Association Between the Medial-Lateral Quadriceps and Hamstring Muscle Thickness and the Knee Kinematics and Kinetics During Single-Leg Landing

Jiyoung Jeong, BSc,[†] Dai-Hyuk Choi, PhD,[‡] and Choongsoo S. Shin, PhD*[†]

Background: Muscle thickness can influence the joint kinematics and/or kinetics during dynamic activities. The relationship between the muscle thickness of individual quadriceps and hamstrings or medial-to-lateral thigh muscle thickness ratio and the knee kinematics/kinetics with respect to anterior cruciate ligament (ACL) injury risk remains unclear.

Hypothesis: Higher medial-to-lateral thigh muscle thickness ratio would be associated with lower knee valgus angle/moment and lower tibial internal rotation angle/moment during single-leg landing.

Study Design: Cross-sectional.

Level of Evidence: Level 4.

Methods: Muscle thickness of the vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), and semitendinosus (ST) of 30 healthy participants (16 males and 14 females) were measured using ultrasound. Knee joint kinematics and kinetics during single-leg landing were obtained. Stepwise multiple regression analysis, a follow-up Fisher's r to z test to examine the sex as a moderator, and independent t tests to evaluate sex difference were performed.

Results: Both knee valgus moment ($R^2 = 0.466$, $P < 0.001$) and tibial external rotation moment ($R^2 = 0.330$, $P < 0.001$) at peak anterior tibial shear force during single-leg landing were negatively correlated with medial-to-lateral (ie, (VM+ST):(VL+BF)) thickness ratio regardless of sex, whereas medial-to-lateral thigh muscle thickness ratio was not correlated with knee valgus and tibial external rotation angles. Male participants exhibited higher (VM+ST):(VL+BF) thickness ratio than female participants ($P = 0.005$), and lower knee valgus moment ($P = 0.04$) and tibial external rotation moment ($P = 0.05$), as well.

Conclusion: The knee joint moments in frontal and transverse planes during single-leg landing were associated with the medial-to-lateral thigh muscle thickness ratio; thus, the medial-lateral thigh muscle thickness could be a potential contributor to frontal and transverse plane knee joint loading during dynamic movement.

Clinical Relevance: Strength training that aims to selectively strengthen the medial/lateral thigh muscles might be considered in a new ACL injury prevention training program to alter the biomechanical parameters associated with ACL injuries.

Keywords: anterior cruciate ligament; lower extremity; muscle strength; sex difference; ultrasound imaging

From [†]Department of Mechanical Engineering, Sogang University, Seoul, Republic of Korea, and [‡]Department of Physical Education, Graduate School of Education, Sogang University, Seoul, Republic of Korea

*Address correspondence to Choongsoo S. Shin, PhD, Department of Mechanical Engineering, Sogang University, 35 Baekbeom-ro, Mapo-gu, Seoul 04107, Republic of Korea (email: cshin@sogang.ac.kr).

The following author declared potential conflicts of interest: C.S.S. received grants from the Ministry of Education of Republic of Korea and the National Research Foundation of Korea (NRF-2018S1A5A2A01035058).

DOI: 10.1177/19417381231152476

© 2023 The Author(s)

Anterior cruciate ligament (ACL) injury is among the most common injuries in sport, and most ACL injuries occur in noncontact situations.[5] Numerous studies investigating the biomechanical risk factors of noncontact ACL injuries reported that the ACL injury mechanism has been described as having components of tibial rotation and knee valgus.[2,12,13,25,30] Video analyses have shown that dynamic valgus and tibial axial rotation with nearly full extended knee was observed most frequently in ACL injury,[19,25] and Hewett et al[13] reported that higher knee valgus angle and moment are predictive of ACL injury occurrence. In addition, female subjects tend to demonstrate these "at-risk" frontal and transverse plane knee motions and moments during landing and cutting maneuvers more often than male subjects,[23,24] which is thought to contribute to their greater risk of ACL injury.[1] Given that the knee is frequently exposed to considerable frontal and transverse plane motions and moments during sports-related tasks, it is worthwhile investigating the factors that contribute to knee joint kinematic and/or kinetic parameters in both the frontal and transverse planes.

