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ORIGINAL RESEARCH

RELATIONSHIPS BETWEEN CORE ENDURANCE, HIP STRENGTH, AND BALANCE IN COLLEGIATE FEMALE ATHLETES

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ABSTRACT

Purpose/Background: Lower extremity injuries such as Anterior Cruciate Ligament (ACL) tears remain a concern in collegiate female athletes. Core endurance and hip strength reportedly influence ACL and lower extremity injury risk. Good neuromuscular control, as measured by the Star Excursion Balance Test (SEBT) test is associated with decreased lower extremity injuries. The exact relationships between core endurance, hip strength, and balance (SEBT scores), and how they impact one another in the female collegiate athlete remain unclear. Thus, the purpose of this study was to investigate relationships between core endurance, hip strength, and balance in collegiate female athletes.

Methods: Forty collegiate female athletes (19.6 ± 1.1yrs, 163.1 ± 7.8cm, 61.3 ± 6.5kgs) performed the SEBT in anterior, posterolateral, and posteromedial directions bilaterally (% leg length), McGill's anterior, posterior, and left and right plank core endurance tests (seconds), and hip abductor, flexor, extensor, and external rotator isometric strength tests bilaterally (N) using handheld dynamometry. Pearson's product moment correlations examined relationships between core endurance, hip strength, and balance. A linear regression analysis examined whether core endurance and hip strength influenced balance ($p \leq 0.05$).

Results: Anterior SEBT scores were fairly positively correlated with hip flexor and extensor strength. Posterolateral SEBT scores were fairly positively correlated with hip abductor, extensor, and flexor strength (p = 0.02-to-0.004; r = 0.26-to-0.45). Fair positive correlations existed between posterior core endurance and hip extensor strength bilaterally (right: $p = 0.02$, $r = 0.37$; left: $p = 0.003$, $r = 0.47$). Core endurance and SEBT scores were not correlated ($p > 0.05$). Core endurance and hip strength did not influence SEBT scores ($p = 0.47$).

Conclusions: Overall, hip strength, but not core endurance was related to SEBT scores in collegiate female athletes. Females with greater hip flexor, extensor, and abductor strength also had better anterior and posterolateral SEBT scores. Having females participate in hip muscle strengthening programs may help improve their SEBT balance scores, as a measure of their neuromuscular control and influence their ACL and lower extremity injury risk.

Level of Evidence: 2b

Keywords: Anterior Cruciate Ligament (ACL); lower extremity; Star Excursion Balance Test (SEBT); trunk endurance

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INTRODUCTION

Annually, more than 250,000 Anterior Cruciate Ligament (ACL) knee injuries occur in the United States alone. ACL injury direct surgical costs alone near 850 million dollars annually,[1] with an additional 2 billion dollars of indirect costs for post-surgical care and rehabilitation, with many long-term additional sequelae possible (e.g. early-onset knee osteoarthritis).[2] Despite clinicians implementing prevention programs,[3] ACL injury incidence rates remain high.[4] Overall, the ACL injury problem continues to be of great concern to female athletes.[5,6]

Females have a 3-8 times greater risk for ACL injury than similarly trained males.[7] Females are at greater risk for ACL injury than males due to many reasons,[7] including non-modifiable (anatomical, hormonal) and modifiable (neuromuscular) risk factors,[6,8] especially in sports that require cutting and landing motions, (e.g. lacrosse, basketball).[5,9,10] Neuromuscular control of the core[8,11] and hip musculature[12–14] plays an important role in lower extremity mechanics and may influence ACL and lower extremity injury risk.

The core plays an important role in stabilizing the lower extremity and knee movement during activity.[15–17] The core musculature includes the rectus abdominus, transversus abdominis/internal obliques, external obliques, and erector spinae.[15–19] During reaction-based tasks (e.g. running, landing) the transversus abdominis/internal obliques are key dynamic stabilizers of the spine, lumbopelvic region, and the whole trunk-pelvis segment, collectively referred to as the 'core'.[17,20–22] The rectus abdominis, external obliques, and erector spinae control trunk position relative to its base of support.[17] The transversus abdominis is the first muscle activated during lower body movements.[17] In a series of prospective studies examining the effects of core stability on lower extremity injury risk,[19,23] Zazulak et al reported that a logistic regression model that included core-specific factors including trunk displacement, low back pain history, and proprioception was able to predict knee ligament injury with 91% sensitivity and 68% specificity. Further, this model predicted knee, ligament, and ACL injury risk in female athletes with 84%, 89% and 91% accuracy, respectively. Overall, previous researchers suggest that core musculature influences lower extremity movement and injury risk during activity.

