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Original research

Relationship of Hip and Trunk Muscle Function with Single Leg Step-Down Performance: Implications for Return to Play Screening and Rehabilitation

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ABSTRACT

Objectives: Evaluate the relationship of hip and trunk muscle function with the Single Leg Step-Down test (SLSD).
Study design: Laboratory study.
Setting: Biomechanics Laboratory.
Participants: 71 healthy participants with no history of anterior cruciate ligament (ACL) or lower extremity injury in the last 3 months completed this study (38 males, 33 females; mean 25.49 ± 0.62 years).
Main outcomes: Hip abduction (HABD), external rotation (HER), and extension (HEXT) peak isometric force were measured. Trunk endurance was measured with plank (PL) and side plank (SPL) tests. SLSD repetitions in 60-s and dynamic knee valgus (VAL) were recorded.
Results: PL, SPL, HABD, HER, and HEXT were positively correlated with SLSD repetitions. PL ($r = 0.598$, $p < 0.001$) was most correlated with SLSD repetitions, and regression demonstrated that PL ($p = 0.001$, $R^2 = 0.469$) was a predictor of SLSD repetitions. VAL trended toward negative correlation with PL and SPL. Sex-specific differences were present, with PL, SPL, HABD, and HER showing stronger relationships with SLSD in females.
Conclusion: Hip and trunk muscle function were positively correlated with SLSD performance, and these relationships were strongest in females. PL predicted performance on the SLSD. Further research is needed to investigate the utility of SLSD as a screening or return-to-play test for lower extremity conditions such as ACL injury and patellofemoral pain.

1. Introduction and background

Lower extremity injuries are an increasingly common occurrence among athletes of all ages. Over three million people in the United States seek emergency room treatment for sports related injuries each year (NEISS Database, 2014). Most of these injuries involve the lower extremity, with the knee being one of the most common sites (Burns & Lowery, 2011; Conn, Annest, & Gilchrist, 2003). These injuries result in significant healthcare and societal costs (Adirim & Cheng, 2003; Conn et al., 2003), especially injuries such as anterior cruciate ligament (ACL) tears. For instance, there are over 200,000 ACL injuries in the United States each year (Maffulli & Osti, 2013); over 175,000 ACL reconstructions (ACL-R) are performed annually at a total cost of over $2 billion (McCullough et al., 2012). Despite recent advances in surgical technique and rehabilitation protocols, the return to play rate of 63–69% after ACL-R is less than ideal (McCullough et al., 2012; Shah, Andrews, Fleisig, McMichael, & Lemak, 2010), with patients at an increased risk for reinjury (Brophy et al., 2012; Hettrich, Dunn, Reinke, Group, & Spindler, 2013; Paterno, Rauh, Schmitt, Ford, & Hewett, 2014) and premature osteoarthritis (Lohmander,

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Englund, Dahl, & Roos, 2007; Maffulli & Osti, 2013). The far-reaching effects of lower extremity injury have led to an increased focus on injury prevention mechanisms, and a call for more objective and cost-effective screening (E. Swart et al., 2014).

A growing body of evidence shows a connection between lower extremity injury with hip and trunk neuromuscular dysfunction (Hollman et al., 2009; Ireland, Willson, Ballantyne, & Davis, 2003; Noehren, Wilson, Miller, & Lattermann, 2013; Powers, 2010; Reiman, Bolgla, & Lorenz, 2009; Stearns & Powers, 2014). For instance, weakness and poor control of the hip muscles in patients with patellofemoral pain has been reported (Ireland et al., 2003; Noehren et al., 2013). Further, Leetun, Ireland, Willson, Ballantyne and Davis (2004) observed that athletes who sustained lower extremity injuries were more likely to have weak hip abduction and external rotation strength, and hip external rotation has been correlated with ACL injury risk (Khayambashi, Ghoddosi, Straub, & Powers, 2016). There is also evidence to suggest that poor neuromuscular control of hip and trunk affects females more than males (Ireland, 1999; Ireland et al., 2003; Leetun et al., 2004). In addition to the hip, trunk strength and poor trunk control have also been implicated as risk factors for lower extremity injury (Abt et al., 2007; Hewett & Myer, 2011; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007). These findings have led to calls for greater emphasis on core (hip and trunk) strengthening for both prevention of injury and for and rehabilitation after injury (Fredericson & Moore, 2005; Shi et al., 2012). One challenge that remains is how to identify individuals with weak hip and trunk strength who need these prevention and treatment interventions the most. Although the step-down test has been well described (Earl, Monteiro, & Snyder, 2007; Hollman et al., 2009; Lewis, Foch, Luko, Loverro, & Khuu, 2015; Olson, Chebny, Willson, Kernozek, & Straker, 2011), the relationship between single leg step-downs and core muscle function is not well established.

