EXAMINING THE RELATIONSHIP BETWEEN HIP STRENGTH MEASURES AND KNEE INJURY RISK FACTORS DURING SIDE-CUTTING

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Introduction

Injuries to the knee joint are prevalent throughout high school[1], collegiate[2] and professional[3] athletics. Dependent on competition levels, females are 2-2.5 times more likely to sustain an anterior cruciate ligament (ACL) injury compared to males[2-8]. This occurrence is most predominantly observed in cutting and jumping sports such as basketball or soccer[2-8]. Most ACL injury mechanisms are non-contact during deceleration, changing directions, or upon landing[4,5,7,9,10]. A key risk factor for non-contact ACL injury has been identified as excessive dynamic knee valgus consisting of detrimental amounts of hip adduction and internal rotation, tibial rotation in either direction, and knee abduction[9-14]. This may place the knee in a dangerous valgus position and stress the ACL beyond normal limits[7,11,12,14]. These positions are theorized to stem from proximal hip weakness and may have a hazardous influence on knee mechanics[14-17]. Understanding how hip strength and stability factors play a role in ACL injury and prevention is crucial. This information may offer clinicians the greatest interventional development and application in high-risk populations.

Hip strength is important regarding ACL injury prevention as the muscles surrounding the hip joint function as stabilizers, most notably during single-leg stance[18-20]. It is important to be able to quantitatively evaluate hip function and to effectively interpret measurements to assess ACL injury risk. There are different measurement tools and body positions used in research and clinical settings to evaluate hip strength. Isokinetic devices and handheld dynamometers (HHD) are common and are used in a traditional non-weight bearing (NWB) position[15,16,21,22]. The NWB methods typically consist of the patient lying on a table with the limb not in contact with the ground[15,21-24]. Previous research has found low to moderate correlations between lower extremity strength and dynamic knee valgus when utilizing the NWB methods[15,21]. It is possible

that these testing positions do not accurately reflect how muscles perform to prevent excessive dynamic knee valgus during complex, closed kinetic chain motions. Weight bearing (WB) positions have shown to be a more reliable method of strength assessment when compared to the traditional NWB methodology[18]. Utilizing a more dynamic approach when evaluating hip musculature may provide increased validity in determining the relationship between hip muscle weakness, dynamic knee valgus, and knee injury risk factors.

During cutting tasks, females have exhibited greater external hip adduction moments compared to males[9]. This may indicate that females lack hip control during dynamic sports movements. The gluteus maximus and medius muscles prevent the knee from moving into dynamic knee valgus during athletic activity[20,24]. Previous studies have assessed gluteus maximus and medius strength in a NWB position[15,21-24], which may be less appropriate as typical athletic activity is WB. During double leg squat and lunge maneuvers, both the gluteus maximus and medius play an active role in preventing dynamic knee valgus[18,24,25]. However, there is a lack of research done evaluating strength in WB positions and analyzing WB strength measurements to side-cutting biomechanics. Athletes with identifiable weakness during double leg squat and lunge maneuvers may be at a greater risk for ACL injury. Measurements obtained from WB assessments may more accurately represent dynamic muscle action and be a greater predictor for knee injury risk factors.

Studies have revealed that there are gender differences in side-cutting biomechanics, with females displaying greater dynamic knee valgus and increased risk of non-contact ACL injury[13,26,27]. Side-cutting tasks elicit tri-planar rotation on lower extremity joints and may stress the ACL to dangerous degrees[13,27]. Analyzation of side-cutting maneuvers, which place multi-

planar loads on the knee joint, may best assess excessive dynamic knee valgus[13,28,29] and more accurately predict loading on the knee that occurs during single-leg movement[30].

Clinical assessment of lower extremity hip strength to quantify dynamic knee valgus and knee injury risk factors in females is of great importance. Studying this specific population of athletes allows clinicians to better understand how muscular hip strength and biomechanics of side-cutting are related to those at higher risk of ACL injury. It is hypothesized that the novel WB strength assessment method may provide clinicians a more valuable tool in identifying ACL injury risk factors. Therefore, the purpose of this research study is to investigate the relationship between hip strength measurements and knee injury risk factors during a side-cutting maneuver in female soccer and basketball athletes ages 15-25.

Methodology

Participants

Female soccer, basketball, and volleyball athletes (age range of 12-25 years old) were recruited for the research study. Inclusion criteria included participants with the following: 1) age range of 12-25, 2) at least two years of soccer or basketball experience at the high school or collegiate level, and 3) free of any injuries. All participants completed the Physical Activity Readiness Questionnaire (PAR-Q) to screen for those who may be excluded due to recent inactivity or illness. Exclusionary criteria included meeting one of the following conditions: 1) a history of knee surgery, 2) previous ACL injury, 3) a lower extremity injury in the past six months that caused a reduction in physical activity, or 4) are, or suspect, current pregnancy. Consent forms were signed by participants over the age of 18 years old prior to participation. Assent and consent forms were signed by participants under the age of 18 and their legal guardian.

Assessment Instruments

Anthropometric data were collected utilizing a wall-mounted stadiometer (Seca Telescopic Stadiometer, Gays Mills, WI, USA) to obtain height, and a DETECTO Certifier calibrated scale (Detecto Inc., Webb City, MO, USA) for body mass. A standardized tape measure was used to determine leg and segment lengths and an anthropometer caliper (DKSH, Zurich, Switzerland) measured knee and ankle joint widths. A MicroFet2 HHD (Hoggan Health Industries Inc., West Jordan, UT) was used to assess strength (MVIC) in the NWB and WB positions.

A three-dimensional motion capture system (Vicon, Inc., Centennial, Colorado, USA) with 18 cameras and software (Vicon Nexus, Version 2.2.3) was utilized to capture dynamic motion during the side-cutting task. Kinematics were collected at 240hz and smoothed with a 10hz cutoff filter. Kinetic data were collected at 960hz via a force plate (Advanced Mechanical Technology Incorporated, Boston, Massachusetts, USA) embedded flush with the floor surface. GRFs were smoothed with a 50hz filter and external moments with a 10hz filter. Reflective markers were placed at 35 specific bony landmarks with double-sided tape. The reflective markers were placed on the following landmarks: C7, T10, inferior angle of scapula, superior notch of the sternum and xiphoid process and bilateral markers at the calcaneus, head and base of 5^{th} metatarsal, head of 2^{nd} metatarsal, head of the 1^{st} metatarsal, dorsum of the foot, lateral and medial malleoli, lateral shank, lateral and medial epicondyles of the knee, mid-thigh shank, greater trochanter, anterior superior iliac spines, posterior superior iliac spines, iliac crest and acromioclavicular joint. Speedtrap II infrared sensors (Brower Timing Systems, Draper, Utah) determined approach velocity prior to foot contact on the force plate during the side-cutting maneuver.

Procedures

The data collection consisted of a single data collection session, with an approximate length of one hour, at the University of Hawai‘i at Mānoa Human Performance Lab. Each participant completed a standardized warm-up consisting of jogging on the treadmill for 5 minutes. Hip strength was assessed via an isometric break test for both NWB and WB positions, beginning on the dominant leg first. Submaximal trials were completed to ensure correct positioning and familiarization with the assessment. A 90-second rest between trials was given to avoid fatigue. Use of adjacent muscles or deviation from the intended motion were monitored and corrected if observed. Verbal encouragement and force feedback were given to facilitate a maximal effort. The highest force value out of three successful trials were normalized to segment length and body mass and used for data analyses. Side-cutting biomechanics were assessed following strength measurements.

Non-Weight Bearing Strength Assessment

NWB strength assessments were conducted in the following order: hip external rotation (HER), hip abduction (HAB), and hip extension (HEXT). HER was tested in a side-lying, clam position. Both legs were at 45° of hip flexion and 90° of knee flexion, and the tested knee was raised up in 30° of hip abduction with both feet together. This position demonstrates the best activation of the superior gluteus maximus muscle as a hip external rotator and abductor, while minimizing the tensor fascia latae[31]. The examiner provided support to the trunk and positioned the HHD just proximal to the lateral femoral condyle with resistance implemented against the test leg for the motion of hip external rotation.