Zazulak et al noted decreased hip muscle (specifically gluteus maximus) activity in females than males during landing and suggested that it may be an important factor in the increased susceptibility of female athletes to ACL injuries.[24] Researchers have also found that individuals with greater hip abduction strength had lesser knee valgus motion during single leg squats, [12] and individuals with greater hip external rotation strength had lower vertical ground reaction forces and external knee adduction and flexor moments during landing,[14] all of which are potentially harmful to the ACL. Stearns and Powers found that when recreationally active women participated in a hip-focused training program, the participants' lower knee/hip extensor moment ratios and lower knee adductor moments were positively affected, and their lower extremity mechanics changed in a manner consistent with decreased ACL injury risk during a drop-jump task.[25]

Deficits in neuromuscular postural stability or balance tests have also been suggested to increase lower extremity injury risk.[26,27] The terms postural stability and balance are often used interchangeably but may describe different constructs. In this study, balance was operationalized as the ability to maintain postural stability (standing on one leg) while performing a reach with the other leg (reaching as far as possible with the other leg in a specified direction without losing support) as described in performance of the Star Excursion Balance Test (SEBT).[28,29] Poor SEBT performance has been noted to predict increased lower extremity injury risk on multiple sports.[27,30,31] Plisky et al[31] also found that female athletes with lower SEBT balance reach distances (less than 94% of leg length) were 6.5 times more likely to have a lower extremity injury than athletes with higher reach distances.

Overall, increased core endurance, greater hip muscle strength, and better performance on the SEBT have been reported to be associated with reduced ACL and lower extremity injury risk.[8,15,17,19,23,32] Still, the exact interrelationships among these factors remain unclear. The purpose of this study was to investigate relationships among core endurance, hip strength and balance performance on the SEBT. A secondary purpose was to determine if core endurance and hip strength influenced SEBT performance.

METHODS

Participants

Forty collegiate female athletes (19.6 ± 1.1 years, 163.1 ± 7.8 cm, 61.3 ± 6.5 kg) recruited from a universities' lacrosse and soccer teams participated in the study. Participants were excluded if they had a lower extremity injury or any neurological or musculoskeletal condition affecting their mobility or balance or were not otherwise healthy at the time of testing.

Procedures

The local Institutional Review Board approved all testing procedures. All participants signed an informed consent form prior to participation. All testing was performed in a single session in a controlled research laboratory. The same investigators measured the same tasks throughout the study. The following were the outcome measures for the study:

Star Excursion Balance Test (Lower Quarter)

Lower quarter balance was measured using the SEBT.[31] The SEBT uses a single-leg stance and requires participants to perform a maximal reach of the opposite leg along marked lines while keeping the stance leg placed stable at the center, and then return to the initial upright posture without losing balance.[28,29]

The SEBT was performed based on previously published methods.[31,33,34] Specifically, participants performed the SEBT in three reach directions: anterior ($SEBT_{ANT}$-Figure 1A), posterolateral ($SEBT_{PL}$-Figure 1B), posteromedial ($SEBT_{PM}$-Figure 1C). All participants were taught how to perform the test by the same investigator using both verbal instruction and demonstration. Participants were allowed 3 practice trials in each direction before actual test performance.

All participants performed reaches first on the right leg and then the left leg. The direction of reaches was in the following order: anterior, posteromedial, and finally posterolateral. Participants had 15-second rest intervals between each trial on the same leg and the same direction and a 1-minute rest interval between reaches in the different directions and when changing feet. So an exemplar trial order and rest period interval was as follows: right leg anterior trial 1 – 15-second rest interval – right leg anterior trial 2 – 15-second rest interval – right leg anterior trial 3 – 1-minute rest interval (switching directions); then right leg posteromedial trial 1 – 15-second rest interval – right leg posteromedial trial 2, and so on.

A trial was disregarded and repeated if: (1) the participant was unable to maintain single leg stance, (2)