In fact, there have been very few investigations into the relationship between hip strength and single leg step-downs (Colby, Hintermeister, Torry, & Steadman, 1999; Olson et al., 2011; Pollard, Sigward, & Powers, 2010), and only one that examined trunk strength and single leg squats (Stickler, Finley, & Gulgin, 2015). For example, Willson, Ireland, and Davis (2006) demonstrated that females with weak hip external rotation strength had a more medial frontal plane projection angle (FPPA) during step-downs, and Olson et al. (2011) subsequently showed that the FPPA improved (along with hip strength) after a neuromuscular training program. Similarly, Dolak et al. (2011) found patients with patellofemoral pain syndrome were able to perform more step-down repetitions after a hip-strengthening program. However, none of these studies assessed any parameters of trunk muscle function related to step-down performance. In a recent study assessing single leg squats and trunk strength, only coronal plane knee kinematics were used as dependent variables. No parameters of functional performance or measures of participant activity level were assessed (Stickler et al., 2015). Furthermore, previous research has suggested that measuring coronal plane angles on the single-leg step-down may not be sensitive enough to detect lower extremity muscle dysfunction (Lewis et al., 2015).

Thus, the goal of this study was to evaluate the relationship between trunk and hip muscle function (using isometric hip strength and trunk endurance on bridging plank tests as measures of muscle function) and the maximum number of successful repetitions completed on the timed 60-s single leg step-down (SLSD) test. Secondary objectives were to compare hip strength and trunk endurance with coronal plane dynamic knee valgus during step-down, and to determine if the relationships between hip and trunk strength and SLSD differed between men and women. We hypothesized that hip and trunk muscle function would be positively correlated with the number of successful repetitions on the timed SLSD test, and that decreased hip and trunk muscle function would be correlated with increased dynamic knee valgus during performance of a step-down. We also hypothesized that these relationships would be of greater magnitude for female as compared to male participants.

2. Methods

The study protocol was approved by our university's Institutional Review Board. All participants read and signed an informed consent form prior to participation.

2.1. Participants

Seventy-three participants were recruited for this study. Study participants were recruited from a population of convenience via flyers posted on our university medical center campus, and included college students, medical and surgical residents, physical therapists, physical therapy students, and doctoral students. Two participants were excluded from final analysis due to incomplete testing, leaving a total of 71 voluntary participants. There were 33 females and 38 males, ranging from 19 to 45 years of age. All participants were healthy and met the following inclusion criteria: (1) age between 18 and 45 years, (2) currently free of any trunk, hip, or knee injuries within the last three months, and (3) no previous history of injury or surgery that may affect their trunk, hip, or knee function. In order to assess for any differences among baseline activity levels, all participants completed a Tegner Activity Scale that was indicative of their current level of physical activity.

2.2. Procedures

Peak isometric torque (adjusted for mass) was calculated using participants' femur and tibia lengths for the following muscle groups: hip extensors, hip abductors, and hip external rotators. Normalization was performed using the method described by Bazett-Jones, Cobb, Joshi, Cashin, and Earl (2011). For hip extension and hip abduction torque, the following formula was used: torque = [(isometric force in N * (femur length in cm))/mass in kg]. Hip external rotation strength was calculated as follows: torque = [(isometric force in N * (tibia length in cm))/mass in kg]. Trunk endurance was assessed using the plank and side plank tests. All test positions were based on those identified in the literature and were similar to previously described testing (Kline, Johnson, Ireland, & Noehren, 2015; Leetun et al., 2004; Loudon, Wiesner, Goist-Foley, Asjes, & Loudon, 2002; Maeo, Takahashi, Takai, & Kanehisa, 2013; Tong, Wu, & Nie, 2014).

2.3. Strength and functional testing

For the isometric hip strength tests, non-stretchable nylon straps were used to stabilize the participant, and a handheld dynamometer (Lafayette Instruments, Lafayette, IN) was used to record peak isometric force (Fig. 1). This method has been shown in previous trials to be reliable and reproducible (Katoh & Yamasaki, 2009). For each test, one practice and three experimental trials were performed for 5 s, with 15 s of rest between contractions. The dynamometer was re-zeroed between each trial. All measurements were taken on the right leg for uniformity. The average of the three experimental trials was used for calculations.