HAB was tested side-lying in 10° of abduction, the knee fully extended, and the non-tested leg in 30° of hip and knee flexion. This position elicits maximum voluntary contraction

for the gluteus medius muscle[23]. The examiner provided support to the trunk and position the HHD just above to the lateral femoral condyle with resistance implemented against the test leg for the motion of hip abduction.

HER was tested in a standing prone position in 60° of hip flexion, 30° of abduction, 20° of external rotation, and 90° of knee flexion. The non-test leg was positioned in 60° of hip flexion with the knee slightly flexed and in contact with the floor for stability. This position elicits the greatest gluteus maximus activity versus prone[32], while minimizing the muscular activity of the hamstring and lower back musculature[33-34]. The examiner positioned the HHD just proximal to the popliteal fossa on the medial aspect with resistance implemented against the test leg for the motion of hip extension.

Weight Bearing Strength Assessment

Combined WB hip abductor and external rotator strength was assessed in a double leg squat bilaterally (SqB) and in a double leg squat unilaterally (SqU) as described by Lee et al. (2013)[18]. Participants stood in 30° of hip flexion and 50° of knee flexion with neutral lumbar lordosis, feet parallel and shoulder width apart, and arms folded across their chest[18]. This position is moderately correlated (r= 0.75, $p < 0.01$) with the traditional side-lying hip abduction position but showed greater test-retest reliability (ICC= 0.99)[18] compared to Widler et al. (2009) (ICC= 0.90)[23]. Participants were instructed to hold the squat position and resist their knees from moving inward while assessing the abductors and external rotators. They were then instructed to resist their knees from displacing outwards during testing of the adductors and internal rotators.

Combined WB hip abductor and external rotator strength was also assessed in a lunge (LNG) position with the feet neutrally positioned at a distance of 60% of the participant's height and 60° of knee flexion. The non-tested leg was externally rotated 45° to provide

stability. Participants were instructed to maintain their feet shoulder width apart and arms folded across their chest. This position is based on increasing the muscular demands of the gluteus maximus muscle[25]. The examiner positioned the HHD just proximal to the lateral femoral condyle with resistance applied against the tested leg laterally from the participant's lunge.

Side-Cutting Maneuver

A side-cutting task was performed based on a simulated competition side-cutting maneuver[30]. A plastic skeleton was set up 20-centimeters behind the edge of the force plate and in the original direction of movement to simulate a live defender. The participants were told to perform their regular sidestep cut, trying to fake a static defender into going one way while cutting to the other side. The defender was static during recording and adjusted between trials to make sure the participants hit the force platform with their normal side-stepping technique. A successful trial was defined as the tested foot fully contacting the force plate, an approach velocity of 3.0-4.0 m/s with a goal of 3.5 m/s, and an approach angle of 60-65° on the y-axis of the runway. Participants started 5-meters back and 2.5-meters laterally from the force plate. Three familiarization trials were performed, followed by three trials with the participants' right leg contacting the force plate for data analyses. Kinematic variables of interest included tri-planar hip and knee excursion. Excursion was defined as the range of motion from initial contact to peak position prior to mid-stance. Excursion X, Y, and Z accounted for movement occurring in the sagittal, frontal, and transverse plane. Kinetic variables included vertical (vGRF) and braking ground reaction force (posterior GRF), as well as external hip flexion, adduction, and internal rotation moments, and knee flexion, valgus, and internal rotation moments.

Statistical Analysis

All statistical analyses were performed using SPSS Statistical software 23.0 (SPSS, Inc., Chicago, IL.) with statistical significance established at $\alpha \leq 0.05$. Means and standard deviations were calculated for the variables of interest. Pearson's correlation coefficients were used to determine the relationship between hip strength values and biomechanical variables of interest during the side-cutting maneuver. Separate multiple regression models were used to evaluate either WB or NWB strength assessment methods prediction of knee injury risk factors during side cutting. Each trio of strength assessments, (WB: SqB, SqU, and LNG; NWB: HEXT, HABD, and HER) were the predictors of biomechanical measures in regression models. Raw and scaled kinetics (e.g. normalized by body mass or body mass * height) were used in each models.

Results

The participants were divided into an adolescent (AD) group (ages 12-16) and a young adult group (ages 17-25). Participants' descriptive data is presented in Table 1. NWB and WB strength assessment measures are presented in Table 2, and side cutting biomechanics data is presented in Table 3. Table 4 describes significant regression models separated by NWB and WB strength assessments and by age group.

Table 1. Participant's Descriptive Data

Variable	Overall (n=46)				Adolescent (n=27)				Young Adults (n=17)			
	Mean ± SD	Min	Max		Mean ± SD	Min	Max		Mean ± SD	Min	Max	
Age (years old)	16.3 ± 3.6	12.0	25.0		13.8 ± 1.0	12.0	16.0		20.5 ± 2.2	17.0	25.0	
Height (m)	1.6 ± 0.1	1.5	1.8		1.6 ± 0.1	1.5	1.8		1.7 ± 0.1	1.5	1.8	
Body Mass (kg)	58.3 ± 11.9	34.8	88.0		53.0 ± 9.2	34.8	75.3		67.3 ± 10.5	49.4	88.0	
BM*HT	94.8 ± 23.3	51.3	158.4		84.6 ± 17.9	51.3	125.4		112.1 ± 21.5	74.0	158.4	

Abbreviations: BM=body mass, HT=height.

Table 2: Strength Assessment Data (N/kg)

	Overall (n=46)				Adolescent (n=27)				Young Adults (n=17)			
MMT	Mean ± SD	Min	Max		Mean ± SD	Min	Max		Mean ± SD	Min	Max	
HER	3.96 ± 0.84	2.32	5.71		3.90 ± 0.81	2.32	5.63		4.06 ± 0.90	2.67	5.71	
HEXT	3.22 ± 0.64	2.11	5.08		3.21 ± 0.57	2.34	4.46		3.23 ± 0.76	2.11	5.08	
HABD	3.77 ± 0.98	2.05	6.13		3.60 ± 0.89	2.05	5.45		4.05 ± 1.10	2.49	6.13	
SqB	6.22 ± 1.06	4.13	8.56		6.59 ± 0.98	4.74	8.56		5.59 ± 0.89	4.13	7.38	
SqU	4.15 ± 0.62	3.05	5.54		4.27 ± 0.61	3.22	5.54		3.94 ± 0.60	3.05	5.44	
LNG	2.43 ± 0.47	1.53	3.46		2.43 ± 0.45	1.65	3.43		2.43 ± 0.51	1.53	3.46	

Abbreviations: MMT=manual muscle test, HER=hip external rotation, HEXT=hip extension, HABD=hip abduction, SqB=squat bilateral, SqU=squat unilateral, LNG=lunge.