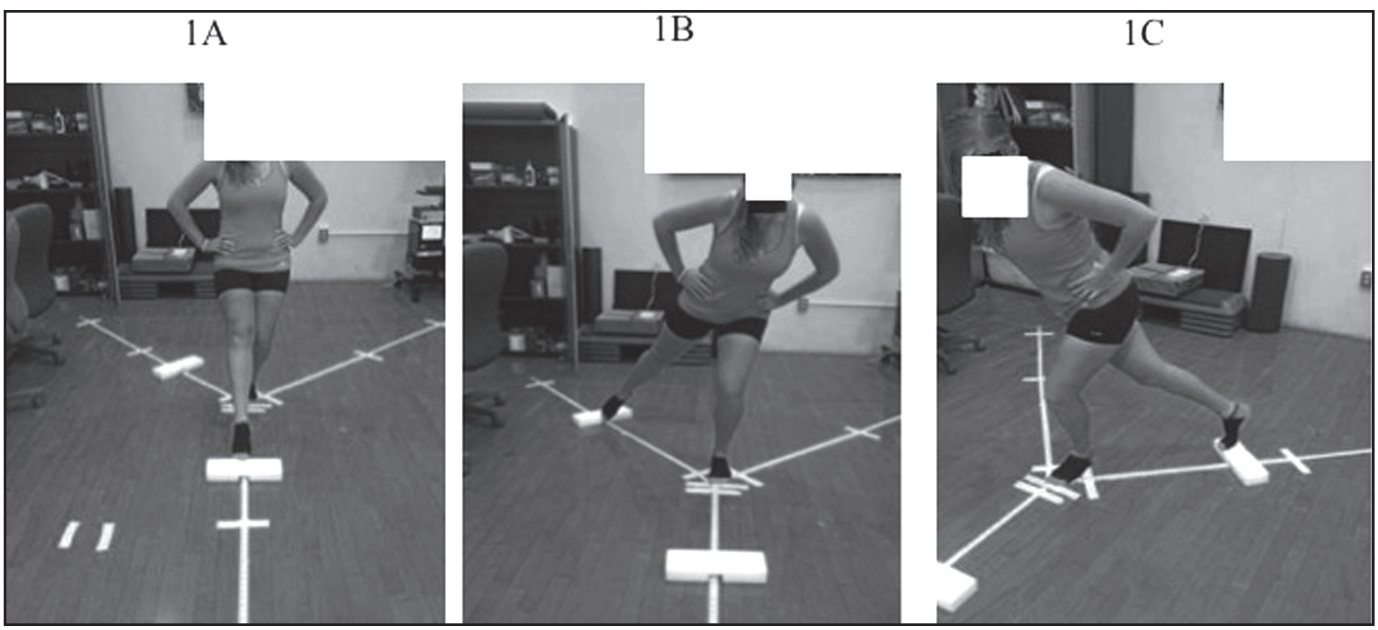

Figure 1. *Star Excursion Balance Test (SEBT) Directions; 1A – Anterior Reach Direction; 1B – Posterolateral Reach Direction; 1C – Posteromedial Reach Direction.*

the heel of the stance foot did not remain in contact with the floor, (3) weight was shifted onto reach foot, or (4) the participant did not maintain start and return positions for one full second.

Reach distances for each direction's three trials were averaged and normalized to limb length (%LL, cm) which was measured from the anterior superior iliac spine to the medial malleolus bilaterally.[29] Overall, 6 different SEBT scores were calculated: 3 directional scores on the right ($_{-R}$) leg ($SEBT_{ANT-R,}$ $SEBT_{PL-}$R, and $SEBT_{PM-R}$) and 3 directional scores on the left ($_{L}$) leg ($SEBT_{ANT-L,}$ $SEBT_{PL-}$L, and $SEBT_{PM-L}$). Finally, all of these 6 SEBT were averaged to result in a single composite SEBT score per participant ($SEBT_{COM}$).

McGill's Core Endurance Tests

McGill's tests were used to examine participants' core endurance. These tests consisted of four positions: the trunk anterior flexor test, the right and left lateral plank, and trunk posterior extensor test.[35] Participants performed one practice trial that lasted a few seconds to confirm position and then one actual test trial was recorded per position where the maximum time (seconds) participants could hold a static position was measured. The same investigator visually determined the end of all tests. This investigator verbally used the word 'start' and 'stop' to inform the participant to begin and end the test while an assistant investigator recorded the times using a stopwatch, except in the trunk posterior extensor test where the assistant held straps to stabilize the lower body and the investigator determined the start and end of the test.

For the trunk anterior flexor test, participants sat with their backs flat against a wooden wedge angled at 60° with hands across their chest and their knees both flexed to a 90-degree angle as determined by a goiniometer (Figure 2A). Time recording started when the wedge was moved back 10 cm (Figure 2B), and stopped when the trunk deviated either forward or backward from the 60° angle.

For the left lateral musculature plank test, participants' feet were placed one on top of the other, the right arm was perpendicular to the floor, elbow resting on the mat, with the left arm across the chest