Hip abduction strength (HABD; Fig. 1A) was tested by positioning the participant in a left side lying position on a flat exam table. A strap was placed over the iliac crest for stability. The participant's pelvis was held in neutral alignment, and soft padding

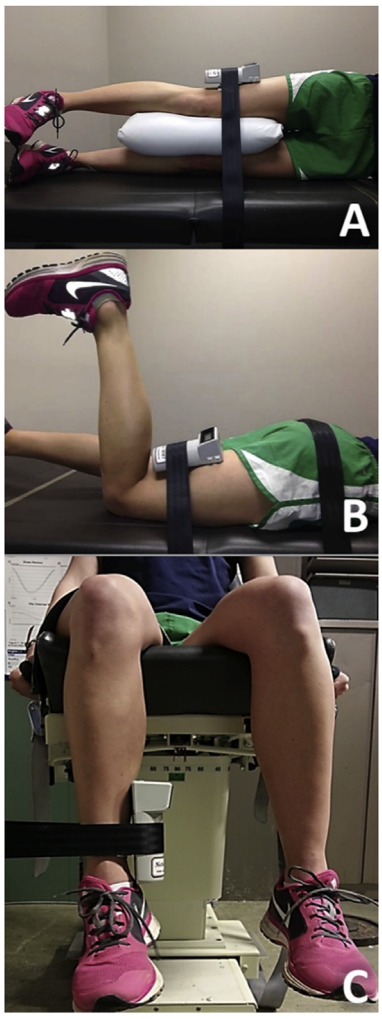

Fig. 1. Demonstration of isometric hip strength tests. Peak hip isometric hip strength was measured with a handheld dynamometer and stabilization straps. A) Hip abduction, B) Hip extension, and C) Hip external rotation.

was placed between the participant's legs such that the right hip was in neutral abduction. A mark was made 5 cm proximal to the lateral joint line of the right knee, and a dynamometer was secured over this mark with a stabilization strap.

Hip extension strength (HEXT; Fig. 1B) was tested in the prone position. The participant was placed on a padded exam table, and a strap was placed around the table and over the iliac crests. A mark was made on the posterior thigh 10 cm proximal to the lateral knee joint line. The dynamometer was placed such that the center of force was over this mark. The knee was kept in approximately 90° of flexion during testing.

Hip external rotation strength (HER; Fig. 1C) was tested with the participant in a seated position with the hips and knees flexed to 90°. A stabilization strap was placed over the thigh of the tested leg to limit the contribution of the hip adductors to force production. A mark was made 2 cm proximal to the medial malleolus on the tested leg, and the dynamometer was placed such that the center for the force was directly over this mark. A strap was placed around the leg and around the base of a stationary object during testing.

Trunk endurance was measured using timed plank and side plank bridging tests (Fig. 2). For the plank test (PL), the participant assumed a prone position supported by their forearms and feet. The participant was instructed to keep the arms in a vertical position, with the elbows directly below the shoulders, and the legs and trunk inline and in a neutral position. A wooden dowel was placed longitudinally over the dorsum of the participant during the trial period to provide proprioceptive reinforcement to proper truck and hip position. Similarly, the side plank (SPL) was used as a measure of lateral trunk muscle strength. Participants were positioned in a right side lying manner with one foot directly on top of the other. The support arm (right arm) was placed vertically such that the elbow was directly under the shoulder, and the contralateral arm was held across their chest. The correct position consisted of the hips being elevated off of the floor and the trunk and hips forming a straight line as viewed in the coronal and sagittal planes. The participant was both instructed in proper form in each position and given a chance to practice with feedback from the tester. For the experimental trial, the participant was required to hold the described plank positions for as long as possible. The participant was given one verbal correction with a chance to correct poor form if necessary. If the participant failed to correct the improper form, or returned to improper form, the timer was stopped. Otherwise, the timer was stopped when the participant was no longer able to maintain proper position or when they voluntarily ended the test due to fatigue. The participant was not allowed to know the elapsed time at any point during the test.

The Single Leg Step-Down test (SLSD) was performed similar to the method described by Loudon et al. (2002) and Kline et al. (2015). The participant was instructed to stand on a riser (17.5 cm height) with a digital scale (2.5 cm height, Ozeri ZB15, Ozeri USA, San Diego, CA) placed directly in front of the riser (Fig. 3). The distance between the top of the riser and the top of the scale was 15 cm. The starting position consisted of the participant standing with both feet facing forward. The right leg, or stance leg, was held in full knee extension, with the toes even with the front edge of the riser. The left foot was held slightly forward with the posterior aspect of the heel just in front of the riser while maintaining even height with the top of the riser. A SLSD repetition consisted of the participant flexing the stance knee, touching the scale with the left heel at less than 10 percent of their body weight, and then stepping back up such that the heel was even with the top of the riser (Fig. 3).

