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Relationships Between Knee Valgus, Hip-Muscle Strength, and Hip-Muscle Recruitment During a Single-Limb Step-Down

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Context: Reduced strength and activation of hip muscles might correlate with increased weight-bearing knee valgus. ***Objective:*** To describe relationships among frontal-plane hip and knee angles, hip-muscle strength, and electromyographic (EMG) recruitment in women during a step-down. ***Design:*** Exploratory study. ***Setting:*** Laboratory. ***Participants:*** 20 healthy women 20 to 30 years of age. ***Interventions:*** Frontal-plane hip and knee angles were measured. Gluteus maximus and medius recruitment were examined with surface EMG. Hip-abduction and -external-rotation strength were quantified with handheld dynamometry. ***Main Outcome Measurements:*** The authors analyzed correlation coefficients between knee and hip angles, gluteus maximus and medius EMG, and hip-abduction and -external-rotation strength. ***Results:*** Hip-adduction angles ($r = .755$, $P = .001$), gluteus maximus EMG ($r = -.451$, $P = .026$), and hip-abduction strength ($r = .455$, $P = .022$) correlated with frontal-plane projections of knee valgus. ***Conclusions:*** Gluteus maximus recruitment might have greater association with reduced knee valgus in women than does external-rotation strength during step-down tasks. Gluteus medius strength might be associated with increased knee valgus. ***Keywords:*** biomechanics, electromyography, medial collapse

Understanding lower extremity (LE) mechanics is important. Pathomechanical coupling between segments might influence the etiology of anterior cruciate ligament (ACL) injury,[1] patellofemoral pain syndrome,[2–4] iliotibial band syndrome,[5] and other disorders.[6] Insufficient muscular control of frontal- or transverse-plane hip motion during single-limb weight bearing, for example, might be associated with excessive femoral adduction and internal rotation leading to knee valgus, tibial internal rotation, and excessive foot pronation (Figure 1), a series of postural malalignments described as medial collapse.[7] The increased knee valgus characterizing medial collapse might be associated with knee injuries.[8,9]

The relationship between hip-muscle function and knee valgus might be particularly important. The gluteus maximus (GMax) extends and externally rotates

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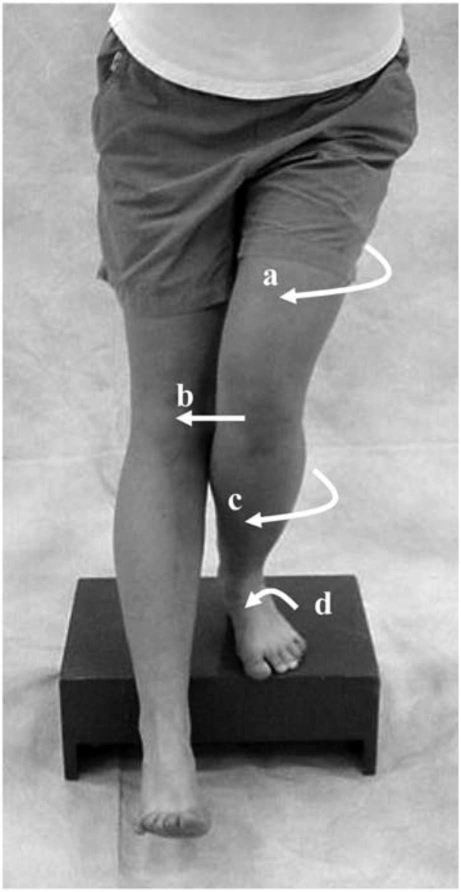

Figure 1 — Example of medial collapse of the lower extremity during single-limb weight bearing. Medial collapse is characterized by (a) adduction and/or internal rotation of the femur, (b) valgus at the knee, (c) internal rotation of the tibia, and (d) pronation of the foot.

the hip and assists hip abduction, and the gluteus medius (GMed) abducts the hip and assists internal rotation. When recruited at appropriate levels to meet external moment demands during weight-bearing activities, the muscles contract to maintain alignment between the femur and pelvis in the sagittal, frontal, and transverse planes. Variations in the magnitude of electromyographic (EMG) recruitment in hip muscles, such as differences in EMG recruitment reported between men and women,[10–12] might therefore account for variations in LE mechanics. Zazulak et al,[12] for example, reported that GMax EMG recruitment is lower in women than men after single-limb jump landings. Although kinematics were not examined, when considered within the context of multiple studies[13–18] reporting gender differences in hip and knee alignment, insufficient GMax recruitment might be associated with excessive knee valgus in women. Zeller et al,[17] for example, postulated that increased knee valgus in women during single-leg squats might occur because of decreased neuromuscular control in the hip muscles.