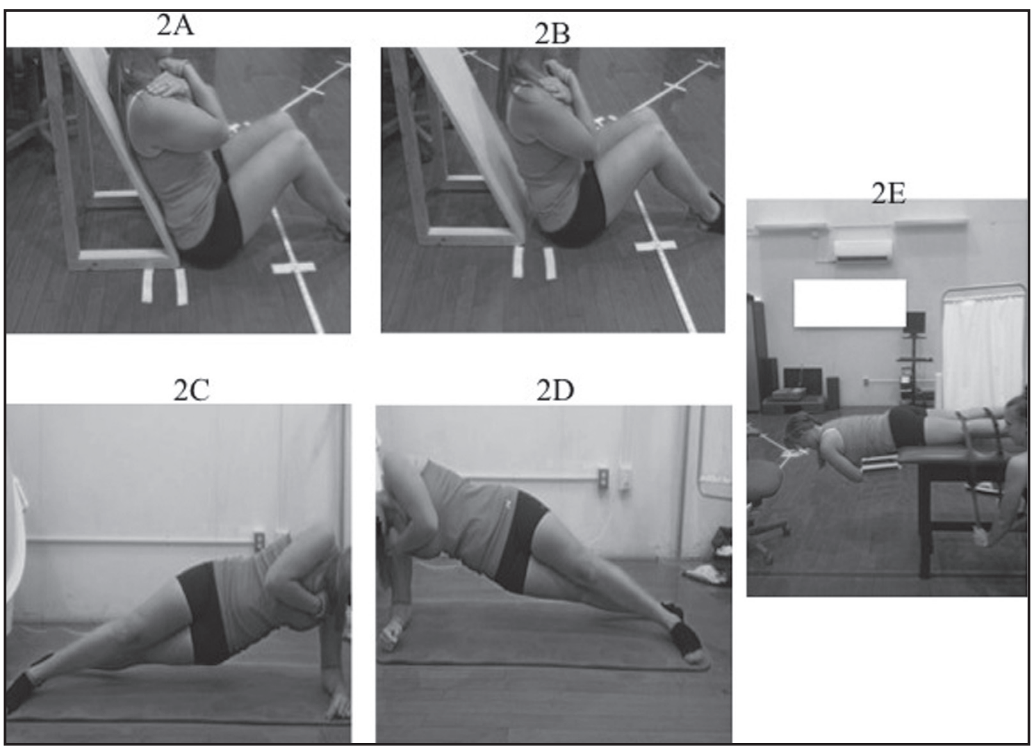

Figure 2. *McGill's Core Endurance Tests; 2A – McGill's Anterior Trunk Flexor Test, Starting Position; 2B – McGill's Anterior Trunk Flexor Test, Testing Position; 2C – McGill's Left Lateral Musculature Plank Test; 2D – McGill's Right Lateral Musculature Plank Test; 2E – McGill's Posterior Trunk Extensor Test.*

and the left hand on the right shoulder (Figure 2C). A similar position for the right lateral musculature plank test, but with the left arm perpendicular to the floor (Figure 2D). Time was stopped when the investigator visually determined that the line between the participants' trunk or lower body segments (thigh or shank) was not maintained.

For the trunk posterior extensor test, participants lay prone on an examination table with both their ASIS's on the edge of the table, their hands on the seat of a chair placed in front of them at the edge of the table. An assistant held straps above and below their knees to secure participants' lower body (Figure 2E). Time was started when participants assumed a horizontal position of the trunk, removing their hands off of the chair and crossed them across their chest, and stopped when participants were unable to remain in that position.

Isometric Hip Strength

Isometric hip strength (of the hip abductors $_{(ABD)}$, flexors $_{(FL)}$, external rotators $_{(ER)}$ and extensors $_{(EXT)}$) was measured bilaterally using a handheld dynamometer using a make test (Muscle Commander, J-Tech Medical Inc. Midvale, Utah, USA). The handheld dynamometer has been shown to be a reliable instrument for measuring isometric hip extension strength.[36–38] The same investigator gave verbal encouragement to each participant while the assistant examined the computer screen to ensure that the strength scores were being recorded by the dynamometer system. The testing protocol and positions were based on manufacturer recommendations and previously published reliable manual muscle testing positions.[37,38] All testing was performed first on the left then the right leg with a 10-second rest period after each of four trials, per manufacturer recommendations. Each testing trial was maintained for four seconds. Four trials were performed for each muscle group with the first trial being a practice trial, and the other three trial scores averaged for analyses (N).

For the hip abductors (Figure 3A), participants lay on their left or right side with their knees and hips flexed to 45° on the examination table. No other pelvic stabilization was provided. The investigator placed resistance on the lateral aspect of the distal femur as the participants tried to move their hip into abduction against the investigator's isomeric manual resistance using a make test.

For the hip flexors, participants sat on the edge of the examination table with their legs hanging and their hands holding the sides for the table (Figure 3B). The investigator placed resistance on the anterior aspect of the distal femur as the participants tried to flex their hip against the investigator's isomeric manual resistance.

For the hip external rotators, participants sat on the table with their hands holding the side and a towel between their thighs (Figure 3C). The investigator placed resistance on the medial surface of the distal tibia as the participants tried to externally rotate their hip and move their foot towards the other leg against the investigator's isomeric manual resistance.

For the hip extensors, participants lay prone with their hips off the table and feet on the ground (Figure 3D) with the test knee flexed to 90 degrees and the hip relaxed. The investigator applied resistance to the posterior mid portion of the femur as participants tried to extend their hip towards the ceiling against the investigator's isomeric manual resistance.

Statistical Analyses

Pearson's product moment correlations were used to examine relationships between core endurance tests, measures of isometric hip strength, and SEBT reaches. A linear regression analysis with core endurance and hip strength variables as predictors entered simultaneously was used to examine whether these variables predicted SEBT scores. All data were examined with the PASW 19.0 software (IBM Corp, Armonk, NY). An *apriori* alpha level of 0.05 was used for all tests. The strength of the relationships was described as detailed by Portney and Watkins, where 0.00-0.25 = little or no relationship; 0.26-0.50 = fair degree of relationship; 0.51-0.75 = moderate to good relationship, and 0.76-1.00 = good to excellent relationship.[39]

RESULTS

Balance and Hip Strength

All SEBT, McGill's and hip strength descriptive statistics (means and standard deviations) are presented in Table 1.