There are modifiable factors that contribute to joint kinematics and/or kinetics during sports-related tasks. In particular, muscles play important roles in controlling movement and maintaining knee stability. Biomechanical cadaveric studies have been demonstrated that the tibial internal rotation and varus rotation was increased as the medial hamstring and quadriceps forces increased,[29,34] and also lateral hamstring can cause both tibial external rotation and valgus rotation.[10] Thus, assessing the muscle forces of individual components of quadriceps and hamstrings and/or medial-to-lateral muscle force ratio on the knee biomechanics in the frontal and transverse planes is needed. However, since measuring the individual medial and lateral thigh muscle strength using an isokinetic dynamometer is unavailable, the muscle morphology derived from ultrasound imaging has been an appropriate alternative. Among the morphological variables, muscle thickness is used to indirectly predict the force production capacity, which presents strong positive correlation with maximal muscle strength ($R > 0.838$).[31] Previous studies reported that muscle thickness is among the factors that influence joint kinematics and/or kinetics. Guadagnin et al[9] reported that thickness of the vastus lateralis (VL) muscle showed a positive correlation with walking speed and step length, and thickness of the tibialis anterior muscle thickness showed positive correlations with toe clearance during walking. In addition, a recent study suggested that gluteus medius thickness was associated with hip abduction and external rotation moments during walking.[6] All things considered, medial and lateral quadriceps and hamstring muscle thickness can be factors that influence knee joint kinematics and/or kinetics in the frontal and transverse planes during dynamic tasks, but the relation between the muscle thickness of individual components of quadriceps and hamstrings and/or medial-to-lateral muscle thickness ratio and the biomechanical parameters with respect to ACL injury risk remains unclear.

The purpose of this study was to examine the relationship between the muscle thickness of individual components of quadriceps and hamstrings and/or medial-to-lateral muscle thickness ratio and the knee kinematics/kinetics during single-leg landing. It was hypothesized that a higher medial-to-lateral thigh muscle thickness ratio would be associated with lower knee valgus angle/moment and the tibial internal rotation angle/moment during single-leg landing. In addition, it was also hypothesized that there would be sex differences in the individual muscle thickness of quadriceps and hamstrings, medial-to-lateral thigh muscle thickness ratio, and the corresponding kinematic/kinetic parameters.

METHODS

Subjects

A total of 30 recreationally active male and female subjects, defined as participating in some form of physical activity for a minimum of 20 minutes, 3 times per week, participated in this study (Table 1). Subjects were excluded if they had a lower extremity and/or trunk injury experience in the past 6 months that prevented participation in physical activity for more than 2 weeks, or had a history of ACL injuries or other musculoskeletal injuries requiring surgery. Before participation, all subjects were asked to sign an informed consent form approved by the institutional review board.

Experimental Protocol

Ultrasound images of the VL, vastus medialis (VM), biceps femoris (BF), and semitendinosus (ST) on the dominant limb were collected by 1 rater using a B-mode ultrasound system (MicrUs EXT-1H, TELEMED Ultrasound Medical System) with a linear array probe (10 MHz). Ultrasound setting including gain (60 dB), depth (70 mm), and frequency (10 MHz) were set before testing. Sufficient ultrasound gel was used to minimize the muscle compression with the probe head. With the participant lying supine and both feet fixed to prevent hip external rotation, the thickness of VM was measured at 20% of the distance between the superior tip of the patella and the anterior superior iliac spine, and VL at 50% of this distance above the patella.[8] All ultrasound images of BF and ST were scanned in the sagittal plane at 50% of the distance between the greater trochanter and the lateral joint line of the knee in the prone position, with the lower limb extended and relaxed.[26] For each session, 2 ultrasound images were taken, and the mean was calculated for each of the muscle thicknesses.

A 3-dimensional motion capture system equipped with 10 infrared cameras (9 Eagle, and 1 Raptor, Motion Analysis Corp.) was used to record the motion of knee joint at a sampling rate of 400 Hz. Reflective markers (ie, Φ12.5 mm spheres) were placed on the anatomical bony landmarks: left and right acromion, sternum, right scapula, bilateral anterior superior iliac spines, sacrum, greater trochanter, midpoint of femur, lateral and medial epicondyles of the femur, lateral and medial plateau of tibia, midpoint of tibia, lateral and medial malleolus, calcaneus, and 1st and 5th metatarsal heads. A force plate (9260AA6, Kistler) embedded in the floor was used at a

Table 1. Anthropometric data for male and female subjects (mean ± SD)

	Age, y	Height, cm	Mass, kg	BMI, kg/m^2
Male (n = 16)	22.4 ± 2.2	174.7 ± 2.6	69.8 ± 7.1	22.9 ± 2.0
Female (n = 14)	21.6 ± 1.3	160.7 ± 4.9	55.2 ± 7.1	21.4 ± 2.5

BMI, body mass index.

sampling rate of 1200 Hz, which was synchronized with the motion capture system to calculate the joint moments.

All participants were instructed to perform a single-leg landing by stepping off of a 0.3-m platform without jumping up, using the dominant limb, with arms folded across the chest. Leg dominance was defined as the preferred leg for kicking a ball. The participants were instructed to remain balanced on their dominant leg for at least 2 seconds after landing. If a participant jumped up or failed to adopt a stable landing posture by losing balance, then the corresponding trials were discarded. To remove the effect of footwear, all participants wore the same running shoes: Nike Downshifter 8 (NIKE Inc.).