Table 3: Biomechanics Data

	Overall (n=46)			Adolescent (n=27)			Young Adults (n=17)		
Kinematics°	Mean SD	Min	Max	Mean SD	Min	Max	Mean SD	Min	Max
Hip Excursion X	2.42 ± 2.78	0.00	10.06	2.25 ± 2.56	0.00	7.88	2.72 ± 3.19	0.00	10.06
Hip Excursion Y	3.63 ± 3.69	0.00	13.05	3.45 ± 3.65	0.00	13.05	3.95 ± 3.85	0.00	10.78
Hip Excursion Z	5.10 ± 4.41	0.07	15.53	5.03 ± 5.07	0.07	15.53	5.22 ± 3.09	0.16	10.14
Knee Excursion X	30.92 ± 5.98	16.50	41.91	30.73 ± 6.34	18.25	40.38	31.23 ± 5.50	16.50	41.91
Knee Excursion Y	4.42 ± 2.03	0.41	9.90	4.23 ± 1.96	0.41	8.69	4.74 ± 2.18	0.67	9.90
Knee Excursion Z	5.72 ± 5.47	0.09	20.49	3.49 ± 3.75	0.09	15.11	9.53 ± 5.92	2.45	20.49
Kinetics									
Moments (N*m)	Mean SD	Min	Max	Mean SD	Min	Max	Mean SD	Min	Max
Hip FLX	4.80 ± 1.82	1.72	12.69	4.70 ± 2.08	1.72	12.69	4.99 ± 1.30	2.72	7.37
Hip FLX/BM*HT	0.05 ± 0.02	0.02	0.12	0.06 ± 0.02	0.02	0.12	0.05 ± 0.01	0.03	0.08
Hip ADD	2.29 ± 0.68	1.12	4.20	2.20 ± 0.68	1.12	3.81	2.44 ± 0.68	1.27	4.20
Hip ADD/BM*HT	0.03 ± 0.01	0.01	0.05	0.03 ± 0.01	0.01	0.05	0.02 ± 0.01	0.01	0.04
Hip IR	0.14 ± 0.10	0.04	0.49	0.12 ± 0.06	0.04	0.34	0.17 ± 0.14	0.06	0.49
Hip IR/BM*HT	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00	0.00 ± 0.00	0.00	0.00
Knee FLX	3.54 ± 0.56	2.53	4.80	3.42 ± 0.56	2.54	4.42	3.73 ± 0.53	2.53	4.80
Knee FLX/BM*HT	0.04 ± 0.01	0.02	0.07	0.04 ± 0.01	0.03	0.07	0.03 ± 0.01	0.02	0.05
Knee Valgus	-1.06 ± 0.43	-2.28	-0.37	-1.04 ± 0.39	-2.00	-0.45	-1.09 ± 0.51	-2.28	-0.37
Knee Valgus/BM*HT	-0.01 ± 0.01	-0.03	0.00	-0.01 ± 0.01	-0.03	-0.01	-0.01 ± 0.01	-0.02	0.00
Knee IR	0.70 ± 0.25	0.17	1.34	0.70 ± 0.23	0.26	1.34	0.71 ± 0.30	0.17	1.28
Knee IR/BM*HT	0.01 ± 0.00	0.00	0.02	0.01 ± 0.00	0.00	0.02	0.01 ± 0.00	0.00	0.01
GRF (N)	Mean SD	Min	Max	Mean SD	Min	Max	Mean SD	Min	Max
Posterior	-261.42 ± 112.15	-513.27	-109.15	-229.18 ± 99.17	-513.27	-109.15	-316.43 ± 114.29	-501.26	-184.12
Posterior/BM*HT	-2.76 ± 0.90	-4.66	-1.34	-2.69 ± 0.84	-4.66	-1.34	-2.87 ± 1.01	-4.31	-1.62
Vertical	1412.78 ± 350.20	824.25	2235.24	1272.35 ± 307.71	824.25	2193.55	1652.35 ± 287.22	1145.73	2235.24
Vertical/BM*HT	15.09 ± 2.45	11.37	21.34	15.12 ± 2.20	11.44	20.62	15.03 ± 2.90	11.37	21.34

Abbreviations: FLX=flexion, BM= body mass, HT=height, ADD=adduction, HER=hip external rotation, HEXT=hip extension, HABD=hip abduction, SqB=squat bilateral, SqU=squat unilateral, LNG=lunge, IR= internal rotation, GRF= ground reaction forces.

Table 4: Young Adults Biomechanics Data

	Overall (n=46)					Young Adults (n=17)				
Kinematics°	Mean		SD	Min	Max	Mean		SD	Min	Max
Hip Excursion X	2.42	±	2.78	0.00	10.06	2.72	±	3.19	0.00	10.06
Hip Excursion Y	3.63	±	3.69	0.00	13.05	3.95	±	3.85	0.00	10.78
Hip Excursion Z	5.10	±	4.41	0.07	15.53	5.22	±	3.09	0.16	10.14
Knee Excursion X	30.92	±	5.98	16.50	41.91	31.23	±	5.50	16.50	41.91
Knee Excursion Y	4.42	±	2.03	0.41	9.90	4.74	±	2.18	0.67	9.90
Knee Excursion Z	5.72	±	5.47	0.09	20.49	9.53	±	5.92	2.45	20.49
Kinetics										
Moments (N*m)	Mean		SD	Min	Max	Mean		SD	Min	Max
Hip FLX	4.80	±	1.82	1.72	12.69	4.99	±	1.30	2.72	7.37
Hip FLX/BM*HT	0.05	±	0.02	0.02	0.12	0.05	±	0.01	0.03	0.08
Hip ADD	2.29	±	0.68	1.12	4.20	2.44	±	0.68	1.27	4.20
Hip ADD/BM*HT	0.03	±	0.01	0.01	0.05	0.02	±	0.01	0.01	0.04
Hip IR	0.14	±	0.10	0.04	0.49	0.17	±	0.14	0.06	0.49
Hip IR/BM*HT	0.00	±	0.00	0.00	0.00	0.00	±	0.00	0.00	0.00
Knee FLX	3.54	±	0.56	2.53	4.80	3.73	±	0.53	2.53	4.80
Knee FLX/BM*HT	0.04	±	0.01	0.02	0.07	0.03	±	0.01	0.02	0.05
Knee Valgus	-1.06	±	0.43	-2.28	-0.37	-1.09	±	0.51	-2.28	-0.37
Knee Valgus/BM*HT	-0.01	±	0.01	-0.03	0.00	-0.01	±	0.01	-0.02	0.00
Knee IR	0.70	±	0.25	0.17	1.34	0.71	±	0.30	0.17	1.28
Knee IR/BM*HT	0.01	±	0.00	0.00	0.02	0.01	±	0.00	0.00	0.01
GRF (N)										
Posterior	-261.42	±	112.15	-513.27	-109.15	-316.43	±	114.29	-501.26	-184.12
Posterior/BM*HT	-2.76	±	0.90	-4.66	-1.34	-2.87	±	1.01	-4.31	-1.62
Vertical	1412.78	±	350.20	824.25	2235.24	1652.35	±	287.22	1145.73	2235.24
Vertical/BM*HT	15.09	±	2.45	11.37	21.34	15.03	±	2.90	11.37	21.34

Abbreviations: FLX=flexion, BM= body mass, HT=height, ADD=adduction, HER=hip external rotation, HEXT=hip extension, HABD=hip abduction, SqB=squat bilateral, SqU=squat unilateral, LNG=lunge, IR= internal rotation, GRF= ground reaction forces.

Non-Weight Bearing Regression Models

Knee IR moment/(BM*HT) had the highest r^2 value for the NWB regression model ($p = 0.007$, $r^2 = 0.378$) for the AD group and was predicted by HEXT ($p = 0.001$, $r = 0.529$). This was followed by frontal plane hip excursion ($p = 0.009$, $r = 0.363$) which was predicted by both HER ($p = 0.001$, $r = -0.450$) and HABD ($p = 0.026$, $r = -0.058$). Knee FLX moment/(BM*HT) ($p = 0.082$, $r^2 = 0.231$) and raw knee IR moment ($p = 0.101$, $r^2 = 0.217$) regression models were not significant. However, these models had significant predictors. Knee FLX moment/(BM*HT) was significantly predicted by HEXT ($p = 0.031$, $r = 0.247$), and raw knee IR moment was significantly predicted by HER ($p = 0.027$, $r = 0.296$).

In the YA group, 43% of sagittal plane knee excursion was described by HABD ($p = 0.029$, $r = -0.658$) and was the lone significant NWB regression model. The frontal plane hip excursion regression model was not significant ($p = 0.153$, $r^2 = 0.324$), but had significant predictors of HABD ($p = 0.027$, $r = -0.213$) and HER ($p = 0.044$, $r = 0.033$). The transverse plane knee excursion model was also not significant ($p = 0.079$, $r^2 = 0.395$), but it was significantly predicted by HER ($p = 0.031$, $r = -0.414$).