Reduced hip-abduction and -external-rotation strength might also be associated with increased knee valgus. Willson et al,[16] studying single-leg squats in athletes, reported that reduced hip-external-rotation strength was correlated with increased knee valgus. Ireland et al[2] reported that women with patellofemoral pain had reduced hip-abduction and -external-rotation strength compared with age-matched healthy subjects. Niemuth et al[19] reported that runners with overuse injuries had reduced hip-abduction strength compared with uninjured limbs and with healthy subjects. Although neither study[2,19] examined LE alignment specifically, the authors postulated that insufficient hip strength might have resulted in abnormal mechanics leading to LE injury. Despite limitations of the aforementioned studies, they collectively suggest that reduced hip-muscle strength might be associated with LE malalignments, particularly knee valgus, and with knee injury.

Whether neuromuscular recruitment of hip muscles, hip-muscle strength, or both are responsible for maintaining optimal hip and knee alignment during single-limb support warrants further investigation. The purpose of this study, therefore, was to measure relationships between frontal-plane knee alignment, hip alignment, hip-muscle strength, and hip-muscle EMG recruitment during single-limb weight bearing in healthy women. We hypothesized that hip adduction would correlate with knee valgus during a single-leg step-down and that GMax and GMed EMG recruitment and hip-abduction and -external-rotation strength would correlate negatively with knee valgus. Information gained from studying these relationships might provide clinicians with a better understanding of mechanisms associated with knee valgus. Secondarily, we compared knee-valgus and hip-adduction alignment, and GMax and GMed EMG recruitment, between single-leg stance and the step-down to quantify the magnitudes of change in the variables that occurred during the maneuver.

Methods

Participants

Twenty women age 20 to 30 years participated in the study (mean age = 24.0 ± 2.6 years, height = 169.1 ± 9.4 cm, mass = 66.4 ± 9.2 kg). The study was conservatively powered to detect correlation coefficients of .50 or greater at $\alpha = .05$ while protecting against type II error with a statistical power of .70. Eligible participants included healthy, active women age 18 to 35 who could ambulate independently in the community and ascend and descend a flight of stairs without assistive devices. Women with musculoskeletal, neuromuscular, cardiopulmonary, or integumentary pathology that impaired motor function and those with antalgic gait because of LE injury were excluded. Although we did not exclude subjects with a past history of LE injury, all subjects were symptom free at the time of testing. The Mayo Foundation Institutional Review Board approved the study. All participants provided informed consent.

Instrumentation

Muscle strength was quantified with a MicroFET 2 handheld dynamometer (Hoggan Health Industries, Inc, West Jordan, UT). Kinematics were measured with Motion Analysis Tools DX9–Shareware version 2.6 software (The Rehabilitation Centre, Ottawa, Ontario, Canada) with video captured by a 30-Hz Sony DCR-HC65 digital camcorder (Sony Corp of America, New York, NY). EMG was sampled at 1000 Hz with D-100 bipolar Ag-AgCl surface electrodes and a model 544 multichannel EMG system (Therapeutics Unlimited, Inc, Iowa City, IA). The interelectrode distance was 22 mm and the electrodes were encased in preamplifier assemblies with a gain of 35. The main amplifier permitted a gain of 1000 to 100,000, and its bandwidth frequency was 20 to 4000 Hz. The common-mode rejection ratio was 87 dB at 60 Hz, and input impedance exceeded 15 MΩ at 100 Hz. EMG signals were processed with WinDaq data-acquisition software (DATAQ Instruments, Inc, Akron, OH).