Data Analysis

All ultrasound images were analyzed by 1 investigator using ImageJ software (Version 1.51k, National Institutes of Health) to measure the muscle thickness. Muscle thickness of VL, VM, BF, and ST was defined as the distance between the superficial and deep fascia of each muscle (Figure 1). The medial-to-lateral thigh muscle thickness ratio (ie, [VM+ST]:[VL+BF] thickness ratio) was calculated as the sum of the muscle thickness of VM and ST divided by the sum of the muscle thickness of VL and BF.

Each trial was defined as the period from the initial foot contact to the toe-off, as determined by the force plate recordings. The initial contact of single-leg landing was identified by finding the first frame at which the vertical ground reaction force exceeded 20 N. The measured kinematic and kinetic data were filtered using a zero-lag fourth-order Butterworth low-pass filter at a cut-off frequency of 10 and 20 Hz, respectively.[35] To calculate the joint kinematics, the coordinate systems for each body segment were defined following previous methods,[15] and the joint angle was calculated with rotations in the following order: internal-external (Z), varus-valgus (Y), and flexion-extension (X). The joint moments were calculated by solving an inverse dynamics problem with Newton-Euler equations.[33] Joint moments were normalized to the bodyweight and height of each participant, and forces were normalized to the bodyweight. Previous studies have demonstrated that anterior shear force can increase the ACL strain and combination of the anterior shear force, knee valgus and tibial internal rotation moments resulted in highest increases in peak ACL strain,[17,22] thereby contributing to noncontact ACL injury. Thus, the knee joint angles were sampled both at initial contact and at peak anterior tibial shear force, and the moments were sampled at peak anterior tibial shear force during single-leg landing.

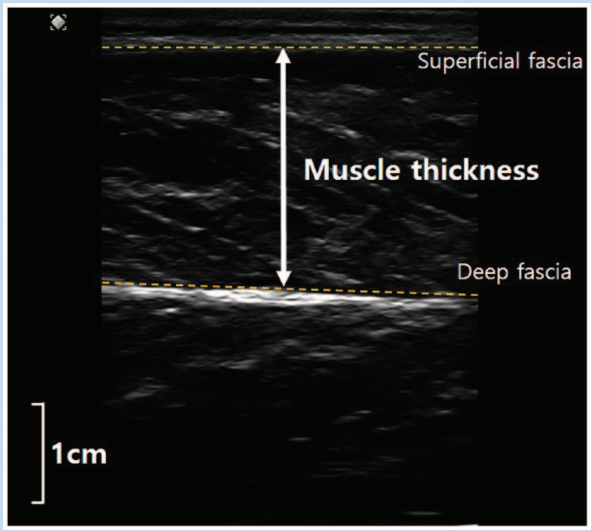


Figure 1. An example of ultrasound thickness measurement.

Statistical Analysis

The 2 successful trials were averaged individually, and then averaged to generate group mean values and standard deviation. The Kolmogorov-Smirnov test was performed to check the normality of data distribution. The results revealed that all of the recorded data were distributed normally ($P > 0.05$). To assess the agreement in muscle thickness between data measured across 2 trials on separate days by 1 rater, a 2-way mixed-model (intraclass correlation coefficient [ICC]$_{3,1}$) analysis was performed.[14] As the result, the high degrees of ICC ranging between 0.961 and 0.983 for intra-rater reliability of medial/lateral quadriceps and hamstrings muscle thickness was demonstrated.[14] Stepwise multiple regression analysis was performed to determine the relationship between the muscle thickness of individual quadriceps and hamstrings and medial-to-lateral thigh muscle thickness ratio and the knee joint kinematic and kinetic variables. Subsequently, Fisher's r to z test