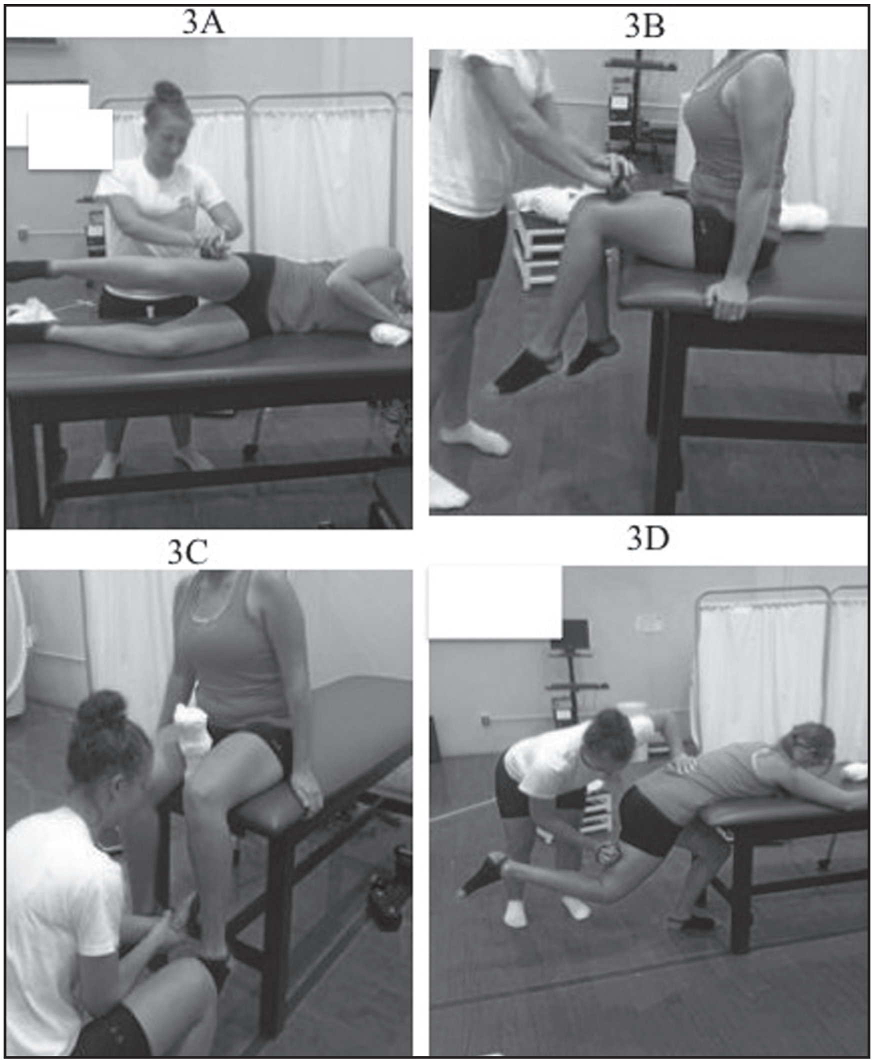

Figure 3. *Hip Muscle Strength Tests; 3A – Hip Abductors; 3B – Hip Flexors; 3C – Hip External Rotators; 3D – Hip Extensors.*

SEBT combined scores ($SEBT_{COM}$) were fairly positively correlated with H_{ABD-R} ($r = 0.34$, $p = .03$), H_{FL-L} ($r = 0.38$, $p = .02$), H_{EXT-R} ($r = 0.38$, $p = .01$), and H_{EXT-L} ($r = 0.34$, $p = .03$) (Table 2). Right anterior SEBT scores ($SEBT_{ANT-R}$) were fairly positively correlated with hip flexor and extensor strength bilaterally: H_{FL-R} ($r = 0.43$, $p = .005$), H_{FL-L} ($r = 0.44$, $p = .005$), H_{EXT-R} ($r = 0.42$, $p = .007$), and H_{EXT-L} ($r = 0.34$, $p = .03$). Left anterior SEBT scores ($SEBT_{ANT-L}$) were fairly positively correlated with hip flexors strength bilaterally: H_{FL-R} ($r = 0.36$, $p = .02$) and H_{FL-L} ($r = 0.37$, $p = .02$) (Table 2).

Right posterolateral SEBT scores ($SEBT_{PL-R}$) were fairly positively correlated with right hip abductor and extensor strength: H_{ABD-R} ($r = 0.44$, $p = .005$) and H_{EXT-R} ($r = 0.33$, $p = .004$) (Table 2). Left posterolateral SEBT reach scores ($SEBT_{PL-L}$) were fairly positively correlated with right hip abductor (H_{ABD-R}) ($r = 0.38$, $p = .02$) and left hip flexor (H_{FL-L}) ($r = 0.32$, $p = .005$) strength.

Bilateral posteromedial SEBT reach scores ($SEBT_{PM-R}$ and $SEBT_{PM-L}$) were not correlated with any of the hip strength scores (Table 2; $p \leq 0.05$).