Procedures

Muscle Strength. Muscle strength was operationally defined as maximum isometric force-production capability. Tests of hip-abduction and -external-rotation strength were conducted in standard positions described by Hislop and Montgomery.[20] Specifically, hip-abduction strength was tested with the subject in a side-lying position. With the limb in slight extension, the subject abducted the limb approximately 30°. The examiner stabilized the pelvis with one hand and applied medially directed resistance with the handheld dynamometer in the other hand just proximal to the greater trochanter of the femur. Hip-external-rotation strength was tested with the subject in a seated position. With the hip and knee in flexion, the subject externally rotated the femur approximately 30°. The examiner stabilized the thigh with one hand and applied resistance with the handheld dynamometer in the other hand just proximal to the medial malleolus. Examiners recorded peak force obtained with the handheld dynamometer during a 5-second manually resisted contraction. Force values were normalized to body weight (BW).

Intrarater reliability of strength testing was assessed with the model 3, form 1, intraclass correlation coefficient ($ICC_{3,1}$).[21] The examiner was blinded to results and repeated each test within a single session, while a second examiner recorded data from the dynamometer. Two minutes were allotted for recovery between tests. Data from all subjects were included in the analysis. The reliability coefficient for hip abduction was .934 (95% CI = .878–.964) with a standard error of measurement (SEM) of 1.9% BW and for external rotation was .951 (95% CI = .909–.974) with an SEM of 1.8% BW.

Joint Alignment. Two-dimensional (2D) frontal-plane projection angles of hip and knee alignment (Figure 2) were measured during a single-leg step-down performed from a 15-cm step. A digital video camera was placed at the height of the subject's knee, 3 m anterior to the subject, and aligned perpendicular to the frontal plane. The frontal-plane projection angle of hip adduction/abduction was defined as the angle subtended by one line connecting the anterior superior iliac spines (ASISs) bilaterally and a second line connecting the ASIS of the test limb with the midpoint of the tibiofemoral joint (Figure 2[a]). The frontal-plane projection angle of knee valgus/varus was defined as the angle subtended by a line connecting the ASIS with the midpoint of the tibiofemoral joint and a second line connecting the midpoint of the tibiofemoral joint and the talocrural joint (Figure 2[b]). To facilitate digitization of bony landmarks with the motion-analysis software, 2.54-cm-diameter markers were placed on subjects' ASISs bilaterally (Figure 2). Similar to methods employed by Willson et al,[16] the midpoints of the tibiofemoral and talocrural joints were estimated visually and digitized manually.

Subjects' preferred kicking limbs were tested. Subjects maintained a position of single-leg stance for a 2-second duration and then performed the step-down over 2 seconds, gently made floor contact with the heel of the contralateral foot, and ascended to the starting position. Subjects were allowed to practice the task until they completed it consistently at the desired rate. During practice movements,

