original research

Hip-Extensor Strength, Trunk Posture, and Use of the Knee-Extensor Muscles During Running

Hsiang-Ling Teng, PhD, PT*†; Christopher M. Powers, PhD, PT, FACSM, FAPTA†

*Department of Physical Therapy, California State University, Long Beach; †Division of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles

Context: Diminished hip-muscle performance has been proposed to contribute to various knee injuries.

Objective: To determine the association between hip-extensor muscle strength and sagittal-plane trunk posture and the relationships among hip-extensor muscle strength and hip- and knee-extensor work during running.

Design: Descriptive laboratory study.

Setting: Musculoskeletal biomechanical laboratory.

Patients or Other Participants: A total of 40 asymptomatic recreational runners, 20 men (age = 27.1 ± 7.0 years, height = 1.74 ± 0.69 m, mass = 71.1 ± 8.2 kg) and 20 women (age = 26.2 ± 5.8 years, height = 1.65 ± 0.74 m, mass = 60.6 ± 6.6 kg), participated.

Main Outcome Measure(s): Maximum isometric strength of the hip extensors was assessed using a dynamometer. Sagittal-plane trunk posture (calculated relative to the global vertical axis) and hip- and knee-extensor work (sum of energy absorption and generation) during the stance phase of running were quantified while participants ran over ground at a controlled speed of 3.4 m/s. We used Pearson product moment correlations to examine the relationships among hip-extensor strength, mean sagittal-plane trunk-flexion angle, hip-extensor work, and knee-extensor work.

Results: Hip-extensor strength was correlated positively with trunk-flexion angle ($r = 0.55$, $P < .001$) and hip-extensor work ($r = 0.46$, $P = .003$). It was correlated inversely with knee-extensor work ($r = -0.39$, $P = .01$). All the correlations remained after adjusting for sex.

Conclusions: Our findings suggest that runners with hip-extensor weakness used a more upright trunk posture. This strategy led to an overreliance on the knee extensors and may contribute to overuse running injuries at the knee.

Key Words: energetics, kinetics, gait

Key Points

- Runners with weaker hip extensors exhibited a more upright trunk posture, less hip-extensor work, and more knee-extensor work, whereas runners with stronger hip-extensors exhibited a more forward-leaning trunk posture, more hip-extensor work, and less knee-extensor work during running.
- Hip-extensor weakness was related to a more upright trunk posture, which in turn can minimize the demand on the hip extensors during running.
- Using a more upright trunk posture appeared to be associated with an overreliance on the knee extensors during running and may contribute to overuse injuries at the knee.

A high incidence of lower extremity running injuries has been reported in the literature, with values ranging from 19% to 79%.[1,2] Of all lower extremity running injuries, the knee is the most common injury site, and half of knee injuries are related to the patellofemoral joint.[1,2] In recent studies, researchers have suggested that sagittal-plane trunk posture may play an important role in the development of knee injuries. Specifically, a more upright trunk posture has been associated with higher knee-extensor moments and patellofemoral-joint stress during running.[3,4] Moreover, incorporating a forward-lean trunk posture has been shown to reduce knee-extensor moment, knee energy absorption, and patellofemoral stress during running.[4–6]

The hip and knee extensors work in conjunction to decelerate and accelerate the body's center of mass during the stance phase of running. During the deceleration phase, they contract eccentrically to counteract the external hip- and knee-flexion moments (ie, negative work).[7–10] After the deceleration phase, they contract concentrically to extend the hip and knee joints and accelerate the center of mass forward (ie, positive work).[7–10] Given the interdependence of the hip and knee extensors, a decrease in hip-extensor work may lead to an increase in knee-extensor work during running that is similar to what has been reported after anterior cruciate ligament reconstruction during gait.[11]

Diminished hip-muscle strength has been commonly reported in individuals with knee conditions, such as patellofemoral pain, iliotibial band syndrome, and osteoarthritis, and may underlie the higher risk of anterior cruciate ligament injury in females.[12–16] Research[17] has suggested that individuals with reduced hip-muscle strength may adopt altered movement strategies to reduce mechanical demands on the hip, but in turn, these strategies predispose the knee joint to higher-than-normal loading in the sagittal and frontal planes. A more upright trunk posture has been

Table 1. Participant Demographics (Mean ± SD)

Variable	Men (n = 20)	Women (n = 20)
Age, y	27.1 ± 7.0	26.2 ± 5.8
Height, m	1.74 ± 0.69	1.65 ± 0.74
Mass, kg	71.1 ± 8.2	60.6 ± 6.6
Running distance per week, km	22.1 ± 10.5	22.7 ± 10.9

associated with lower hip-extensor moments and higher knee-extensor moments during walking,[18] hop landing,[19] and stair ascent.[20] Therefore, this posture may be used as a compensatory strategy during running to reduce the work of the hip extensors.