Balance and Core Endurance

Participants' right posteromedial SEBT reach scores on the right leg ($SEBT_{PM-R}$) were fairly positively correlated with left lateral McGill's test scores ($r = .32$; $p = .04$) (Table 3). No other significant correlations were found between SEBT scores and McGill's test scores ($p \leq 0.05$) (Table 3).

Table 1. *Star Excursion Balance Test (SEBT) Scores (% leg length), McGill Test Scores (s), and Hip Strength (N) (Means + SD)*

Test	Side	Direction	M	SD
SEBT				
	Right			
		Anterior	68.69	±6.41
		Posteromedial	107.45	±10.34
		Posterolateral	106.18	±10.19
	Left			
		Anterior	68.48	±6.46
		Posteromedial	111.67	±10.32
		Posterolateral	103.06	±10.07
Overall SEBT Composite Score ($SEBT_{COM}$)			87.97	±6.49
		Trunk flexor	57.12	±37.64
McGill's Tests		Trunk extensor	71.00	±26.30
		Right lateral	36.51	±13.82
		Left lateral	36.85	±14.49
Hip Strength	Right			
		Abduction	27.23	±3.22
		Flexion	26.24	±3.50
		Extension	14.18	±2.26
		External Rotation	26.41	±4.73
	Left			
		Abduction	26.59	±3.55
		Flexion	26.27	±3.20
		Extension	13.11	±1.75
		External Rotation	26.50	±4.73

Core Endurance and Hip Strength

Participants' posterior McGill's (trunk extensor) test scores were fairly positively correlated with their hip extensor strength bilaterally H_{EXT-R} (r = .47; p = .003) and H_{EXT-L} (r = .37; p = .02) (Table 4). No other significant correlations were found between McGill's and hip strength test scores (Table 4; p≤0.05).

Regression Analyses

McGill's test and hip strength scores did not influence SEBT scores (p = .47).

DISCUSSION

The primary findings of this study include significant positive relationships between: 1) anterior balance and hip flexor and extensor strength; 2) posterolateral balance and hip abductor, extensor, and flexor strength, and 3) posterior core endurance and hip extensor strength bilaterally. Hip strength and core endurance did not influence SEBT balance scores.

Balance and Hip Strength

In this study, isometric hip abductor, flexor, external rotator, and extensor muscle strength were measured because these muscle have been shown to be active during the SEBT directional reaches.[32] While muscle activation does not directly indicate muscle strength, the two measures are associated.[29] Isometric strength measure of the flexors, extensors, and abductors demonstrated positive correlations with SEBT scores. Generally, individuals who had greater hip strength scores also had overall better SEBT scores. Previous researchers have noted that female basketball players with worse SEBT composite scores (less than 94% of their limb length) were 6.5 more times more likely to have a lower extremity injury than those with higher SEBT scores.[31] Rasool et al demonstrated that SEBT scores could improve between 11-36% after 2-4 weeks of neuromuscular balance training.[40] Hip strengthening exercises have been noted to improve sagittal plane dynamic balance (anterior reach on the Y-balance test) three

Table 2. *Pearson Correlations among Hip Abduction (ABD-R, -L), Flexion (FL-R, -L), External Rotation (ER-R, -L), and Extension (EXT-R, -L) strength (N) for the Right and Left legs and Star Excursion Balance Test (SEBT) (% Leg Length) scores in the Anterior (ANT-R, -L), Posterolateral (PL-R, -L), Posteromedial (PM-R, -L), Right Leg Combined (COM-R), Left Leg Combined (COM-L), and Both Legs Combined (COM)*

		H_{ABD-R}	H_{ABD-L}	H_{FL-R}	H_{FL-L}	H_{ER-R}	H_{ER-L}	H_{EXT-R}	H_{EXT-L}
$SEBT_{ANT-R}$	r	.21	.14	.43	.44	.22	.33	.42	.34
	p	*.21*	*.41*	*.005**	*.005**	*.18*	*.04**	*.007**	*.03**
$SEBT_{ANT-L}$	r	.20	.18	.36	.37	.24	.25	.25	.26
	p	*.23*	*.28*	*.02**	*.02**	*.15*	*.11*	*.12*	*.10*
$SEBT_{PL-R}$	r	.44	.30	.17	.30	.20	.19	.33	.27
	p	*.005**	*.07*	*.30*	*.06*	*.22*	*.24*	*.04**	*.09*
$SEBT_{PL-L}$	r	.38	.22	.20	.32	.13	.18	.26	.30
	p	*.02**	*.18*	*.22*	*.05**	*.43*	*.28*	*.10*	*.07*
$SEBT_{PM-R}$	r	.19	.03	-.04	.14	.27	.22	.31	.20
	p	*.24*	*.86*	*.79*	*.41*	*.10*	*.17*	*.05*	*.23*
$SEBT_{PM-L}$	r	.11	-.05	.01	.10	.02	.14	.29	.16
	p	*.52*	*.76*	*.95*	*.53*	*.91*	*.38*	*.07*	*.32*
$SEBT_{COM-R}$	r	.38	.27	.37	.45	.27	.31	.41	.36
	p	.02*	.10	.01*	.004*	.10	.05*	.008*	.02*
$SEBT_{COM-L}$	r	.29	.14	.21	.31	.14	.22	.33	.29
	p	.07	.41	.20	.06	.40	.16	.04*	.07
$SEBT_{COM}$	r	.34	.21	.29	.38	.20	.27	.38	.34
	p	.03*	.21	.07	.02*	.21	.09	.01*	.03*