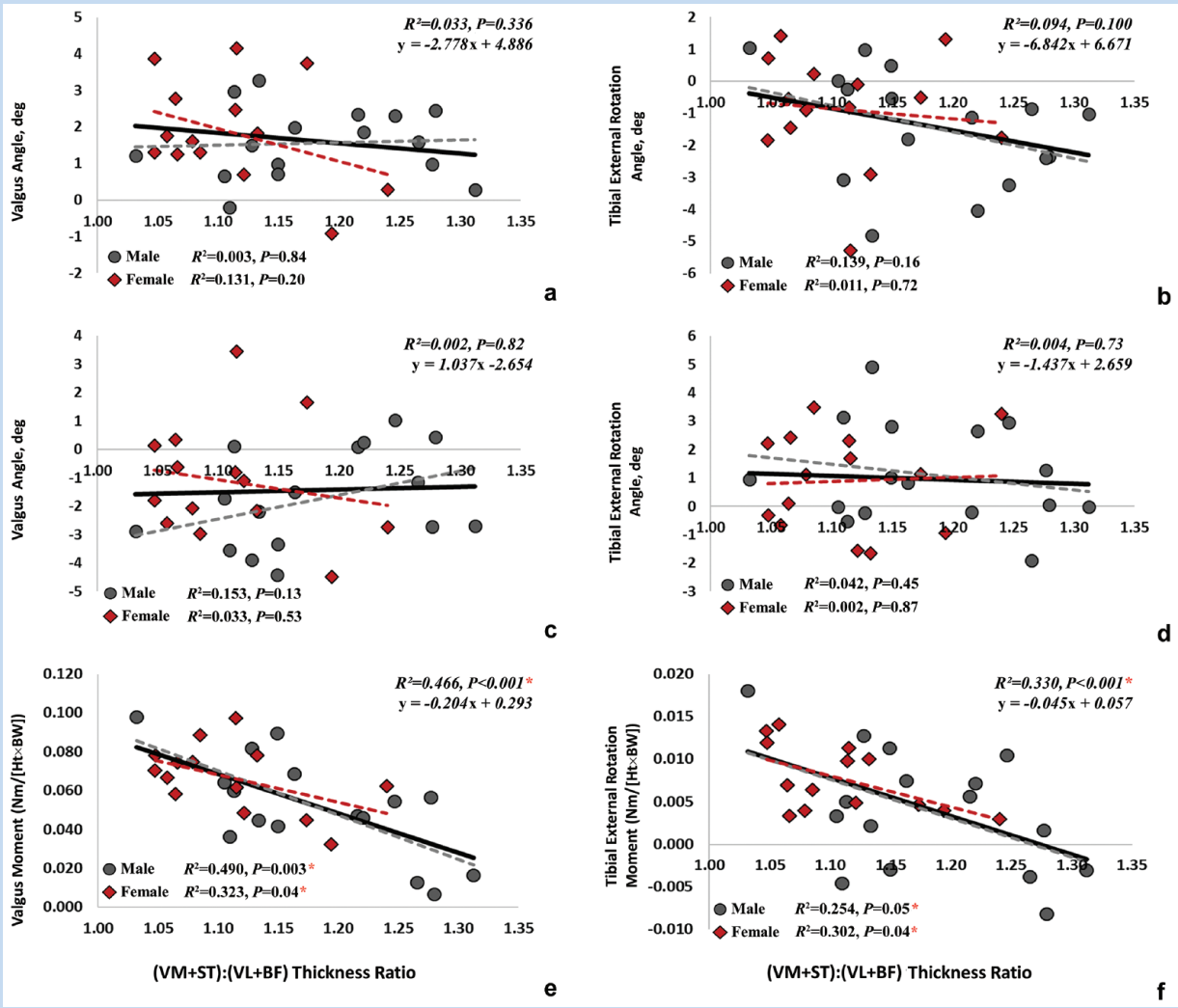


Figure 2. Relationship between the medial-to-lateral thigh muscle thickness ratio and the knee kinematics/kinetics in both frontal and transverse plane during single-leg landing. (a,b) Joint angles sampled at initial contact. (c-f) Joint angles and moments sampled at peak anterior tibial shear force. Positive values are the valgus angle, tibial external rotation angle, valgus moment, and tibial external rotation moment, respectively. BF, biceps femoris; ST, semitendinosus; VL, vastus lateralis; VM, vastus medialis.

was used to examine sex as a moderator of the significant associations from multiple regression analysis. In addition, independent *t* tests were performed to compare both the morphologic and biomechanical variables between sexes. All statistical analyses were performed using MATLAB Version R2018b (Mathworks Inc.).

RESULTS

As a result of multiple regression analysis, the (VM+ST):(VL+BF) thickness ratio was the only predictor, explaining 46.6% and 33.0% of the variance in the valgus moment and the tibial external rotation moment at peak anterior tibial shear force, respectively. Both the knee valgus moment (R^2 = 0.466, R = −0.683, P < 0.001; Figure 2) and the tibial external rotation moment at peak anterior tibial shear force (R^2 = 0.330, R = −0.574, P < 0.001; Figure 2) during single-leg landing were correlated negatively with the medial-to-lateral thigh muscle (ie, [VM+ST]:[VL+BF]) thickness ratio. At this time point, the knee flexion angle was 41.2 ± 6.0°. The results of Fisher's r to z test revealed that there were no significant differences in sex difference of the correlations between the medial-to-lateral thigh muscle thickness ratio with the valgus moment (z = 0.535, P = 0.30) and with tibial external moment (z = −0.152, P = 0.44) at peak anterior tibial shear force. The medial-to-lateral thigh muscle thickness ratio was not correlated with the knee valgus or the tibial external rotation angles at both initial contact and peak anterior shear force (Figure 2).