Whereas the effect of diminished hip-abductor strength on trunk and lower extremity biomechanics has been studied,[13,21–24] few researchers have investigated the relationships among hip-extensor strength, trunk posture, and lower extremity kinetics during dynamic activities. Stearns et al[25] reported that individuals with weaker hip extensors relative to the knee extensors exhibited higher knee-extensor moments relative to hip-extensor moments during a double-legged drop-jump task. The greater contribution of the knee extensors relative to the hip extensors in these individuals may have resulted from a more upright trunk posture. However, Stearns et al[25] did not assess trunk kinematics. Ford et al[26] observed that hip-extensor strength was associated with transverse-plane trunk motion during running but not with sagittal-plane or frontal-plane motion. They quantified trunk kinematics in range of motion,[26] which may not reflect the actual trunk posture relative to the pelvis. In addition, they did not evaluate lower extremity kinetics.

Therefore, the primary purpose of our study was to examine the associations between hip-extensor muscle strength and sagittal-plane trunk posture during running. We also evaluated the relationships among hip-extensor muscle strength and hip- and knee-extensor work during running. We hypothesized that hip-extensor strength would be positively correlated with trunk-flexion angle and hip-extensor work and inversely correlated with knee-extensor work. An understanding of these relationships will inform the development of rehabilitation and injury-prevention efforts to reduce knee injuries during running.

METHODS

Participants

A total of 40 recreational runners (20 men, 20 women) participated (Table 1). They ran at least 8.05 km per week and were natural heel strikers, which was verified using sagittal-plane images obtained from high-speed video with a sampling rate of 125 Hz. Volunteers were excluded from participation if they reported any of the following: (1) lower extremity or low back pain at the time of the study, (2) a history of lower extremity or low back surgery, and (3) a lower extremity or low back pathologic condition that caused pain or discomfort during running in the 6 months before the study. All participants provided written informed consent, and the study was approved by the University of Southern California Health Sciences Institutional Review Board.
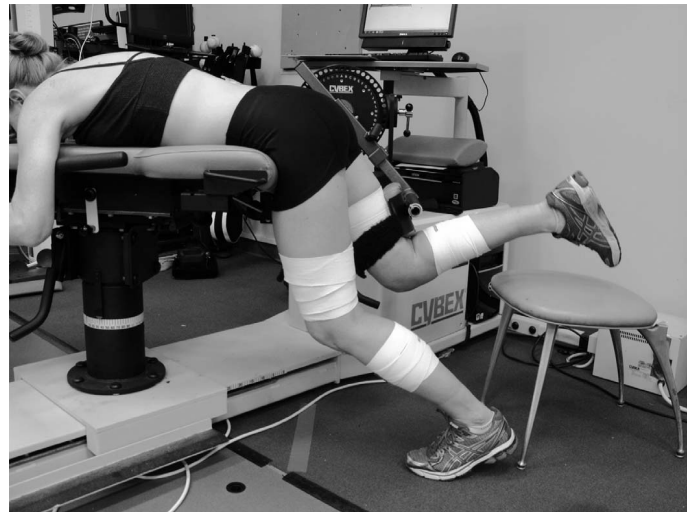

Figure 1.   Testing position for hip-extensor muscle strength.

Instrumentation

Hip-extensor strength was assessed using a motor-driven dynamometer (Cybex with HUMAX NORM; Computer Sports Medicine Inc, Stoughton, MA). The dynamometer provided force values in newton-meters, with a precision of 0.02% (full scale). The sampling frequency was 100 Hz. Three-dimensional trunk and lower extremity kinematics were collected using an 11-camera motion-capture system (Qualisys, Gothenburg, Sweden) at a sampling rate of 250 Hz. Ground reaction forces were obtained at a sampling rate of 1500 Hz using a single force plate (AMTI, Newton, MA).

Procedures

Participants wore shorts, tank tops, and their personal running shoes during the evaluation. We obtained data from the *dominant leg*, which was defined as the lower extremity that the participant preferred to use when kicking a ball.

To assess isometric hip-extensor strength, participants were positioned prone on the dynamometer testing table with the nondominant leg on the ground (Figure 1). The dominant leg was positioned with the hip and knee at 60° and 90° of flexion, respectively.[25,27] We aligned the axis of the dynamometer with the greater trochanter of the dominant leg. The lower end of the resistance pad was positioned just proximal to the lateral knee-joint line and secured to the distal thigh with straps. We instructed participants to push with maximal effort against the resistance pad. Oral encouragement was given throughout testing. Three trials of 5-second maximal voluntary isometric contractions were obtained. We provided a 40-second break between trials to minimize muscle fatigue.[28] Participants performed 2 practice trials before the test to become familiar with the task.