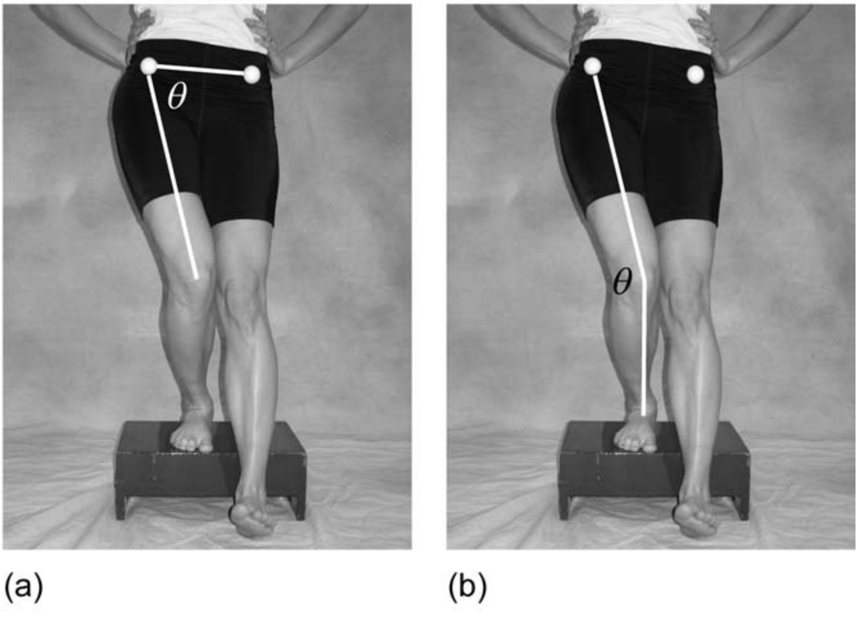

Figure 2 — (a) Hip adduction/abduction frontal-plane projection angles were defined as the angle θ subtended by one line connecting the anterior superior iliac spines (ASIS) and a second line connecting the ASIS of the test limb with the midpoint of the tibiofemoral joint. The angle was calculated with the equation hip angle = $90° - \theta$, where 0° was assumed to be a neutral position of hip adduction/abduction. Hip adduction was therefore a positive value, and hip abduction was a negative value. (b) Knee valgus/varus frontal-plane projection angles were defined as the angle θ subtended by a line connecting the ASIS with the midpoint of the tibiofemoral joint and a second line connecting the midpoint of the tibiofemoral joint with the midline of the talocrural joint. The angle was calculated with the equation knee angle = $180° - \theta$, where 0° was assumed to be a neutral position of knee valgus/varus. Knee valgus was therefore a positive value, and knee varus was a negative value.

subjects were verbally cued to avoid lateral trunk leaning or trunk rotation if the investigators observed compensatory movement strategies. Time was allotted between the practice trials and test condition to minimize fatigue effects. We analyzed joint alignments at 2 distinct points during the task. First, we measured static alignment in single-limb stance to provide an estimate of baseline hip and knee alignments. Second, we measured hip adduction and knee valgus during the eccentric phase of the step-down when the frontal-plane knee angle was maximally departed from the baseline position.

Reliability of the software for measuring joint angles was examined with an $ICC_{3,1}$. Similar to the reliability analysis for the strength tests, data from all subjects were used in the analysis. At the second measurement, the investigator was blinded to the original measures. Reliability coefficients were .958 (95% CI = .922–.978) for hip adduction (SEM = 1.3°) and .987 (95% CI = .975–.993) for knee valgus (SEM = 1.0°).

EMG. Subjects' skin was cleansed with alcohol wipes. Electrodes were placed, as described by Cram et al,[22] over the GMax (half the distance between the sacral vertebrae and greater trochanter) and GMed (proximal third of the distance between the lateral iliac crest and greater trochanter) in parallel with the muscles' respective lines of action. The ground electrode was placed at the tibial tuberosity. Data obtained during testing were normalized to EMG signals acquired during maximal voluntary isometric contractions (MVIC). To elicit maximal contractions from the GMax, subjects were tested in prone with the knee flexed and the hip extended as described by Kendall et al.[23] To elicit maximal contractions from the GMed, subjects were tested in side lying with the limb abducted.[23] The pelvis was stabilized manually during MVIC trials to minimize compensatory movements.

EMG signals were processed with a root-mean-square algorithm at a time constant of 55 milliseconds. We specifically analyzed mean EMG recruitment obtained over a 500-millisecond epoch during single-limb stance and mean EMG recruitment during a 500-millisecond epoch surrounding peak activation (± 250 milliseconds) during the step-down.

Data Analysis

Descriptive data were calculated for each variable. Paired *t* tests were used to compare joint angles and EMG magnitudes between the static and dynamic phases of the step-down. Relationships among the strength, joint-alignment, and EMG-recruitment variables during the step-down were quantified with Pearson product–moment (r) correlation coefficients. Statistical significance was established at $\alpha = .05$. SPSS 15.0 statistical software (SPSS, Inc, Chicago, IL) was used to analyze data.

Results

Joint Alignment

Descriptive data are presented in Table 1. Hip adduction increased during the step-down (95% CI of the change = 6.9–11.3°, $t = 8.760$, $P < .001$). Knee valgus

Table 1 Descriptive Data (Mean ± SD) and Comparisons Between the Static (Stance) and Dynamic Phases of the Step-Down Task

	Static phase	Dynamic phase	Mean change	95% CI	*t*	*P*
Joint alignment (°)						
hip adduction	12.4 ± 2.4	21.5 ± 4.4	9.1	6.9–11.3	8.760	.001
knee valgus	5.3 ± 2.4	6.4 ± 6.9	1.1	−2.0–4.3	0.764	.454
EMG recruitment (% MVIC)						
gluteus maximus	4.2 ± 2.1	9.2 ± 4.1	5.0	3.6–6.5	7.216	.001
gluteus medius	10.2 ± 4.0	21.9 ± 13.1	11.7	6.1–17.3	4.401	.001
Muscle strength (% BW)						
abduction	26.4 ± 5.9					
external rotation	24.5 ± 5.0					

Abbreviations: 95% CI, 95% confidence interval of difference between means.

increased also, although the change was not significant (95% CI of the change = –2.0° to 4.3°, $t = 0.764$, $P = .454$).