Weight Bearing Regression Models

Raw knee FLX moment was the lone significant WB regression model for the AD group ($p = 0.002$, $r^2 = 0.444$) and was predicted by SqU ($p = 0.035$, $r = -0.503$) and LNG ($p = 0.035$, $r = 0.571$). The transverse plane knee excursion ($p = 0.093$, $r^2 = 0.223$) and knee FLX moment/(BM*HT) ($p = 0.094$, $r^2 = 0.222$) models were not significant, but SqU significantly described 12% of transverse plane knee excursion ($p = 0.053$, $r = -0.340$) and SqB significantly accounted for 12% of knee FLX/(BM*HT) ($p = 0.023$, $r = 0.363$).

Raw vGRF had the highest r^2 value for the WB regression model ($p = 0.004$, $r^2 = 0.625$) for the YA group and was predicted by LNG ($p = 0.010$, $r = -0.777$). This was followed by transverse plane hip excursion ($p = 0.031$, $r^2 = 0.483$) which was predicted by the LNG strength assessment ($p = 0.060$, $r = -0.655$). The normalized vGRF model was not significant ($p = 0.058$, $r^2 = 0.427$) but was significantly predicted by SqB ($p = 0.019$, $r = 0.287$) and LNG ($p = 0.026$, $r = -0.0218$. The LNG position accounted for 32% of raw posterior GRF ($p = 0.047$, $r = 0.564$), but the overall regression model was not significant ($p = 0.069$, $r^2 = 0.410$). Posterior GRF/(BM*HT) was also not significant ($p = 0.101$, $r^2 = 0.371$) but was significantly predicted by SqB ($p = 0.040$, $r = -0.104$) and LNG ($p = 0.050$, $r = 0.337$).

Table 5: NWB and WB Strength Predictors of Side Cutting Biomechanics

NWB Models

		Regression Model			Significant Predictors		
Group	Biomechanics Variable	P	r	r^2	Assessment	P	r
AD	Hip Excursion Y	0.009	0.603	0.363	HER	0.001	-0.450
					HABD	0.026	-0.058
	Knee FLX Mom/BM*HT	0.082	0.481	0.231	HEXT	0.031	0.247
	Knee IR Mom	0.101	0.466	0.217	HER	0.027	-0.296
	Knee IR Mom/BM*HT	0.007	0.615	0.378	HEXT	0.001	0.529
YA	Hip Excursion Y	0.153	0.569	0.324	HABD	0.027	-0.213
					HER	0.044	0.033
	Knee Excursion X	0.014	0.740	0.548	HABD	0.029	-0.658
	Knee Excursion Z	0.079	0.629	0.395	HER	0.031	-0.414

WB Models

		Regression Model			Significant Predictors		
Group	Biomechanics Variable	P	r	r^2	Assessment	P	r
AD	Knee Excursion Z	0.093	0.472	0.223	SqU	0.053	-0.340
	Knee FLX Mom	0.002	0.666	0.444	SqU	0.035	-0.503
					LNG	0.035	-0.571
	Knee FLX Mom/BM*HT	0.094	0.471	0.222	SqB	0.023	0.363
YA	Hip Excursion Z	0.031	0.695	0.483	LNG	0.060	-0.655
	vGRF	0.004	0.791	0.625	LNG	0.010	-0.777
	vGRF/BM*HT	0.058	0.654	0.427	SqB	0.019	0.287
					LNG	0.026	-0.218
	Posterior GRF	0.069	0.640	0.410	LNG	0.047	0.564
	Posterior GRF/BM*HT	0.101	0.609	0.371	SqB	0.040	-0.104
					LNG	0.050	0.337

Abbreviations: NWB=non-weight bearing, WB=weigth bearing, AD=adolescence, YA=young adult, FLX=flexion, Mom=moment, BM=body mass, HT=height, IR=internal rotation, vGRF=vertical ground reaction force, GRF=ground reaction force, HER=hip external rotation, HEXT=hip extension, HABD=hip abduction, SqB=squat bilateral, SqU=squat unilateral, LNG=lunge.

Table 6: NWB Correlations Data

		Significant Correlations		
Age Group	Biomechanics Variable	Assessment	P	r
AD	Hip Excursion Y	HER	0.007	-0.450
	Knee FLX Mom/BM*HT	HEXT	0.004	0.479
	Knee Valgus Mom/BM*HT	HEXT	0.043	-0.324
	Knee IR Mom/BM*HT	HEXT	0.002	0.529
	vGRF	HEXT	0.035	-0.342
	vGRF/BM*HT	HER	0.013	0.412
YA	Hip Excursion Z	HER	0.018	-0.513
		HEXT	0.029	-0.468
		HABD	0.014	-0.532
	Hip FLX Mom	HABD	0.050	-0.412
	Hip IR Mom	HEXT	0.015	-0.526
	Hip IR Mom/BM*HT	HEXT	0.018	-0.513
	Knee Excursion X	HER	0.025	-0.480
		HEXT	0.012	-0.545
		HABD	0.002	-0.658
	Knee Excursion Z	HER	0.049	-0.414

Abbreviations: NWB=non-weight bearing, WB=weigth bearing, AD=adolescence, YA=young adult, FLX=flexion, Mom=moment, BM=body mass, HT=height, IR=internal rotation, vGRF=vertical ground reaction force, GRF=ground reaction force, HER=hip external rotation, HEXT=hip extension, HABD=hip abduction, SqB=squat bilateral, SqU=squat unilateral, LNG=lunge.

Table 7: WB Correlations Data

		Significant Correlations		
Age Group	Biomechanics Variable	Assessment	P	r
AD	Hip Excursion X	SqB	0.042	0.327
	Hip FLX Mom	SqU	0.026	-0.365
		LNG	0.014	-0.408
	Knee Excursion X	LNG	0.039	0.333
	Knee Excursion Z	SqU	0.036	-0.340
	Knee FLX Mom	SqU	0.003	-0.503
		LNG	0.001	-0.571
	Knee FLX Mom/BM*HT	SqB	0.026	0.363
YA	Hip Excursion X	LNG	0.027	-0.474
	Hip Excursion Z	SqU	0.010	-0.559
		LNG	0.002	-0.655
	Hip FLX Mom	SqB	0.005	-0.606
		LNG	0.050	-0.412
	Knee FLX Mom/BM*HT	SqB	0.017	0.515
		LNG	0.030	0.465
	Knee IR Mom/BM*HT	SqB	0.033	0.456
	vGRF	SqB	0.019	-0.507
		SqU	0.006	-0.597
		LNG	0.000	-0.777
	Posterior GRF	SqU	0.047	0.420
		LNG	0.009	0.564

Abbreviations: NWB=non-weight bearing, WB=weight bearing, AD=adolescence, YA=young adult, FLX=flexion, Mom=moment, BM=body mass, HT=height, IR=internal rotation, vGRF=vertical ground reaction force, GRF=ground reaction force, HER=hip external rotation, HEXT=hip extension, HABD=hip abduction, SqB=squat bilateral, SqU=squat unilateral, LNG=lunge.

Discussion

To our knowledge, this is the first study to analyze weight bearing and non-weight bearing strength assessments' relationship with side-cutting knee mechanics. We expected the novel weight bearing strength assessment method to be more superior than the traditional non-weight bearing method for predicting common knee injury risk factors during side-cutting. This hypothesis was partially supported by the results. The most important finding of this study was that 7/22 (32%) and 8/22 (36%) of side-cutting biomechanical variables were significantly predicted by multiple models of non-weight bearing and weight bearing hip strength assessments. Since no consistent pattern was found, neither strength assessment method nor individual sub-positions were found to be superior to the other in terms of predicting commonly reported knee injury risk factors. This may suggest that clinical strength assessment techniques should be multimodal in order to successfully examine strength relationships and dynamic movement. This study was unique, as it was the first research design to use weight bearing strength assessments to predict side-cutting biomechanics, therefore direct comparison to other studies must be taken with care.