Performance on the test was recorded as the number of successful repetitions completed in a 60 s period. A repetition was not counted if (1) the heel did not touch the scale, (2) the participant

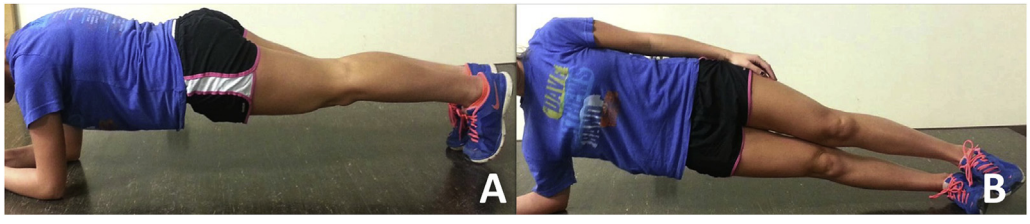

Fig. 2. Demonstration of plank tests. Performance on the plank tests is measured by the duration of time which the participant can hold proper form. The timer is stopped when the participant can no longer hold the proper form. He or she is given allowance for one verbal correction during the test. A) Plank and B) Side plank.

Fig. 3. Demonstration of the single leg step-down test. Participant starts with his stance leg (right leg in this picture) in full extension, and then steps down, touching the scale with his left heel, and returns to the original starting position. Performance on the test is measured by number of successful repetitions in 60 s. A successful repetition occurs when the participant touches his heel to the scale with less than 10% of his body weight, and then returns to the starting position with his left heel level with the top of the box.

landed with more than 10% of their total body weight registering on the scale, or (3) the participant failed to return completely to the start position. Intrarater reliability for the timed SLSD has previously been examined and found to be high with an intraclass correlation coefficient of 0.94 (Loudon et al., 2002).

2.4. 2D image data

Reflective adhesive markers were placed on each participant's anterior superior iliac spines (ASIS) and the center of the tibio-femoral joints. Prior to the start of the timed SLSD test, digital two-dimensional (2D) images were recorded with a digital camera (Olympus FE-5020, Olympus, Center Valley, PA) in both the start position and the heel-touch position (knee flexed, heel touching the scale) in the coronal plane. The participant was asked to hold each position for approximately 1 s to allow adequate image quality and consistency. The camera was stabilized on a tripod 350 cm directly in front of the step-down box and 30 cm from the ground. Two-dimensional image data was measured using open source ImageJ software (National Institutes of Health, Bethesda, MD). The baseline coronal plane knee valgus angle was calculated as the angle formed by a line going from the ASIS to the center of the tibio-femoral joint, and a line going from the center of the tibio-talar joint to the center of the tibio-femoral joint. The change in frontal plane knee valgus angle was calculated as the difference between the stance leg frontal plane knee valgus angle while the knee was fully extended, and the stance leg frontal plane knee valgus angle during the heel-touch phase of the step-down. Any frontal plane knee valgus angle greater than 180° was considered varus, and less than or equal to 180° was considered valgus. If the change in frontal plane knee valgus angle was a negative number, the stance knee moved into relative varus during heel-touch phase, and if the change in frontal plane knee valgus angle was positive, the stance knee moved into greater valgus during heel-touch. We defined this movement of the knee frontal plane knee valgus angle into relative valgus during flexion as "dynamic step-down valgus (VAL)." This measurement is similar to the FPPA reported in previous studies (Stickler et al., 2015; Willson et al., 2006).

2.5. Statistical analysis

The Statistical Package for the Social Sciences (version 22.0; SPSS, Chicago, Illinois) and Wizard (version 1.4.1; Ethan Miller, Chicago, Illinois) for Mac were used for all statistical analyses. The correlation between each strength test and performance on the SLSD test was examined using the Pearson product–moment correlation coefficients. To describe the strength of the correlation, the following scale was used for the absolute value of the correlation coefficient (r): strong relationship ($0.50 \leq r \leq 1.0$), moderate relationship ($0.3 \leq r < 0.5$), and weak relationship ($r < 0.3$) (Peat, Barton, & Elliot, 2009). Multivariate linear regression models, using variables having a p-value of ≤ 0.05 in univariate analysis, were used to identify independent predictors of SLSD performance (Fig. 4). In addition to analyzing the data on the participant group as a whole, we also performed gender-specific analysis. The level of significance for all analyses was set at $p \leq 0.05$, with $0.05 < p \leq 0.1$ considered as approaching, or showing a trend toward, statistical