EMG

GMax EMG recruitment (Table 1, Figure 3[a]) during the step-down was 9.2% MVIC, an increase in recruitment compared with single-leg stance (95% CI of the change = 3.6–6.5% MVIC, $t = 7.216$, $P < .001$). GMed EMG recruitment (Table 1, Figure 3[b]) during the step-down was 21.9% MVIC, which similarly represented an increase in recruitment compared with static stance (95% CI of the change = 6.1–17.3% MVIC, $t = 4.401$, $P < .001$).

Correlations

Knee valgus and hip adduction were correlated ($r = .755$, $P < .001$) during the step-down (Table 2). GMax EMG recruitment was negatively correlated with knee valgus ($r = –.451$, $P = .026$). Abduction and external-rotation strength were not correlated with knee valgus or hip adduction in a direction consistent with our hypothesis. Rather, abduction strength was positively correlated with knee valgus ($r = .455$, $P = .022$). Muscle strength and EMG recruitment were not significantly correlated.

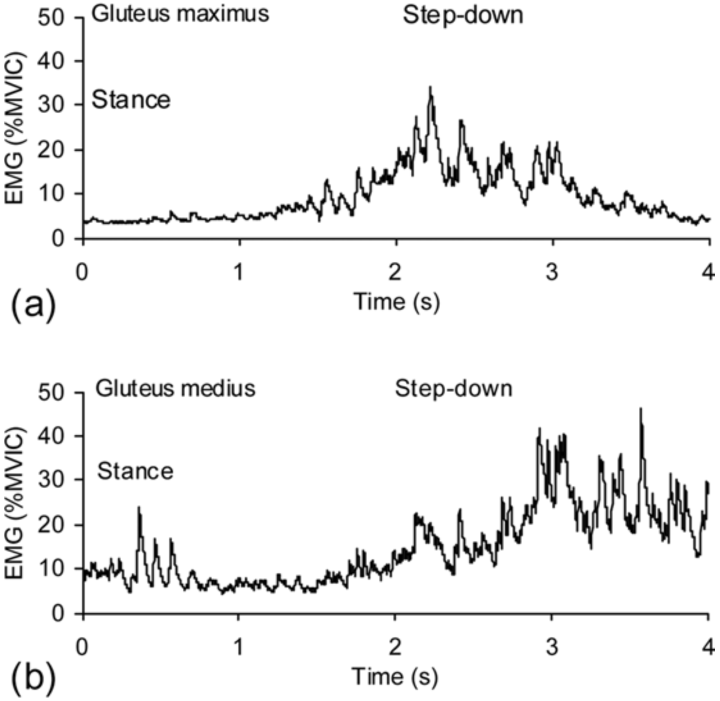

Figure 3 — Characteristic plots of (a) gluteus maximus and (b) gluteus medius EMG recruitment during the static (stance) and dynamic phases of the step-down task.

Table 2 Pearson Product–Moment Correlation Coefficients

	Hip adduction	Knee valgus	Glut max EMG	Glut med EMG	Abd strength	ER strength
Hip adduction	—	.755*	−.295	−.248	.227	−.238
Knee valgus		—	−.451*	−.022	.455*	.124
Glut max EMG			—	.218	−.065	.032
Glut med EMG				—	−.111	.184
Abd strength					—	.574*
ER strength						—

Abbreviations: Glut max, gluteus maximus; Glut med, gluteus medius; Abd, abduction; ER, external rotation.

*$P < .05$.

Discussion

Although impaired hip-abduction and -external-rotation strength[2,19] and reduced GMax recruitment[12] have been implicated as contributing factors to altered LE biomechanics and excessive knee valgus, relationships between hip-muscle strength and recruitment and LE alignment have been described primarily through theoretical reports.[7] One study examined relationships between hip-muscle strength and LE alignment but did not examine neuromuscular recruitment.[16] To our knowledge, no study has concurrently examined relationships between hip-muscle EMG recruitment, hip-muscle strength, and LE alignment during single-limb weight bearing. We therefore explored the relationships in a single study.