Table 3. *Pearson Correlations among McGill's Test scores (s) in the Trunk Flexor, Trunk Extensor, Right Lateral, and Left Lateral directions for the Right (-R) and Left (-L) legs and Star Excursion Balance Test (SEBT) scores (% Leg Length) in the anterior (ANT-R, -L), posterolateral (PL-R, -L), posteromedial (PM-R, -L) directions for the right and left legs*

		McGill's Test			
		Trunk Flexor	Trunk Extensor	Right Lateral	Left Lateral
$SEBT_{ANT-R}$	r	.02	.06	-.22	-.11
	p	*.90*	*.69*	*.17*	*.49*
$SEBT_{PL-R}$	r	.17	.17	.17	.12
	p	*.29*	*.30*	*.31*	*.47*
$SEBT_{PM-R}$	r	.11	.18	.26	.32
	p	*.51*	*.28*	*.10*	*.04**
$SEBT_{ANT-L}$	r	.03	-.09	-.27	-.23
	p	*.88*	*.60*	*.09*	*.15*
$SEBT_{PL-L}$	r	.02	.20	.13	.12
	p	*.93*	*.22*	*.42*	*.45*
$SEBT_{PM-L}$	r	.18	.23	.15	.24
	p	*.27*	*.16*	*.36*	*.13*

months post ACL reconstruction as compared to traditional rehabilitation.[41] Similarly, Filipa et al found that a lower extremity strengthening and core stability program increased SEBT scores in soccer players.[34] When combined with prior work, the current findings of greater hip strength being associated with better SEBT performance are important for clinicians to consider as they can use this information to encourage female athletes to participate in hip strengthening and balance training programs.

In the anterior direction, SEBT scores were positively correlated with hip flexion strength bilaterally. This finding suggests that when the hip flexors (e.g. the quadriceps) are stronger, an individual can reach farther in the anterior direction. In support, Earl et al. found that both vastus medialis, and vastus medialis obliquus activation (both components of the quadriceps muscles) was greater in anterior

Table 4. *Pearson Correlations among Hip abduction (ABD-R, -L), flexion (FL-R, -L), external rotation (ER-R, -L), and extension (EXT-R, -L) Strength (N) for the Right and left Legs and McGill's Test (s) in the Trunk Flexor, Trunk Extensor, Right Lateral, and Left Lateral directions*

		McGill's Test			
		Trunk Flexor	**Trunk Extensor**	**Right Lateral**	**Left Lateral**
H_{ABD-R}	r	-.01	.07	.26	.16
	p	*.93*	*.69*	*.11*	*.32*
H_{FL-R}	r	-.001	.06	-.05	-.06
	p	*.99*	*.71*	*.74*	*.70*
H_{ER-R}	r	.11	-.12	.12	.08
	p	*.48*	*.45*	*.46*	*.61*
H_{EXT-R}	r	-.07	.47	.29	.20
	p	*.68*	*.003**	*.07*	*.21*
H_{ABD-L}	r	.02	.03	.21	.10
	p	*.92*	*.83*	*.19*	*.52*
H_{FL-L}	r	.10	.02	-.05	-.01
	p	*.56*	*.92*	*.78*	*.95*
H_{ER-L}	r	.17	-.16	.004	.05
	p	*.30*	*.32*	*.98*	*.75*
H_{EXT-L}	r	-.13	.37	.28	.20
	p	*.41*	*.02**	*.08*	*.23*

* Significant Correlations at $p \leq 0.05$

excursions in other SEBT directions.[32] While both these quadriceps muscle components do not cross the hip joint themselves, the authors are reasonably confident that these muscle activations reflect overall quadriceps muscle activity patterns during SEBT anterior reaches.

SEBT anterior scores were also fairly positively correlated bilaterally with hip extension strength. This finding may suggest that the hip extensors are important and required to control the pelvis and trunk during anterior reaches while maintaining balance. SEBT right anterior scores were also fairly positively correlated with left hip external rotator muscle strength but not right hip external rotator muscle strength. This observation may relate to the fair degree of the relationships i.e. as the motion in the anterior reach is primarily in the sagittal plan, the external rotators may not be as influential in this direction. Still, the lack of consistent relationships between anterior directional reaches and hip external rotator and abductor strength should be examined using muscle measurement techniques including electromyography. Overall, several SEBT scores were positively correlated with multiple hip muscle strength measures, suggesting that examining the anterior reach may provide a general measure of hip muscle strength and vice versa.