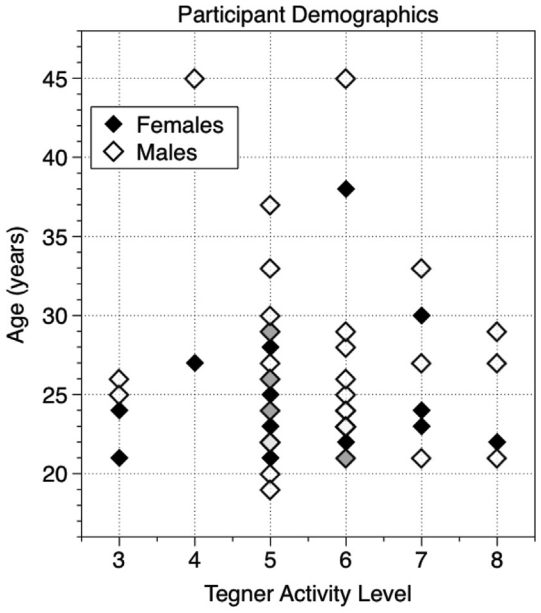

Fig. 4. Age, Tegner activity scale, and gender of participants. Age in years is shown on the *Y*-axis and self reported Tegner Activity Scale level is shown on the *X*-axis. Gender is shown by degree of shading.

significance. All data was tested for normality using the Shapiro–Wilk test.

3. Results

Seventy-one participants with a mean age of 25.49 ± 0.62 completed the functional test and strength testing (Fig. 4). Total number of step-down repetitions were normally distributed and ranged from 10 to 65 with a mean of 39.17 ± 1.46 (Table 1). Quartile data is available in Table 2. In univariate analysis of all participants, PL, SPL, HABD, HER, HEXT, and Tegner activity level all had a statistically significant positive correlation with SLSD performance (successful repetitions; Table 3). Age ($r = 0.009$, $p = 0.939$), gender ($r = 0.121$, $p = 0.313$), height ($r = 0.049$, $p = 0.683$), and weight ($r = -0.075$, $p = 0.536$) did not have a significant correlation with SLSD performance. For the male and female subsets, PL, SPL, HABD, and HER each had a statistically significant positive correlation with SLSD performance (Table 3). For the female subset, Tegner activity level had a significant positive correlation with SLSD performance, although this was not the case for males. For both the male and female subsets, HEXT was positively correlated with SLSD performance, although it did not reach statistical significance (Table 3). For the male ($r = 0.407$, $p = 0.011$) and female ($r = 0.805$, $p < 0.001$) subsets, as well the entire study population ($r = 0.598$, $p < 0.001$), PL was most positively correlated with SLSD performance (Table 3).

Multivariate linear regression analysis was then performed with those variables that had a statistically significant correlation with SLSD performance by univariate analysis ($p \leq 0.05$). These variables included Tegner activity level, PL, SPL, HABD, HER, HEXT. For the male and female subgroups, HEXT was not included in this model, and Tegner Activity Scale was not included in the male subgroup, as those variables did not meet inclusion criteria for the regression models in gender-specific analyses.

For all participants ($R^2 = 0.469$), PL ($p = 0.001$) proved to be an independent predictor of SLSD in regression analysis. HABD ($p = 0.055$) showed a trend toward predicting SLSD performance. PL was an independent predictor of SLSD performance for the female subset ($R^2 = 0.729$, $p = 0.005$) and showed a trend toward a positive association for the male subset ($R^2 = 0.317$, $p = 0.088$; Table 4).

Of the 71 total participants who completed the functional and strength tests, 69 had adequate image data to perform 2D image analysis (Table 5). Dynamic step-down knee valgus was not significantly correlated with number of SLSD repetitions, hip strength, or PL in the group as a whole. However, there was a trend toward negative correlation with PL ($r = -0.223$, $p = 0.065$) and SPL ($r = -0.235$, $p = 0.052$). In females, greater VAL had a moderate statistically significant negative correlation with PL ($r = -0.387$, $p = 0.031$) and trended toward a moderate correlation with SPL ($r = -0.335$, $p = 0.065$).

Table 1
Summary characteristics and performance of study population.