Two variables correlated with frontal-plane projection angle of knee valgus consistently with our hypotheses: the frontal-plane projection of hip-adduction alignment and GMax EMG recruitment. Although the mean change in hip adduction (9.1°) exceeded the mean change in knee valgus (1.1°), hip adduction correlated strongly with knee valgus ($r = .755$). Variance in hip adduction accounted for 57% of the variance in knee valgus during the step-down ($r^2 = .57$). The relatively greater change in hip adduction that occurred can be accounted for, in part, by femoral adduction coupled with downward tilting of the pelvis in the frontal plane during the step-down. As illustrated in Figure 2(a), for example, downward tilting of the pelvis contributes to the adduction angle. Although the intent of the current study was not to examine frontal-plane pelvic motion specifically, one might postulate that pelvic dropping in the frontal plane could be a movement strategy selected by subjects as they reach for the floor during the step-down task or a function of either reduced strength or reduced recruitment of the frontal-plane stabilizers at the hip, such as the GMax and GMed. GMax EMG recruitment was moderately and negatively correlated ($r = -.451$) with knee valgus, with variance in GMax recruitment accounting for 20% of the variance in knee valgus.

The correlation between hip adduction and knee valgus is logical from both a measurement and a biomechanical perspective. From a measurement perspective, the frontal-plane projection angles of hip adduction and knee valgus are codependent on an identical variable, the line connecting the ASIS and the midpoint of the tibiofemoral joint. One could therefore anticipate that the 2 measures would be correlated. In addition to the measurement issue, however, there is also a plausible biomechanical explanation for the relationship. When the foot is stable on a support surface, hip adduction might be coupled with knee valgus (Figure 1). Powers[7] describes the relationship theoretically, suggesting that coupled hip adduction and knee valgus might increase resultant lateral forces acting on the patella, which in turn might increase lateral patella tracking[24] and lateral patellofemoral joint-contact pressures.[25] Ferber et al[8] reported that women have greater coupled hip adduction and knee valgus than men through the stance phase of running and suggested that women might therefore be at greater risk of injury on the premise that increased valgus increases ACL loading.[9] The correlation between hip adduction and knee valgus provides empirical evidence for the validity of the theoretical model of medial collapse described by Powers.[7] Although our study was not intended to establish cause-and-effect relationships between hip adduction, knee valgus, and knee injury, it is possible that knee injuries associated with excessive knee valgus could be reduced by preventing excessive hip adduction during weight-bearing activities.

The relationship between knee valgus and GMax EMG recruitment therefore might be particularly important. The negative correlation indicates that subjects with lower GMax EMG recruitment had greater knee valgus. Results support assertions that GMax function might be associated with knee valgus during single-limb support. Ireland et al[2] and Niemuth et al,[19] for example, postulated that excessive internal rotation secondary to inadequate hip-muscle function might result in abnormal mechanics that lead to LE injury. Although the GMax is primarily a hip extensor, the muscle also externally rotates the femur and assists abduction. The GMax can therefore eccentrically control femoral internal rotation and adduction during unilateral tasks. Our results suggest that insufficient recruitment of the muscle during single-limb weight bearing to counteract external moment demands and to maintain optimal alignment at the hip might be associated with femoral adduction that places the knee in increased valgus. Our results also suggest that the magnitude of GMax recruitment might have a greater association with frontal-plane knee alignment in women than merely hip-muscle strength.

Some results were inconsistent with our hypotheses. Namely, external-rotation strength was not significantly correlated with knee valgus, and abduction strength was positively correlated with knee valgus, meaning that greater abduction isometric force-production values were associated with greater knee-valgus angles during the step-down. The positive correlation between abduction strength and knee valgus, although not initially hypothesized, might be explained in part by the secondary role of the GMed. The GMed, although primarily a hip abductor, also assists internal rotation. The internal-rotation moment arm of the GMed increases as the hip-flexion angle increases.[26] Although the intent of our methods was to examine strength of the hip-abduction muscles collectively, not the GMed specifically, clearly the GMed contributed to subjects' abduction-force values. We did not measure internal-rotation strength. Because the GMed contributes to internal rotation, and the internal-rotation moment arm of the GMed increases as the hip flexes, as it does during a step-down maneuver, it is possible that increased GMed strength might actually contribute to femoral internal rotation and subsequently adduction movements during single-limb weight bearing that are associated with knee valgus. It is also possible that isolated strengthening of the GMed with the intent to reduce knee valgus, without a concomitant focus on GMax motor training, might be counterproductive. Further research is required to support or refute this contention. The weak correlation between external-rotation strength and knee valgus found in the current study conflicts with reports that reduced external-rotation strength is associated with increased knee valgus during single-leg squats.[16] The differences between our results and those of Willson et al[16] might be partially explained by differences in the subject samples. Whereas our study involved women only, Willson et al[16] studied men and women. They reported an interaction between gender and knee valgus. Knee valgus decreased in men during a single-leg squat, whereas in women it increased. They also reported that mean hip-abduction and -external-rotation isometric strength were greater in men than in women. They did not measure EMG recruitment. Perhaps the relationships between external-rotation strength and knee valgus are stronger in men than in women. Conversely, perhaps the relationship between GMax EMG recruitment and knee valgus is stronger in women than in men. The conflicting results highlight the importance of considering both muscle strength and EMG recruitment factors when considering the relationship between hip-muscle function and knee-joint kinematics.