Table 2. Sex difference in the muscle thickness ratio of the medial-lateral quadriceps and hamstrings and the knee joint kinematics/kinetics in both the frontal and transverse planes during single-leg landing (mean ± SD)[a]

			Male	Female	*P* value
Muscle thickness, mm	VL		24.9 ± 3.0	22.7 ± 2.0	0.03*
	VM		34.3 ± 4.3	26.9 ± 2.4	<0.001*
	BF		22.2 ± 2.5	19.6 ± 2.3	0.005*
	ST		21.3 ± 2.0	19.9 ± 1.8	0.05*
	(VM+ST):(VL+BF) thickness ratio		1.18 ± 0.08	1.11 ± 0.06	0.005*
Knee joint kinematics and kinetics	At initial contact	Valgus angle, deg	1.6 ± 1.0	1.9 ± 1.4	0.25
		Tibial external rotation angle, deg	1.4 ± 1.8	0.9 ± 1.8	0.20
	At peak anterior tibial shear force	Valgus angle, deg	1.8 ± 1.7	1.1 ± 2.0	0.19
		Tibial external rotation angle, deg	1.2 ± 2.1	0.9 ± 1.7	0.32
		Valgus moment[a]	0.0516 ± 0.0261	0.0668 ± 0.0174	0.04*
		Tibial external rotation moment[a]	0.0039 ± 0.0072	0.0076 ± 0.0039	0.05*

BF, biceps femoris; ST, semitendinosus; VL, vastus lateralis; VM, vastus medialis.
[a]Moments in Nm/(bodyweight × height).
*Significant sex difference.

Male subjects exhibited significantly greater muscle thickness of all the medial and lateral thigh muscles when compared with female subjects ($P < 0.05$ for all comparisons, Table 2), and male subjects also had a greater (VM+ST):(VL+BF) thickness ratio ($P = 0.005$, Table 2). As the medial-to-lateral thigh muscle thickness ratio showed significant association with the knee joint moments in the frontal and transverse planes, male subjects showed significantly lower knee valgus moment ($P = 0.04$, Table 2) and tibial external rotation moment ($P = 0.05$, Table 2) at peak anterior tibial shear force. However, no sex differences were found in either the knee valgus angle or the tibial external rotation angle at initial contact, and at peak anterior tibial shear force (Table 2).

DISCUSSION

The main finding of this study was that the medial-to-lateral thigh muscle thickness ratio affects knee kinetics during single-leg landing. Both the knee valgus moment and the tibial external rotation moment at the time of peak anterior tibial shear force were correlated negatively with the (VM+ST):(VL+BF) thickness ratio regardless of sex. The results of the current study suggest that the medial-lateral thigh muscle thickness could be a potential contributor to frontal and transverse plane knee joint loading during dynamic movement; thus, it provides support for the necessity of a new ACL injury prevention training program that aims to selectively strengthen the medial and/or lateral thigh muscles.

The knee valgus moment during landing was associated negatively with medial-to-lateral thigh muscle thickness ratio in this study. This finding agrees with the results of previous studies, which reported that both VL and BF produce valgus moments at the knee joint between knee flexion angles of 20° and 50°,[4] and the lateral muscles of the lower extremity generated valgus moment, while the medial muscles generated varus moment.[36] Considering the lines of action of the medial and lateral thigh muscles on the knee joint, both VL and BF muscle force vectors that act laterally to the knee center in the frontal plane subsequently lead to external knee valgus moment on the knee (Figure 3), whereas the force vectors of medial thigh muscles (ie, VM and ST) act medially to the knee joint center. The association between the knee valgus moment and noncontact ACL injury risk has been identified previously,[2,12] thus it is reasonable to assume that the risk for ACL injury would be reduced by reducing knee valgus moment, if training can selectively strengthen the medial thigh muscles. Taken together, the greater proportion of medial thigh muscles compared with lateral muscles can help athletes decrease valgus moment during landing task, and hence may influence the potential risk of noncontact ACL injury.