	Mean ± SEM	Standard deviation
Age in years ($n = 71$)	25.49 ± 0.62	5.23
Males ($n = 38$)	26.34 ± 0.96	5.92
Females ($n = 33$)	24.52 ± 0.73	4.19
Tegner activity scale	5.85 ± 0.13	1.06
Males	6.03 ± 0.15	0.91
Females	5.64 ± 0.20	1.19
SLSD repetitions (repetitions in 60 s)	39.17 ± 1.46	12.31
Males	40.55 ± 2.13	13.15
Females	37.58 ± 1.96	11.26
Plank time (s)	131.63 ± 8.9	74.80
Males	138.42 ± 9.3	57.46
Females	123.82 ± 15.9	91.12
Side plank time (s)	64.51 ± 3.3	28.00
Males	66.92 ± 3.7	22.83
Females	61.73 ± 5.8	33.13
Hip abduction strength (N cm/kg)	18.79 ± 0.6	4.92
Males	19.91 ± 0.8	5.18
Females	17.50 ± 0.8	4.34
Hip external rotation strength (N cm/kg)	7.02 ± 0.2	2.05
Males	7.98 ± 0.3	1.88
Females	5.92 ± 0.3	1.66
Hip extension strength (N cm/kg)	14.18 ± 0.6	4.90
Males	15.02 ± 0.9	5.26
Females	13.21 ± 0.8	4.31

Table 2
SLSD performance quartiles (in repetitions).

	Mean	Range	Standard deviation
Bottom quartile	22.75	10–27	4.796
Males	21.67	10–27	6.124
Females	24.14	22–27	1.864
2nd quartile	33.06	28–39	3.489
Males	32.20	28–39	4.438
Females	33.39	28–39	3.203
3rd quartile	44.44	40–47	2.479
Males	44.91	40–47	2.212
Females	43.71	40–47	2.870
Top quartile	53.79	48–65	4.803
Males	53.15	48–60	3.436
Females	55.17	48–65	7.167

Table 3
Factors correlated with SLSD performance via univariate analysis.

	r	R^2	p-Value	Strength of correlation
Plank***	0.598	0.358	<0.001	Strong
Males*	0.407	0.165	0.011	Strong
Females***	0.805	0.649	<0.001	Strong
Side plank***	0.479	0.230	<0.001	Moderate
Males*	0.326	0.107	0.045	Moderate
Females***	0.643	0.413	<0.001	Strong
Hip abduction***	0.446	0.199	<0.001	Moderate
Males*	0.399	0.159	0.012	Moderate
Females**	0.491	0.241	0.003	Moderate
Hip external rotation***	0.448	0.201	<0.001	Moderate
Males**	0.471	0.222	0.002	Moderate
Females*	0.422	0.178	0.014	Moderate
Hip extension*	0.303	0.092	0.010	Moderate
Males	0.269	0.072	0.103	Weak
Females[a]	0.319	0.102	0.070	Moderate
Tegner activity scale***	0.391	0.153	<0.001	Moderate
Males	0.059	0.004	0.725	Weak
Females***	0.724	0.525	<0.001	Strong

*$p \leq 0.05$, **$p < 0.01$, ***$p < 0.001$.
NS denotes no statistical significance or trend. SLSD = Single Leg Step-Down.
[a] Denotes a trend toward significance.

4. Discussion

The results of this study confirmed our primary hypothesis that both hip strength and trunk endurance are positively correlated with the maximum number of successful repetitions on the timed

Table 4
Multivariate linear regression analysis of factors influencing SLSD performance.

	Coefficient	Standard error	*p*-Value
Plank**	0.077	0.023	0.001
Males[a]	0.068	0.039	0.088
Females**	0.063	0.021	0.005
Side plank	0.041	0.053	0.440
Males	0.026	0.103	0.801
Females	0.029	0.05	0.572
Hip abduction[a]	0.700	0.359	0.055
Males	0.672	0.52	0.204
Females	0.403	0.306	0.197
Hip external rotation	0.791	0.709	0.268
Males	1.212	1.562	0.443
Females	−0.036	0.823	0.966
Hip extension	−0.051	0.317	0.873
Males	–	–	–
Females	–	–	–
Tegner activity scale	−7.01	1.394	0.617
Males	–	–	–
Females[a]	2.537	1.411	0.081

*$p \leq 0.05$, **$p < 0.01$, ***$p < 0.001$.
– Denotes that the parameter did not meet cutoff criteria to be included in the multivariate analysis. SLSD = Single Leg Step-Down.
[a] Denotes a trend toward significance.

Table 5
Correlation of 2D frontal plane dynamic knee valgus with trunk strength.