Several notable differences are observed when comparing previous literature to the present study. Previous research differences include dynamic task, kinematic and kinetic variables, and statistical model. Studies evaluating strength and tri-planar knee movement have analyzed biomechanics during the drop vertical jump or other dynamic tasks[15,16,21,22.24,35,36]. These studies are kinematic and report results as mean or peak joint angles. The current study analyzed kinematic and kinetic variables, with kinematic variables being reported as joint excursions. Hip strength was assessed via break test for the weight bearing position to mimic what is observed during side cutting. Since joint excursions consider this loading response, this

kinematic variable was measured and reported. Previous literature involving strength and dynamic task assessment used a correlation-based model. Correlations were determined in this study; however, a regression-model was used to analyze strength as a predictor for biomechanical variables. Therefore, comparisons were made to other studies involving similar, but not identical, functional tasks and/or hip strength assessment. A study conducted by Kristianslund et al. (2013) found that knee abduction moment was 6 times higher in side-cutting than during a drop jump (1.58±0.60 Nm/kg vs. 0.25±0.16 Nm/kg)[30]. Therefore, data comparison between these two maneuvers should be done with the understanding that different forces are involved during each task.

Decreased strength in hip external rotation was a significant predictor of increased hip frontal plane excursion in the adolescent group, but not the young adults. Previously, McCurdy et al. (2014) found that weakness during a unilateral (r=-0.57) and bilateral squat (r=-0.65) significantly predicted increased hip adduction angle during single leg drop jumps[35]. Adolescents in the current study who exhibited decreased hip external rotation strength experienced increases in frontal hip excursion (r= -0.45).

Previously, the following variables were predicted by hip external rotation strength during unanticipated single leg landings and side-cutting tasks: sagittal hip excursion (r= 0.49), peak knee internal rotation moment (r = 0.42), transverse knee excursion (r= -0.56) and peak hip external rotation moment (r = -0.48)[36]. Although hip external rotation strength only predicted transverse plane knee excursion in young adults (r= -0.41), a variety of strength positions similarly predicted the significant variables previously mentioned. In both groups, weight bearing hip strength predicted sagittal plane hip excursion (AD: SqB r= 0.33 YA: LNG r= -0.41). Adolescents with greater hip extension strength (r= 0.59) and young adults with greater bilateral

squat strength (r= 0.46) displayed increased knee internal rotation moment/BW*HT. Decreased unilateral squat strength in adolescents (r= -0.34) predicted increased transverse plane knee excursion. Significant observations were not seen for peak hip external rotation moment in the current study. However, decreased hip extension strength in young adults significantly predicted increased hip IR moment/BM*HT (r= -0.51). The results of previous literature and the data collected in this study suggest that females with greater hip strength demonstrate increased dynamic control of the lower extremity during single leg landings and cutting tasks.

Knee valgus angle has been a variable of focus in knee injury risk studies[13,22,24,30,35,37,38]. Suzuki et al. (2015) found that weak hip extension (r= -0.48), hip abduction (r= -0.46), and hip external rotation (r= -0.44) strength was related to increased knee valgus at initial contact during a medial single leg drop landing[22]. McCurdy et al. (2014) found isometric hip external rotation (r= -0.58), modified single leg squat (r= -0.78), and squat (r= -0.83) weakness led to increased knee valgus during single leg drop landings[35]. Frontal plane knee kinematics were non-significant in the current study, however, body mass scaled knee valgus moment was predicted by non-weight bearing hip extension strength (r= -0.32). It is evident that hip muscle strength plays a major role in minimizing knee valgus angle experienced during functional tasks. Therefore, it may be appropriate to conclude that increasing hip strength may decrease knee injuries experienced during dynamic activities. These findings provide further support that hip strength can be analyzed to predict lower extremity mechanics.

Both strength assessment methods provide different information regarding strength and neither are considered the superior technique. A recent study, accepted ahead of print, analyzed the magnitude of difference and correlations between non-weight bearing and weight bearing strength in female athletes (n=51, 16.2±3.5 years, 161.5±8.32 cm, 58.3±11.6 kg)[39]. Isometric

strength was determined using the same methods used in the current study. Results revealed most hip torque was produced in the bilateral squat position (6.13±1.12 N/Kg). A very large magnitude of differences existed when compared to non-weight bearing positions, and positions were moderately correlated (r=0.347-0.419, R^2=0.12-0.18). The least amount of hip torque was produced in the lunge position (2.44±0.48 N/Kg) when compared the non-weight bearing positions, which had small to moderate correlations (r=0.236-0.310, R^2=0.06-0.10). McCurdy et al. (2014) found significant correlations between hip adduction and knee valgus angles during drop jump landing and both NWB isometric strength and squatting assessments[35]. The strongest correlations found between modified single leg squat and unilateral drop jumps (r= -0.81) and bilateral squat strength and bilateral drop jumps (r= -0.83). A moderate correlation (r= -0.42) was found between isometric hip abduction strength and bilateral drop jumps (r= -0.42). These studies support the hypothesis that strength information obtained in weight bearing positions differ from measurements obtained using traditional non-weight bearing assessments. Therefore, it may be important to include both methods to comprehensively analyze strength during clinical assessments.

The current study had limitations regarding the participant sample, experiment design, and testing procedure. The participants in this study utilized female soccer, basketball, or volleyball athletes ages 12-25 years old. This specific sample group may reduce the ability of these results from being generalized to other populations. Each manual muscle strength assessment was actually a break test, because the participants resisted isometrically but did not overcome the examiner's force. The examiner's force application and gender of the participant being tested may warrant different results, making recreating this study difficult[40]. Additionally, there was no way to determine specific muscle activation during each non-weight bearing

assessment since electromyography activity was not measured. However, strength assessment positions were chosen based on previously established research as outlined in the methods. Further examination of weight bearing strength assessment is warranted to better understand their clinical applications for multiple age and gender groups. Due to the limitations of skin-based markers and arrays, there is the potential for unknown amounts of error and marker movement which is associated with dynamic tasks[41]. Physical and/or mental fatigue may have had an unknown effect on the results, since it was not possible to fully randomize the strength assessments. Readers should consider all these limitations when trying to interpret or apply these tests clinically.

Differences in muscle activation have been demonstrated between weight bearing and non-weight bearing activities[42,43]. Therefore, it may not be appropriate to use only one strength assessment method to determine injury risk occurring during dynamic, functional activities. The weight bearing and non-weight bearing assessments examined in this study provide unique information regarding strength and are somewhat independent of one another. To effectively assess overall hip strength, it may be greatly beneficial to utilize all of these strength assessment methods during clinical evaluations. Incorporating a multimodal approach during lower extremity evaluations can provide clinicians with additional information regarding strength and overall lower limb function. It remains unclear which combinations of strength and functional assessments are best for clinical evaluation. However, the results of this study are valuable for clinical practice and may provide additional insight into a more reliable approach for functional assessments and determining injury risk.

Review of Literature

Background & Significance

Anterior cruciate ligament (ACL) injuries are one of the most common knee pathologies in high school[1], collegiate[2], and professional athletics[3]. Females are 2-2.5 times at a greater risk for injuring the ACL compared to males[2-8], with excessive dynamic knee valgus being a major risk factor for non-contact ACL injuries [9-14]. The gluteus maximus and medius muscles develop tension to limit hip adduction (ADD) and internal rotation (IR) during dynamic motions[14,20,24]. Weakness of these muscles may lead to increased hip ADD[15], hip IR, and knee valgus[15,16,24], increasing ACL injury susceptibility in female populations[14]. Strengthening the muscles that surround the hip enhances hip joint function during dynamic movements and results in reduced risk for ACL injury[44]. Therefore, clinical assessment of the hip muscles, and identification of those at greatest risk of injury, is essential for injury prevention.