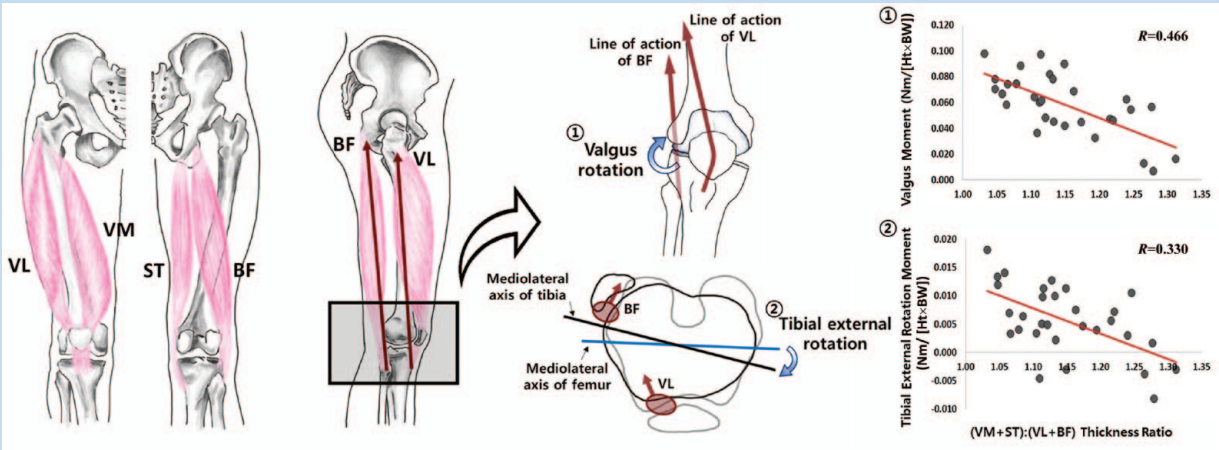


Figure 3. Schematic of the role of the VL and BF on the knee joint. Lateral and posterior direction of the VL and BF force vectors to the knee center caused knee valgus and tibial external rotation in the frontal and transverse plane. Negative correlations between the medial-to-lateral thigh muscle thickness ratio and the knee valgus and tibial external rotation moment are shown. BF, biceps femoris; ST, semitendinosus; VL, vastus lateralis; VM, vastus medialis.

The tibial external rotation moment at peak anterior tibial shear force was also negatively correlated with the (VM+ST):(VL+BF) thickness ratio. A previous study reported that higher force on the lateral hamstring resulted in the increase in tibial external rotation, whereas higher force on the medial hamstring caused the tibia to be more internally rotated.[29] Another cadaveric study demonstrated that higher medial quadriceps tension was associated with higher internal tibial rotation.[34] The BF inserted on the posterior lateral condyle of the tibia and the VL produced a posterior-lateral directed force on the tibia; thereby, the force applied through the BF and VL would induce the external rotation moment (Figure 3). Markolf et al[22] showed that the ACL tensile force was greater with the combined valgus and internal rotation loads than with the combined valgus and external rotation loads, and Shin et al[30] also demonstrated that the combination of the valgus rotation and internal rotation is more relevant to ACL injury mechanism than either alone. However, because ACL impingement and injury may occur with the tibia externally rotated and abducted,[7,12,25] tibial external rotation still remains an important consideration for noncontact ACL injury. Further investigation is required to determine whether an optimum medial-lateral thigh muscle thickness ratio exists to reduce ACL loading.

The results of this study suggest that an ACL injury prevention training program that aims to improve the medial-to-lateral thigh muscle thickness ratio could alter the biomechanical parameters associated with ACL injuries in the frontal and transverse planes. Since strengthening the whole quadriceps and hamstring muscle group did not alter the knee joint angles and moments during sports-related movements,[11,16] strengthening the medial quadricep and hamstring selectively seems to be more effective in alteration of the knee biomechanics associated with the ACL injury. Previous studies demonstrated that the ST/BF activation ratio and VM/VL activation ratio can be changed during standard exercise by altering the position of the foot.[20,32] In addition, a recent study reported that strength training targeted at the medial quadricep and hamstring can selectively strengthen the medial thigh muscles, and hence increase the medial-to-lateral thigh muscle thickness ratio.[14] As noted above, greater muscle thickness of medial muscles compared with lateral muscles in the thigh can not only decrease the knee valgus moment but also increase the tibial internal rotation moment mechanically; thus, there might be conflict with respect to ACL injury risk. Therefore, future studies on the effect of training for the optimal medial-lateral thigh muscle thickness ratio on the biomechanical parameters associated with the ACL injury risk are needed to evaluate whether the post-training changes in medial-to-lateral thigh muscle thickness ratio can actually alter the knee kinematics and/or kinetics.

Difference in the medial thigh muscle proportion compared with lateral thigh muscles between sexes may support further anatomical explanation for high risk of ACL injuries in female participants by affecting "at-risk" biomechanical parameters. The results of this study showed that male participants have significantly greater medial-to-lateral thigh muscle thickness ratio than female participants, and this morphological difference between sexes might be associated with lower knee valgus and tibial external rotation moments at peak anterior tibial shear force during single-leg landing in male participants because there are significant negative correlations regardless of sex. Lower (VM+ST):(VL+BF) thickness ratio in female participants can be partially supported by the previous finding that female participants showed a greater proportion of VL anatomical cross-sectional area to knee extensors than male participants.[3]

With respect to the risk for injury, the larger knee valgus moment observed in female participants compared with male participants has been suggested as a predictor of ACL injuries.[13,23] In addition, Park et al[27] demonstrated that female participants had higher knee joint laxity and lower stiffness in tibial external rotation than male participants, which can increase impingement of the ACL against the intercondylar notch with knee valgus.[7] These biomechanical differences between the sexes are also in accordance with our current study results, and with the greater incidence rate of ACL injuries in female participants.