	Plank	Side plank
Dynamic knee valgus	−0.223, $p = 0.065$[b]	−0.235, $p = 0.052$[b]
Males	−0.054, $p = 0.749$	−0.148, $p = 0.377$
Females	−0.387, $p = 0.031$[a]	−0.335, $p = 0.065$[b]

Expressed as *r*-value (Pearson correlation coefficient).
NS denotes no trend or significant correlation.
[a] Denotes statistically significant correlations.
[b] Denotes a trend toward statistical significance.

60-s SLSD. Furthermore, multivariate regression analysis demonstrated that PL was an independent predictor of number of repetitions on the timed SLSD. These findings were most pronounced in the female participants. Greater plank time was associated with a greater number of step-down repetitions performed within 60 s in the female, but not male, group when assessed by multivariate regression analysis. To the authors' knowledge, no studies have compared number of repetitions on the SLSD test with trunk strength measurements. These results have a number of potential implications for injury prevention and treatment.

Our primary finding was that PL was significantly predictive of timed SLSD performance. Additionally, HABD trended towards predicting the performance of the timed SLSD. Performance on the timed SLSD test and PL both incorporate a component of muscle endurance. This may explain some of the correlation between the two tests, and it likely more accurately represents athletic activity as compared to a peak strength. This test could be utilized as a simple screening test to assess hip and trunk muscle dysfunction with minimal resources, and can easily be performed in both clinics and school training rooms. Having first established this relationship in healthy participants, future research should examine the relationship between the timed SLSD test and individuals who either have had or are at risk for an ACL tear and other lower extremity injury risk. Focusing on individuals who already have had an ACL reconstruction may be warranted as they are at a high risk for re-tear (Paterno et al., 2014), and no set return to play guidelines exist (Makhni et al., 2016; Petersen, Taheri, Forkel, & Zantop, 2014). As SLSD performance can potentially identify individuals with poor trunk strength, it may be beneficial as a component of functional evaluation prior to returning to sports in these populations.

In addition to numerous studies linking hip muscle weakness with increased injury risk (Hewett et al., 2005; Ireland, 1999), poor trunk control has been associated with increased knee abduction moments that are known to increase injury risk (Dempsey et al., 2007; Hewett et al., 2005; Jamison, Pan, & Chaudhari, 2012). Furthermore, Zazulak et al. (2007) showed a connection between poor neuromuscular trunk control and knee ligament injury risk in females, most importantly ACL tear. The results from our study corroborate previous reports and clearly demonstrate that healthy participants, especially females, with poor trunk strength perform worse on a lower extremity functional test. This suggests that lower extremity prevention and rehabilitation programs need to address trunk strength deficiencies, and this is of paramount importance in females, who are already at increased risk for ACL injury.

Our hypothesis regarding dynamic knee valgus on the SLSD test was partially supported. Trunk strength was correlated with dynamic frontal plane knee valgus, but this was statistically significant only in our female participants (Table 4). Females demonstrated an inverse correlation between trunk strength (as defined by plank time) and the amount of dynamic knee valgus that occurred during a single step-down repetition (longer plank times were correlated with less dynamic knee valgus during step down). In support of this Willson et al. (2006) found a positive correlation between trunk extension and side flexion strength with frontal plane projection angles (FPPAs) during a single leg squat with both male and female participants. In further support of our findings, Stickler et al. (2015) observed a positive correlation between side lying plank strength and FPPA during a single leg squat in an analysis of healthy female participants. These findings suggest that not only does trunk muscle function matter for functional performance in females, but that there is also a link to mechanical control of the knee in this sub population. These results suggest that future instrumented assessments of trunk muscle function during a step down test are warranted.

As opposed to previous studies, we did not observe significant associations between hip strength and dynamic knee valgus on the SLSD test. For example, Willson et al. (2006) reported that hip abduction strength and hip external rotation strength correlated with FPPA during a single leg squat. In fact, they stated that hip external rotation strength correlated more strongly than trunk strength to FPPA. Hollman et al. (2009) also reported that hip abduction strength was positively correlated with frontal plane valgus. More recently, Stickler et al. (2015) observed a significant correlation between hip abduction, hip extension, and hip external rotation strength (in addition to side plank strength) and FPPA. The most likely explanation for the differences in our results is that our testing consisted of a single leg step-down (from a height of 15 cm), while the other studies utilized a single leg squat at ground level. It has been reported that a single leg squat produces more dynamic knee valgus than a single leg step-down from a higher position (Lewis et al., 2015). Thus coronal plane FPPA during a squat, as opposed to a step-down, may be a more sensitive marker of hip weakness. Furthermore, we analyzed dynamic knee valgus during peak knee flexion, but not necessarily peak knee valgus, during the SLSD. As such, we may not have recorded maximum knee valgus magnitude in our study.