The current strength assessments recommended include non-weight bearing (NWB)/manual muscle testing (MMT), isokinetics, and functional tests[45]. Given the importance of identifying isolated areas of weakness in the kinetic chain, MMT may be just as important as ever. However, low to moderate correlations between lower extremity NWB strength and dynamic knee valgus have been reported[15,21]. Weight bearing (WB) assessments have shown to be a more reliable strength assessment method than the NWB positions[18]. Not only is there a lack of research utilizing weight bearing (WB) methods to assess lower extremity strength, but additionally current literature has not successfully identified strength as a predictor of knee injury risk factors. Therefore, establishing a clinical strength assessment tool that predicts dynamic knee valgus is important for identifying at-risk individuals and implementing ACL prevention programs.

Side-Cutting Biomechanics

Previous studies have analyzed gender-related differences in knee joint mechanics and revealed that females have increased risk factors for ACL injury[13,26,27]. 55-85% of ACL injuries in female athletes occur during non-contact side-cutting maneuvers, where high external valgus loads are applied to the knee joint[4,5,7,9,10]. Several studies have utilized three-dimensional (3D) video analysis to assess hip and knee biomechanics during dynamic tasks[13,16,26,30,38,46-49,51]. Kristianslund et al. (2013) designed a lab study assessing the relationship between knee biomechanics during side-cutting maneuvers to ACL injury risk factors[30]. Elite female handball athletes (n= 120; age= 22.4 ± 7.1 years) participated in this study. 3D motion analysis was assessed using 8 infrared cameras (ProReflex, 240-Hz) and two force platforms (AMTI, 960-Hz). The side-cutting maneuver was designed to mimic competition, by placing a static skeleton 20-cm behind the force plate to simulate a live defender. Participants started 5-meters back and 2.5-meters laterally from the force plate. The participants were asked to perform their normal side-cutting maneuver trying to fake a static defender. A successful trial was described as the tested foot fully contacting the force plate, an approach velocity of 3.0-4.0 m/s with a goal of 3.5 m/s, and an approach angle of 60-65° on the y-axis of the runway. Three familiarization trials were performed for each task, followed by three trials recorded for each leg for data analyses. Side-cutting results revealed a mean approach speed of 3.4 m/s with a cutting angle of 69°. Results revealed a peak in knee valgus moments of 1.58 ± 0.6 Nm/kg after initial contact (IC). The following knee joint angles were recorded at IC and at maximum: flexion (FLX) of 21.0 ± 5.4° and 62.2 ± 5.1°, valgus of 4.6 ± 3.8° and 11.5 ± 4.9°, and IR of 2.0 ± 7.6° and 12.6 ± 5.2°.

Ford et al. (2005) conducted a study analyzing kinematics of unanticipated movements in young female athletes (n= 72; age= 14.3 ± 1.9 years)[50]. 3D motion analysis was utilized to

assess knee joint angles at IC and at maximum. The participants were asked to perform a forward jump-stop maneuver followed by an unanticipated side-cut to a 45° angle. The following knee joint angles were recorded at IC and maximum: FLX of 30.0 ± 1.1 and 60.0 ± 1.0 and valgus of 3.7 ± 0.9 and 19.1 ± 1.4. Sigward et al. (2006) evaluated knee kinematics, kinetics and activation patterns during a side-step maneuver (n= 15; age= 19.5 ± 1.7 years)[51]. Females ran with an approach speed of 5.7 ± 0.4 m/s. Results revealed knee FLX moments of 1.4 ± 0.7 Nm/kg and a peak knee valgus moment of 0.4 ± 0.5 Nm/kg. Landry et al. (2007) analyzed female adolescent soccer players (n= 21; age= 16.7 ± 1 years) during unanticipated side-cutting maneuvers[52]. Females performed the side-cut between 35° and 60° from the direction of travel at an approach speed of 3.5 ± 0.2 m/s. During the first 20% of stance, females experienced knee valgus moments of 0.23 ± 0.2 Nm/kg. McLean et al. (2004) observed lower extremity kinematics in NCAA Division I female basketball players (n= 10; age= 21.1 ± 3 years) during rapid direction changes[47]. The cutting maneuver was performed between 35° and 55° with an approach speed of 4.5-5.5 m/s. Joint angles were collected at IC and revealed the following: hip ADD of 10.1 ± 4.8°, hip IR of 15.3 ± 10.5°, knee valgus of 2.4 ± 3.7°, and knee IR of 2.0 ± 8.6°. McLean et al. (2005) later evaluated the association between lower extremity posture and knee valgus moments during side-cutting in this same participant sample[13]. Females exhibited a normalized (mass x height) peak knee valgus moment of 0.6 ± 0.20 $Nm/kg^{-1}m^{-1}$ and was associated with greater hip IR (r^2= 0.60) and knee valgus (r^2= 0.35) positions. Pollard et al. (2004) analyzed hip and knee mechanics in collegiate female soccer players (n=12; age= 19.3 ± 1.1 years) during a randomly cued, side-cutting maneuver[46]. Females ran with an approach speed of 5.5-6.5 m/s at a side-cutting angle was 45°. Results revealed the following peak moments experienced during the first 40° of knee FLX in stance: hip ADD of 0.98 ± 0.4 Nm/kg,

hip IR of 0.5 ± 0.2 Nm/kg, and knee valgus of 0.37 ± 0.2 Nm/kg. Peak joint angles were also recorded during the same time frame and resulted in the following: hip abduction (ABD) of 3.4 ± 5.2°, hip IR of 3.4 ± 8.5°, and knee valgus of 2.4 ± 3.5°. Pollard et al. (2007) conducted a similar study analyzing hip mechanics in female collegiate soccer athletes (n= 15; age= 19.5 ± 1.7 years)[26] who previously demonstrated knee valgus moments in a study done with Sigward et al. (2006)[51]. During the 45° side-cut maneuver, females ran with an approach speed of 5.5-6.5 m/s. Researchers observed hip IR (7.7°) and hip ADD moments (1.69 Nm/kg) upon deceleration as females initiated the change in direction. Hip IR, hip ADD, and knee valgus angles are correlated with larger knee valgus moments, which place a high degree of stress on the ACL[9-14]. These results suggest that females experience increased frontal plane excursions and moments that stress the ACL to dangerous limits during side-cutting tasks.

Imwalle et al. (2009) conducted a study observing differences in lower-extremity kinematics during a 45° and 90° side-cutting maneuvers in female soccer players (n= 19; age= 17.6 ± 2.1 years)[48]. Participants were instructed to complete the task as quickly as possible, but mean approach speed was not reported. At peak vertical ground reaction force (GRF), hip and knee IR angles were significantly greater during the 90° cut. Increased knee valgus was not associated with hip IR, but significantly correlated with increased hip ADD (r^2= 0.24). At peak force for both maneuvers, hip ADD was the sole predictor (25%) for knee valgus. Sigward et al. (2015) evaluated side-cutting tasks at 45° and 110° to further analyze side-cutting biomechanics at a greater degree (n=20 females; age 18.5 ± 2 years)[38]. Females exhibited the following during the 45° cut maneuver: knee valgus moment of 0.5 ± 0.07 N/kg-m, hip ABD angle of 2.5 ± 1.4°, and hip IR angle of 7.2 ± 1.3°. During the 110° cut, females displayed the following: knee valgus moment of 1.4 ± 0.1 N/kg-m, hip ABD angle of 17.3 ± 1.5°, and hip IR angle of 3.9 ±

1.7°. At IC for both side-cutting maneuvers, females displayed a knee valgus angle of 3.6 ± 0.6°. Vertical GRF was the largest predictor of knee valgus moment during the 45° cut, followed by lateral GRF, hip IR angle and knee valgus angle. Together these variables explained 62.9% of the variance in knee valgus moment. Posterior GRF was the largest predictor of knee valgus moment during the 110° cut, followed by hip IR angle and knee valgus angle. McLean el al. (2004) analyzed female basketball players (n=10; age= 21.1 ± 3 years) performing a change of direction maneuver to a large degree[47]. Once the players made contact with the force platform, they were asked to cut 180° from the original direction of travel. Approach speeds for all trials were 4.5-5.5 m/s. Data revealed the following joint angles measured at IC: hip ADD of 19.2 ± 5.6°, hip IR of 11.6 ± 6.9°, knee valgus of 7.3 ± 3.2°, and knee IR of 7.3 ± 15.7°. These findings suggest increased angles place larger force demands on the body to redirect movement and that this re-direction was accomplished through different lower extremity mechanics.