There are major limitations to this study. First, muscle thickness of only the medial/lateral quadriceps and hamstrings were examined, and other lower extremity muscles were not measured. Additional measurements of the non-knee-spanning muscles are recommended to gain a deeper understanding of the effect of muscle thickness of lower extremity on the joint kinetics/kinematics, because non-knee-spanning muscles, such as gluteal muscles, can also contribute to the knee joint moments in the frontal and transverse planes during dynamic movement.[21] Second, muscle thickness at only a single site was measured in this study, so it may not reflect the muscle volume, which is associated directly with muscle strength. The quantification of muscle volume using magnetic resonance imaging (MRI) is recognized as the gold standard for providing accurate estimations of muscle size, but with relatively simple and less expensive measurements, measurement of muscle thickness using ultrasound can be more useful as a means of predicting the individual muscle strength and knee joint moment associated with ACL injury during sports-related tasks. In addition, in the current study, moments were sampled at peak anterior tibial shear force. The timepoint of peak anterior shear force (0.131 ± 0.713 s) preceded the timepoint of peak knee valgus moment (0.145 ± 0.572 s) by 14 ms; thus, it may not show the same results as the current study when the moments were sampled at the timepoint of peak valgus moment. Finally, the joint moments were computed using marker and force data filtered at the different cut-off frequencies in this study. Some previous studies have recommended the same cut-off frequencies for marker and force data because of the risk for fluctuation of joint moments when applying the unmatched filtering conditions.[18,28] However, the filter frequencies in this study were chosen from the previous research investigating the cut-off frequencies with the most appropriate signal-to-noise ratio in landing task.[35] In addition, our main result, which is that the knee joint moments in the frontal and the transverse planes during single-leg landing showed negative correlations with the medial-to-lateral thigh muscle thickness ratio regardless of sex, was not changed when applying the same cut-off frequencies (10 Hz).

CONCLUSION

The knee joint moments in the frontal and transverse planes during single-leg landing were correlated with the medial-to-lateral thigh muscle thickness ratio. Greater muscle thickness of VM and ST compared with VL and BF was associated with lower knee valgus moment and tibial external rotation moment at peak anterior tibial shear force regardless of sex. Therefore, strength training that aims to improve the medial-to-lateral thigh muscle thickness ratio might be considered to alter the biomechanical parameters associated with ACL injuries.

ORCID ID

Choongsoo S. Shin https://orcid.org/0000-0003-4674-6222

REFERENCES

1. Agel J, Arendt EA, Bershadsky B. Anterior cruciate ligament injury in National Collegiate Athletic Association basketball and soccer: a 13-year review. *Am J Sports Med*. 2005;33(4):524-530.
2. Bates NA, Schilaty ND, Nagelli CV, Krych AJ, Hewett TE. Multiplanar loading of the knee and its influence on anterior cruciate ligament and medial collateral ligament strain during simulated landings and noncontact tears. *Am J Sports Med*. 2019;47(8):1844-1853.
3. Behan FP, Maden-Wilkinson TM, Pain MTG, Folland JP. Sex differences in muscle morphology of the knee flexors and knee extensors. *PLoS One*. 2018;13(1):e0190903.
4. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc*. 2003;35:119-127.
5. Boden BP, Dean CS, Feagin JA Jr, Garrett WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573-578.
6. DeJong AF, Koldenhoven RM, Hertel J. Cross-correlations between gluteal muscle thickness derived from ultrasound imaging and hip biomechanics during walking gait. *J Electromyogr Kinesiol*. 2020;51:102406.
7. Fung DT, Zhang LQ. Modeling of ACL impingement against the intercondylar notch. *Clin Biomech*. 2003;18(10):933-941.
8. Giles LS, Webster KE, McClelland JA, Cook J. Can ultrasound measurements of muscle thickness be used to measure the size of individual quadriceps muscles in people with patellofemoral pain? *Phys Ther Sport*. 2015;16(1):45-52.
9. Guadagnin EC, Priario LAA, Carpes FP, Vaz MA. Correlation between lower limb isometric strength and muscle structure with normal and challenged gait performance in older adults. *Gait Posture*. 2019;73:101-107.
10. Guelich DR, Xu D, Koh JL, Nuber GW, Zhang LQ. Different roles of the medial and lateral hamstrings in unloading the anterior cruciate ligament. *Knee*. 2016;23(1):97-101.
11. Herman DC, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B, Padua DA. The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *Am J Sports Med*. 2008;36(4):733-740.
12. Hewett TE, Myer GD. The mechanical connection between trunk knee and ACL injury. *Exerc Sport Sci Rev*. 2011;39(4):161-166.
13. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492-501.
14. Jeong J, Choi DH, Kim P, Shin CS. The effect of strength training of medial quadricep and hamstring on muscle thickness and quality. *Trans Korean Soc Mech Eng B*. 2020;44:575-582.
15. Jeong J, Choi DH, Shin CS. Core strength training can alter neuromuscular and biomechanical risk factors for anterior cruciate ligament injury. *Am J Sports Med*. 2021;49(1):183-192.
16. Jeong J, Choi DH, Song Y, Shin CS. Muscle strength training alters muscle activation of the lower extremity during side-step cutting in females. *J Mot Behav*. 2020;52(6):703-712.
17. Kiapour AM, Demetropoulos CK, Kiapour A, et al. Strain response of the anterior cruciate ligament to uniplanar and multiplanar loads during simulated landings. *Am J Sports Med*. 2016;44(8):2087-2096.
18. Kristianslund E, Krosshaug T, Van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech*. 2012;45(4):666-671.
19. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35(3):359-367.
20. Lynn SK, Costigan PA. Changes in the medial-lateral hamstring activation ratio with foot rotation during lower limb exercise. *J Electromyogr Kinesiol*. 2009;19(3):e197-e205.