There were several design constraints associated with this study. First, we assessed individuals across a range of activity levels. Although activity level as measured by the Tegner activity scale had a significant correlation with SLSD repetitions in univariate analysis, this did not come out as a significant predictor in the regression analysis. Thus, the relationships between trunk and hip strength and step-down performance persist across all activity levels in our study. This makes the results more applicable to a heterogeneous but healthy population.

Second, the protocol used for the step-down test in this study is less commonly described than other variations of the test (Earl et al., 2007; Kline et al., 2015; Lewis et al., 2015; Loudon et al., 2002). We chose to use a 60-s time limit as opposed to 30-s described in previous studies (Loudon et al., 2002). Based on anecdotal experience alone, we believe that the 60-s test is more sensitive at identifying deficits as compared to the 30-s test. We also believe that adding the scale and maximal body-weight limit on touch-down further adds to the sensitivity and accuracy of the test. It is very difficult to perform a high number of step-downs meeting our criteria (full return to height, no more than 10% weight down) utilizing poor technique. Subjects with poor technique or trunk and hip muscle function usually have to go slower to maintain balance, and occasionally fall off the box and have to reset. As such, we believe the step-down test protocol used for this study improves upon other versions.

Third, the plank tests used in our study mostly represent the trunk endurance aspect of trunk muscle function. Our study did not specifically examine trunk strength or neuromuscular control. However, there is no ideal test described in the literature to assess trunk strength or control (Jamison et al., 2012; Zazulak, Cholewicki, & Reeves, 2008; Zazulak et al., 2007). Furthermore, it has been suggested that trunk endurance as measured by the plank tests may more accurately represent trunk muscle function in a sport setting compared to a single peak isometric strength test (Barati, Safarcherati, Aghayari, Azizi, & Abbasi, 2013), and in some cases muscle strength has been shown to highly correlate with endurance (Vaara et al., 2012).

Fourth, knee valgus as viewed in the frontal plane is not an exact representation of the varus/valgus alignment of the knee in three dimensions, and can be affected by axial rotation. As mentioned above, the measurement obtained at the bottom of the step down repetition may not represent maximum dynamic valgus. However, the image measurements in this test were well defined, have been previously described, are reproducible and reliable, and have been shown to correlate with 3D findings (Hollman et al., 2009; Olson et al., 2011; Pollard et al., 2010; Willson et al., 2006).

Finally, the current study did not directly examine the correlation between SLSD performance and injury risk, although it does potentially identify hip and trunk muscle dysfunction that has been directly related to injury risk (Dufek & Bates, 1991; Frank et al., 2013; Fukuda et al., 2003; Hewett et al., 2005; Hollman et al., 2009; Jamison et al., 2012; Khayambashi et al., 2016; Leetun et al., 2004; Olson et al., 2011; Zazulak et al., 2007).

Despite the limitations listed above, the SLSD test has many characteristics of an ideal injury prevention and return to play screening tool. The SLSD test is inexpensive, the results are quantifiable, it is easy to administer using easily obtainable equipment, and the risks are minimal. It can be administered with minimal training by coaches, physical therapists, athletic trainers, and physicians in a variety of settings, including the training room, at rehabilitation facilities, and in sports medicine outpatient clinics. As the focus on pre-injury screening tests becomes aimed at their cost-effectiveness (E.F. Swart et al., 2014), it is crucial that screening tests are effective and require minimal financial resources. Of note, the present study did not examine the utility of the 60-s SLSD test as a screening test. Future SLSD research will be needed to determine the relationship between SLSD test performance and lower extremity injury risk, and to explore its usefulness as a screening and return-to-play test.

5. Conclusion

Hip muscle weakness and poor trunk endurance are correlated with worse performance (less repetitions) on the timed single leg step-down test. Furthermore, trunk endurance was predictive of the number of successful single leg step-down repetitions, and these relationships were stronger in females than in males. Additionally, step-down repetitions were a better indicator of trunk endurance and hip strength than the degree of dynamic knee valgus as measured during maximal knee flexion. As such, the timed 60-s single leg step-down test may potentially be useful to identify individuals with hip and trunk muscle dysfunction, especially in high risk populations such as female athletes.

Conflict of interest

The authors have no conflicts of interest to disclose.

Ethical approval

This study has been approved by the University of Kentucky Office of Research Integrity and Institutional Review Board.

Location

This study was performed at the BioMotion Laboratory at the University of Kentucky.

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