Strength Assessment

Studies have shown that hip weakness contributes to knee instability during single leg movements[16,22,53], with hip ABD strength being the greatest predictor of frontal plane variance[53]. It is well acknowledged in research that side-cutting biomechanics improves with hip strengthening[44,49]. A 12-year prospective study conducted by Omi et al. (2018) implemented a hip-focused injury prevention program in female collegiate basketball players (n= 757; age= 19.6 ± 1.1 years)[44]. An observation period tracked a total of 309 players for four years to collect and analyze ACL injury incidence rates. An eight-year intervention period followed the observation period to implement a hip-focused ACL injury program for the remaining 448 players. The intervention program consisted of education sessions that were given three times per season and 20-minute training sessions performed three times per week throughout the season. The training

sessions progressed through three different stages during the season that increased in difficulty. The following variables were recorded during and analyzed following the intervention period: athlete-exposures, ACL injuries, mechanisms of injury, relative risk reduction, absolute risk reduction, and numbers needed to treat. Results revealed less ACL injuries occurred during the intervention period (n= 9) compared to the observation period (n= 16). ACL injury incidence rates were lower during the intervention period (0.10/1000 athlete-exposures) than the observation period (0.25/1000 athlete-exposures). Results additionally concluded significant relative risk reduction (0.38; 95% CI, 0.17-0.87; P= 0.017), absolute risk reduction (0.032; 95% CI, 0.027-0.037), and numbers needed to treat (31.6; 95% CI, 27.1-37.7) in the intervention period compared to the observation period (Omi 2018). Therefore, with the hip-focused injury prevention program, female collegiate basketball players displayed significant decreases in non-contact ACL injuries.

A study conducted by Nagelli et al. (2018) implemented a neuromuscular training program in athletes (n= 28; 12 male and 16 female; age=17.7 ± 5.5 years) to assess biomechanical deficits and the improvements afterwards[49]. The injured group (n=18; 8 male and 10 female) was eight months post-ACL reconstructive surgery at the time of pretesting and was compared to an uninjured control group (n=10; 4 male and 6 female). 3D biomechanical analysis sessions were completed pre- and post-training and consisted of both groups performing five drop vertical jumps as described by Hewett et al. (2005)[11]. The following variables were recorded during the drop vertical jumps: hip angles (FLX and ABD), hip moments (FLX, ABD, ER), and peak GRF. The injured group completed a neuromuscular training program that consisted of twelve total training sessions, lasting one hour each session, and was implemented over a six week period. The program consisted of seven exercises that each consisted of four

levels of increasing difficulty. Exercise progression was determined by the athletes' ability to complete three full sets of ten repetitions. Data analysis focused on the effect of neuromuscular training on hip biomechanics at IC. Results found the injured group had a significant session to limb interaction ($p= 0.01$) for hip ER moment and a significant main effect of session for hip FLX angle ($p= 0.049$) and moment ($p < 0.001$). There was a significant change for the involved limb ($p= 0.04$; 528% increase) and uninvolved ($p= 0.04$; 57% decrease) limbs from pre- to post-training for hip rotation moment. The injured group also had an increase in hip FLX angle (14% change) and a decrease in hip FLX moment (65% change) from pre- to post-training. There were no significant interactions ($p > 0.05$) between the injured and control groups. There was a significant main effect of group ($p= 0.02$) for hip FLX angle, as the injured group displayed greater hip FLX angle than the control[49]. Therefore, athletes who had ACL reconstructive surgery experienced improvements in hip deficits, and biomechanical risk factors for ACL injury, following neuromuscular training.

Hip strength has most commonly been assessed in the traditional NWB position with the patient lying or sitting on a treatment table[15,21-24,53], and measured using an isokinetic dynamometer[15,18], a handheld dynamometer (HHD)[16,19,22,24], or a HHD with resistance straps[18,21,53,54]. Low to moderate correlations between lower extremity NWB strength and dynamic knee valgus have been reported[15,21], thereby questioning the reliability of NWB methods to accurately reflect muscular strength exhibited during complex movements. Therefore, it is important to establish a strength assessment method that most accurately parallels athletic activity to better identify knee valgus and predict ACL injury risk.

Lee et al. (2013) designed a study comparing NWB and WB strength methods in assessing isometric hip ABD and ER strength[18]. Participants (n= 20, 10 male and 10 female;

age= 30.3 ± 4.4 years) were tested on two separate days in both a NWB and WB position. For WB measurements, a squat (50° of knee FLX and 30° of hip FLX) was used as the testing position, where participants were instructed to push outward against the resistance strap with a uniaxial force transducer (model LCCA-1K) around the distal thigh. NWB strength was assessed using a isokinetic dynamometer (CYBEX with HUMAC NORM) with participants in a side-lying position and the axis placed at the hip joint. EMG data was recorded for the gluteus medius, gluteus maximus, and tensor fascia latae. The average peak force values from the three WB and NWB trials were used for statistical analysis. The level of agreement between methods was assessed using a linear correlation model. The average normalized EMG muscle activation level from the three trials was used for analysis. Results revealed the WB method was both reliable and consistent (ICC= 0.99%; 95% CI: 0.97, 0.99). In addition, WB strength measures were significantly correlated to the strength measurements obtained through the NWB method.

Widler et al. (2009) conducted a study comparing WB and NWB methods in measuring hip ABD strength (n= 16, 8 male and 8 female; age= 31 ± 6 years)[23]. Unilateral maximum isometric strength and bilateral EMG activity of the gluteus medius was examined in a WB (standing) and two NWB (side-lying, supine) positions. Both dominant limb and non-dominant limb strength was measured using a HHD (Lafayette Manual Muscle Test System), which was attached to the treatment table via a custom-made frame. For the side-lying position, participants laid on their side with the contralateral hip and knee flexed to 30° for stabilization. For the supine position, participants laid on their back with an abdominal belt securing them to the table for pelvic stabilization. For the standing position, participants stood next to the table with the contralateral leg against the wall for overall body stabilization. The HHD was placed proximal to the lateral femoral condyle, and isometric strength was tested at 10° of hip ABD for all testing

positions. During all trials, EMG activity for the tested hip and non-tested hip were recorded. Contralateral-to-tested EMG ratios of unilateral ABD strength (gluteus medius) were compared for all positions. Results found the highest strength measures in the side-lying position, with measures being 30% higher than the supine position ($p < 0.001$) and 10% higher than the standing position ($p < 0.05$). EMG activity was significantly lower in the side-lying position compared to both supine and standing positions. Non-normalized data revealed the highest EMG activity was during the standing position. Based on these results, there may be different muscular recruitment activity during WB that is not seen in NWB positions. Therefore, NWB strength assessments may not reliably reflect muscular activation and strength for dynamic, athletic activity.

There is contradicting experimental data regarding NWB and WB strength assessment methods. Additionally, there is little research done comparing these methods and evaluating which assessment technique better identifies knee valgus and which is a better predictor of ACL injury susceptibility. More research is needed to determine which strength assessment method more accurately reflects how muscles perform to prevent excessive dynamic knee valgus during complex motions.