Right posterolateral SEBT reach scores were positively correlated with right leg hip abductor and extensor strength, and left posterolateral SEBT reach scores were positively correlated with right hip abductor and left hip flexor strength. These findings were not consistently observed in all muscles, and may be a reflection of the moderate 'fair' strength of the correlations between posterolateral reaches and hip strength. Still, these findings generally suggest that individuals with stronger hip abductors, flexors and extensors may be able to reach farther backwards and laterally without losing balance. Such movements are frequently performed in sports that require the individual to backpedal (e.g. basketball or lacrosse or soccer player defending the net or goals respectively). Therefore, posterolateral SEBT scores may also be a good general measure of hip muscle strength and can be used by clinicians to examine athletes' functional performance and progress during training and rehabilitation.

Interestingly, posteromedial SEBT reach scores not correlated (either lower extremity) with hip strength scores. Norris et al[42] found that hip muscle activation in the SEBT posteromedial direction was lowest as compared to the anterior and medial directions. Combining these prior reports with the current findings of no correlations of the posteromedial direction (crossing over backwards) with hip strength suggest that this motion may not be as clinically important to examine as a measure of hip and lower extremity function as compared to the other directions.

Balance and Core Endurance

Fair positive correlations existed between left lateral core endurance and right posteromedial SEBT scores but not in other directions consistently. The authors are unsure of this finding as the core should be active bilaterally during dynamic lower extremity movements Still, from the limited correlations observed, it appears that that include lateral core musculature training programs could potentially improve posteromedial direction balance.

No other correlations existed between core endurance and balance. Similarly, Gordon et al also did not find any relationships among core endurance (as measured by the Bent Knee Lowering test) and balance (as measured by the SEBT).[29] Shirley et al[43] examined core muscle activation during single leg squats and reported that participants who voluntarily activated their core musculature had improved frontal plane hip and knee kinematics than those who did not activate their core.[43] The discrepancy between these prior studies and the current findings may be due to the differing tasks. Overall, when combining prior findings with the findings of the current study, it appears that further investigations are needed to clearly determine if core musculature endurance and SEBT performance are related to each other.

Core Endurance and Hip Strength

Core extensor endurance was positively correlated with hip extensor strength. Most of the prime mover muscles for the lower extremity (e.g. the hamstrings, quadriceps, and iliopsoas muscles) attach in the similar anatomical areas as the core musculature (e.g. the ilium, ischium and pubic bones) leading clinicians to believe that the hip extensors and posterior hip muscles influence the lower back.

Inconsistent relationships existed between hip external rotation measures and lower SEBT scores. In support, Gordon et al who also measured balance using the SEBT did not find significant relationships between hip external rotation strength and these scores.[29] Gordon attributed this to muscles other than the external rotators being involved in complex construct of balance.[29] Therefore, the hip flexors, extensors, abductors, and external rotators were examined in the current study in order to try to assess additional hip muscles. While positive relationships were noted among the hip flexors, extensors, and abductors and SEBT scores, these hip muscles were only measured during an isometric motion and not during a dynamic activity. Future researchers may use dynamic hip strength tests (e.g. isotonic or isokinetic testing) to measure hip musculature and their relationship to measures of balance.

Limitations and Recommendations

The relatively small sample size and age range decreases the generalizability of this study to the general population. Still, to the authors' knowledge, this study is the first combined examination of core endurance, hip muscle strength, and SEBT balance performance as a measure of neuromuscular control in collegiate female lacrosse and soccer players. Further, although the handheld dynamometer instrument has been shown to be reliable and we used manufacturer instructions for all tests, future investigators could use more stable positioning (e.g. straps for stabilizing the investigator, straps for stabilizing pelvis during hip rotation) when performing isometric testing. In addition, while McGill's tests in four directions were used to assess the endurance of the prime movers of the core, other muscles may have contributed to McGill's test scores (e.g. shoulder muscles to support the body in planks). Thus, future researchers should consider other tests to isolate core muscles. The same test order was used for all participants. While adequate rest intervals were given to participants between repetitions of tests to mitigate the role of fatigue, whether there was a systematic order effect for the SEBT should be examined in the future. Also, in addition to the hip muscles, the knee and various other lower leg muscles are involved in balance,[32] and their roles in maintaining balance need further examination.

Clinical Implications

A couple of important clinical implications of this study are the observations that (1) hip strength is associated with SEBT performance and (2) greater hip muscle strength is related to better performance on the SEBT in multiple directions. Prior researchers note that most lower extremity muscles are activated during the SEBT,[32,42] and that a hip-focused training program can decrease ACL injury risk factors.[25] Combining these prior reports with the current observations, it appears that clinicians can use the SEBT to monitor patient progress and guide clinical decision-making if they are using hip strengthening as part of their training or rehabilitation programs.[42]

Conclusions

Overall, the study findings suggest that some hip strength measures, but not core endurance, is related to SEBT scores in collegiate female athletes. Specifically, greater hip flexor, extensor, and abductor strength were related to better anterior and posterolateral SEBT scores. Since prior work suggests that SEBT balance improves after training programs, and that better SEBT performance is associated with reduced lower extremity injury risk, clinicians should encourage female athletes to participate in hip muscle strength training programs.

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