation of passive ROM. Phase II advances active assisted and active ROM as tolerated with a focus on endurance and performance of movement without compensation. Phase III progresses muscular strength by incorporating bands, cords, dumbbells and manual resistance as necessary. Phase IV starts to prepare the individual for return to activity or occupational demands by addressing power, agility and speed. Phase V focuses on returning the athlete back to pre-injury sporting levels. The ultimate goal of rehabilitation is to maximize the patient's ability to return to full ADL, work and recreational activities. The criterion for progression through each phase is based on both functional and objective markers with consideration to tissue healing time frames. The current review has blended current literature and expert opinion to inform the development of the rehabilitation guidelines following SSC repair.

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