Strength Assessment for Predictor of Knee Injury

During side-cutting tasks, females have exhibited greater hip ADD moments compared to males[9]. This may indicate that females lack hip control during dynamic sports movements. Leetum et al. (2004) reported females with hip ABD and ER muscle weakness had overall higher injury rates. Heinert et al. (2008) conducted a study analyzing weak hip ABD strength to lower extremity kinematics while running (n= 30; age= 24.6 ± 4.8 years)[16]. Females with weak hip ABD strength (n=15) were compared to females with strong hip ABD strength (n= 15). Results

revealed the weak hip ABD group demonstrated greater knee valgus angles throughout stance phase ($p= 0.008$). A study was conducted on collegiate female basketball players ($n= 23$; age= 19.9 ± 0.8 years) assessing the influence of hip strength on knee kinematics during a single legged drop landing[22]. A HHD was utilized to measure isometric hip ABD, ER, and extension (EXT) strength. To assess hip EXT, participants were prone on a table with knee FLX between 70°–90°. The HHD was placed 5 cm proximal to the knee joint line. Hip ABD strength was measured in a side-lying position with the hip and knee in neutral position and the non-tested hip and knee flexed to 90°. The HHD was placed 5 cm proximal to the lateral malleolus. ER strength was measured in a sitting and prone lying position. For the sitting position, participants sat on the edge of the table with the hip and knee flexed at 90°. For the prone position, the hip was in a neutral position and the knee was flexed to 90°. The HHD was placed five cm proximal to the medial malleolus for both ER positions. All strength measures were normalized to body weight. Knee kinetics were assessed during a single leg landing task that required participants to jump off a 20-cm box medially onto a force plate. Results revealed the following measures for hip strength: EXT (39.35 ± 8.13% BW), ABD (18.48 ± 4.79% BW), ER sitting (18.73 ± 3.75% BW), and ER prone (19.51 ± 4.19% BW). The results concluded knee valgus angles at IC displayed significant negative correlations with hip ABD ($\rho= -0.46$, $p= 0.03$) and prone ER strength measures ($\rho= -0.44$, $p= 0.04$). These findings suggest that hip ER and ABD strength measures influence knee motion during dynamic movements and may be a vital tool to assess ACL injury susceptibility.

Stickler et al (2015) assessed the relationship between hip strength and frontal plane alignment during a single leg squat[53]. Forty females (age= 22.9 ± 0.3 years) participated in a two-dimensional analysis of single leg squats to a depth of 60° and a hip strength assessment.

Frontal plane projection of knee angle was analyzed during five consecutive single leg squats, with the third being used for analysis. Hip strength was measured using a HHD with straps in the positions described by Willson et al. (2006) for ABD, ER, EXT and side-lying plank[55]. Isometric strength was measured for 5-second trials and was performed three times for each position. The average strength values were normalized to body weight and used for data analysis. Results concluded the following hip strength measures significantly correlated with frontal plane projection of knee valgus angle: ABD (r= 0.47, p= 0.002), ER (r= 0.46, p= 0.003), EXT (r= 0.40, p= 0.012) and side-lying plank (r= 0.43, p= 0.006). Hip ABD strength accounted for 22% of the variance in frontal plane projection angle, suggesting it to be the best overall predictor for knee valgus. Based on linear regression values, hip ER strength also accounted for 22% of the variation and hip EXT strength 16%. Therefore, knee stability is greatly impacted by proximal hip weakness and is most affected by weak hip ABD.

Hollman et al (2009) found hip ABD strength (*r*= 0.46, p= 0.22) to positively correlate with knee valgus in frontal plane projection angle in females (n= 20; age= 24.0 ± 2.6 years)[24]. Participants were asked to perform a single leg step down to assess two-dimensional frontal plane projection angles of the hip and knee. The frontal plane projection angle of hip ADD/ABD was defined as the angle created from two imaginary lines: 1) from the anterior superior iliac spines (ASIS) bilaterally and 2) connecting the ASIS of the test limb to the midpoint of the tibiofemoral joint. The frontal plane projection angle of knee valgus/varus was defined as the angle created from two imaginary lines: 1) from ASIS to the midpoint of the tibiofemoral joint and 2) connecting the midpoint of the tibiofemoral joint to the talocrural joint. The single leg step down was performed on a 15-cm step on the dominant leg. Participants were instructed to maintain a single leg stance then perform the step down over 2 seconds, gently making floor

contact with the contralateral heel, and ascend to the starting position. Maximum isometric hip strength was assessed with a HHD (MicroFET 2) in a standard manual muscle testing described by Hislop et al. (2002) for hip ABD and ER[56]. Examiners recorded peak force for data analysis.

Sigward et al. (2008) did not find any correlation between NWB hip strength and frontal plane excursion in female high school soccer players (n= 39; age= 15.5 ± 1.0 years)[21]. Hip rotation and ankle dorsiflexion was obtained to assess range of motion and three isometric hip strength measurements were measured with a HHD (MicroFET2 Muscle Tester). To assess hip EXT strength, participants were prone with the hip flexed to 45° off the treatment table, the knee flexed to 90° and the upper torso resting on a table[21]. The HHD was secured by a strap over the posterior thigh proximal to the popliteal crease. Hip ABD strength was measured side-lying, with the tested limb in 20° of hip ABD, 5° of EXT, and slight ER[21]. The non-tested hip and knee were comfortably flexed for stability, and the HHD was secured with a strap over the lateral femoral condyle. Hip ER strength was measured in a sitting position with the knee flexed to 90° and the hip in neutral rotation[21]. The HHD was placed over the distal, medial tibia and secured with a strap. Hip ADD during assessment was prevented by the examiner. The highest value of three trials were used for statistical analysis. All isometric force data was converted into torque and normalized by body mass. Frontal plane knee excursion was analyzed during a drop land task via a 3D motion capturing system (Vicon; Oxford Metrics LTD), and GRF was obtained from two force plates at 2400 Hz (OR6-6-1, Advanced Mechanical Technology). Frontal plane knee excursion was defined as the difference between the distance of the right and left lateral knee markers measured at initial contact and the minimum distance between these markers measured during the deceleration phase of the landing.

Willson et al. (2006) conducted a two-dimensional analysis assessing core and hip strength and lower extremity alignment[55]. Female collegiate basketball, soccer and volleyball athletes (n= 22; age= 19.9 ± 2.3 years) were instructed to perform a single leg squat for analysis of knee frontal plane projection angle. For the single leg squat, participants stood in front of an adjustable stool that represented the descent distance needed to achieve 45° of knee FLX. Frontal plane projection angle was assessed by marking participants to create an imaginary straight line from ASIS to midpoint of the tibiofemoral joint and midpoint of the tibiofemoral joint to midpoint of the ankle mortise. A HHD stabilized with a strap was utilized to obtain peak isometric torque for the following muscle groups: trunk EXT, trunk FLX, trunk lateral FLX, hip ABD, hip ER, knee FLX and knee EXT. A total of three strength trials were used for analysis. Results revealed a statistically significant relationship (r= 0.40, p= 0.004) between hip ER strength and frontal plane projection angle. Hip ABD strength had no significant correlation with frontal plane projection angle (r= 0.23, p= 0.07).

A study conducted by Jacobs et al. (2007) assessed single leg landing kinematic and hip ABD function[15]. Fifteen healthy females (age= 23.2 ± 2.9 years) were instructed to perform a two-legged jump and land on a single leg in a target area located on the floor. Jump length and height was controlled to 40% and 15% of the participants' height respectively. Hip strength values were obtained using a dynamometer (Primus) to measure isometric peak torque for hip ABD. Peak torque values were normalized by participant height and weight. The results concluded no significant correlation between peak hip ABD torque and peak knee valgus (r= -0.35, $p < 0.05$) during the single leg landing task.

There are currently inconsistent conclusions regarding hip strength as a predictor of knee injury. The variety in methodology of hip strength assessment and knee kinematic assessment

makes it difficult to definitively compare correlation results. Clinicians and researchers should aim to understand the role hip strength plays in preventing dangerous knee valgus positions during single leg tasks. Therefore, future investigations should aim to analyze dynamic knee valgus during side-cutting movements in combination with hip ABD and ER strength measures to better predict knee injury risk factors and identify potential ‘‘high-risk’’ females.

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