21. Maniar N, Schache AG, Sritharan P, Opar DA. Non-knee-spanning muscles contribute to tibiofemoral shear as well as valgus and rotational joint reaction moments during unanticipated sidestep cutting. *Sci Rep*. 2018;8(1):2501.
22. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GAM, Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res*. 1995;13(6):930-935.
23. McLean SG, Huang X, van den Bogert AJ. Association between lower extremity posture at contact and peak knee valgus moment during sidestepping: implications for ACL injury. *Clin Biomech*. 2005;20(8):863-870.
24. McLean SG, Lipfert SW, van den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc*. 2004;36(6):1008-1016.
25. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004;32(4):1002-1012.
26. Palmer TB, Akehi K, Thiele RM, Smith DB, Thompson BJ. Reliability of panoramic ultrasound imaging in simultaneously examining muscle size and quality of the hamstring muscles in young, healthy males and females. *Ultrasound Med Biol*. 2015;41(3):675-684.
27. Park HS, Wilson NA, Zhang LQ. Gender differences in passive knee biomechanical properties in tibial rotation. *J Orthop Res*. 2008;26(7):937-944.
28. Roewer BD, Ford KR, Myer GD, Hewett TE. The "impact" of force filtering cut-off frequency on the peak knee abduction moment during landing: artefact or "artifiction"? *Br J Sports Med*. 2014;48(6):464-468.
29. Shalhoub S, Fitzwater FG, Cyr AJ, Maletsky LP. Variations in medial-lateral hamstring force and force ratio influence tibiofemoral kinematics. *J Orthop Res*. 2016;34(10):1707-1715.
30. Shin CS, Chaudhari AM, Andriacchi TP. Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Med Sci Sports Exerc*. 2011;43(8):1484-1491.
31. Strasser EM, Draskovits T, Praschak M, Quittan M, Graf A. Association between ultrasound measurements of muscle thickness, pennation angle, echogenicity and skeletal muscle strength in the elderly. *Age*. 2013;35(6):2377-2388.
32. Willis FB, Burkhardt EJ, Walker JE, Johnson MA, Spears TD. Preferential vastus medialis oblique activation achieved as a treatment for knee disorders. *J Strength Cond Res*. 2005;19(2):286-291.
33. Winter DA, Patla AE, Frank JS, Walt SE. Biomechanical walking pattern changes in the fit and healthy elderly. *Phys Ther*. 1990;70(6):340-347.
34. Wünschel M, Leichtle U, Obloh C, Wülker N, Müller O. The effect of different quadriceps loading patterns on tibiofemoral joint kinematics and patellofemoral contact pressure during simulated partial weight-bearing knee flexion. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(7):1099-1106.
35. Xu D, Cen X, Wang M, et al. Temporal kinematic differences between forward and backward jump-landing. *Int J Environ Res Public Health*. 2020;17(18):6669.
36. Zhang LQ, Xu D, Wang G, Hendrix RW. Muscle strength in knee varus and valgus. *Med Sci Sports Exerc*. 2001;33(7):1194-1199.

For article reuse guidelines, please visit Sage's website at http://www.sagepub.com/journals-permissions.