This study had several limitations. Three-dimensional (3D) methods might have provided more accurate measures of LE kinematics. Researchers are challenging the assumption that 3D analyses are necessary for examining dynamic knee valgus, however. Recent studies[27–29] report high correlations between 2D and 3D methods for measuring knee valgus, and the authors conclude that the 2D approach is an acceptable alternative to 3D analyses of knee valgus. Although the correlations between 2D and 3D approaches for measuring frontal-plane hip adduction have not been reported, the mean errors reported between 3D measures and 2D estimates of frontal-plane angles from front- and rear-view cameras are comparable or less for planar-projection angles at the hip than at the knee.[30] The hip angles measured in the current study should therefore be as valid as or more valid than the knee-valgus measures. In addition, movement strategies selected by subjects and how they affected center-of-mass position were not quantified. A medially located center of mass, for example, might have influenced GMed EMG recruitment and potentially frontal-plane hip and knee alignment. Although we monitored participants during testing and instructed them to avoid lateral leaning, relationships between the variables examined in the study might have differed had we accounted for variable movement strategies. Likewise, although we measured hip-abduction and -external-rotation strength isometrically, the GMax and GMed, as well as the smaller rotators of the hip, were likely contracting eccentrically during the step-down, which could partially account for the low or conflicting correlations between knee valgus and muscle strength. Another limitation is that we studied only healthy young women. Relationships among the variables might have been more pronounced had we included subjects with LE dysfunction. Furthermore, our results are not generalizable to men.

The current study explored relationships between knee valgus and hip-adduction alignment, hip-abduction and -external-rotation strength, and GMax and GMed EMG recruitment during a single-leg step-down in active, young-adult women using a 2D measurement approach. The study could be replicated with 3D measurement approaches to further enhance our understanding of the relationship between 3D joint kinematics, muscle strength, and EMG recruitment. In addition, the study was not intended to establish cause-and-effect relationships for knee valgus or knee injury. To improve our ability to care for patients with LE conditions influenced by coupled joint mechanics or to provide improved injury-prevention strategies, therefore, future studies could investigate causative factors for knee valgus and knee injury in women and in men. Studies must be conducted prospectively to examine whether measures of knee valgus, hip adduction, hip strength, or hip-muscle EMG recruitment characteristics provide value with respect to incidence of knee injury or to a person's risk of injury. Then studies can investigate whether intervention strategies can alter dynamic knee valgus or injury risk. Ultimately, researchers need to determine whether an alteration in one's ability to control dynamic knee valgus, if it occurs, prevents injury or enhances rehabilitation from injury.

Conclusion

Three conclusions can be drawn. First, the frontal-plane projection of knee valgus during a step-down was negatively correlated with GMax EMG recruitment in active 20- to 30-year-old women but was not significantly correlated with external-rotation strength. Neuromuscular EMG recruitment of the GMax might therefore have greater association with LE mechanics in women during single-limb weight bearing than does muscle strength. Second, the frontal-plane projection of knee valgus was positively correlated with abduction strength, potentially suggesting that the secondary role of the GMed as a femoral internal rotator might contribute to increased knee valgus, particularly as the hip flexes. Third, the frontal-plane projection of knee valgus was correlated with the frontal-plane projection of hip adduction. Clinically, it might be prudent to focus examinations and interventions on coupled hip and knee mechanics, with particular attention to GMax function, in those with LE injury thought to be associated with medial collapse.

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