After the strength measurement, we placed 21 reflective 14-mm spherical anatomical markers on the following bony landmarks: ends of the second toes, first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral epicondyles of the femurs, greater trochanters, iliac crests, L5–S1 junction, and acromioclavicular joints. In addition, tracking marker clusters mounted on semirigid plastic plates were placed on the lateral surfaces of the thighs,

Table 2. Pearson Product Moment Correlations of Hip-Extensor Strength With Trunk Posture and Knee and Hip Work During Running

Variable	Simple Correlation		Partial Correlation[a]	
	Coefficient (95% CI)	P Value	Coefficient (95% CI)	P Value
Trunk-flexion angle	0.55 (0.28, 0.82)	<.001	0.52 (0.23, 0.82)	.001
Hip-extensor work	0.46 (0.16, 0.75)	.003	0.42 (0.11, 0.74)	.01
Knee-extensor work	−0.39 (−0.70, −0.09)	.01	−0.34 (−0.66, −0.02)	.04

Abbreviation: CI, confidence interval.

[a] Adjusted for sex.

shanks, and heel counters of the shoes. We obtained a standing calibration trial to define the segmental coordinate systems and joint axes. After the calibration trial, the anatomical markers were removed except for those at the iliac crests, L5–S1 junction, and acromioclavicular joints. The tracking markers remained on participants throughout the entire data-collection session.

Next, participants were instructed to run at a controlled speed of 3.4 m/s along a 14-m runway. We used a standardized velocity because running speed can influence hip and knee kinetics.[7,8,29] Two photoelectric sensors were placed 6 m apart in the middle of the runway to delineate the data-collection area. Running speed was calculated within the 6-m data-collection area. Practice trials were permitted to allow participants to become familiar with the running speed. Five successful running trials were obtained. A trial was considered successful if the foot of the dominant leg fell within the borders of the force plate and the running speed was ±5% of the target velocity.

Data Analysis

During the strength test, torque production of the hip-extensor muscles was quantified using MATLAB software (The MathWorks Inc, Natick, MA). Specifically, the maximum 1-second average obtained during the strength measurement was exported for statistical analysis. Kinematic and kinetic data were processed and analyzed using Visual3D software (C-Motion, Germantown, MD). Data for the marker trajectories were low-pass filtered at 12 Hz using a fourth-order Butterworth filter. We defined the trunk segment by markers placed on bilateral iliac crests and acromioclavicular joints.[30] We modeled the pelvis and trunk segments as cylinders and the lower extremity segments as frusta of cones. The local orthogonal coordinate systems of the trunk, pelvis, thigh, shank, and foot segments were derived from the standing calibration trial.

Joint kinematics were calculated using the Cardan rotation sequence in the order of flexion-extension, abduction-adduction, and internal-external rotation.[31] We calculated the trunk angle as the motion of the trunk segment relative to the global coordinate system (global vertical axis). Lower extremity kinematics were calculated as the motion of the distal segment relative to the proximal reference. Net joint moments were computed using inverse-dynamics equations. Kinetic data were expressed as internal moments and normalized to body mass.

We calculated net joint power as the scalar product of angular velocity and net joint moment. The positive and negative values of the joint power were used to identify phases of energy generation and absorption, respectively.[3,32,33] We calculated energy generation and absorption performed by the hip and knee extensors by integrating the respective power-time curves during the stance phase of running. For example, energy absorbed by the hip extensors was computed as the integral of negative power with respect to the time when the hip-extensor moment was positive. The absolute values of energy absorption and generation were summed to provide an estimation of the total work performed by the hip and knee extensors.

Mean trunk-flexion angle, hip-extensor work, and knee-extensor work during the stance phase were exported for statistical analysis. We defined the *stance phase* as when the vertical ground reaction force exceeded 30 N. All variables were calculated for each stride, and the average values of 5 strides were used for statistical analysis.

Statistical Analysis

Pearson product moment correlations were used to examine the relationships among hip-extensor strength, mean sagittal-plane trunk-flexion angle, hip-extensor work, and knee-extensor work. To control for the influence of sex, partial correlations were performed to examine the aforementioned relationships. We set the α level at .05. All statistical analyses were performed using SPSS (version 22.0; IBM Corporation, Armonk, NY).

RESULTS

Results of the Pearson product moment correlations and partial correlations are presented in Table 2. A positive correlation between hip-extensor strength and trunk-flexion angle was observed ($r = 0.55$, $P < .001$; Figure 2). Moreover, hip-extensor strength exhibited a positive correlation with hip-extensor work ($r = 0.46$, $P = .003$; Figure 3) and an inverse correlation with knee-extensor work ($r = -0.39$, $P = .01$; Figure 4). After adjusting for sex, hip-extensor strength remained correlated with trunk-flexion angle, hip-extensor work, and knee-extensor work (Table 2).

DISCUSSION

We sought to elucidate the influence of hip-extensor strength on sagittal-plane trunk posture and hip and knee energy absorption and generation during running. As hypothesized, hip-extensor strength was correlated with trunk posture and hip- and knee-extensor work during running. In total, hip-extensor strength explained 30.5% of the variance in the mean sagittal-plane trunk posture and 21.2% and 15.2% of the variance in the hip- and knee-extensor work, respectively.

Our finding that hip-extensor strength was positively correlated with trunk-flexion angle is in contrast to that of Ford et al,[26] who reported no correlation between hip-
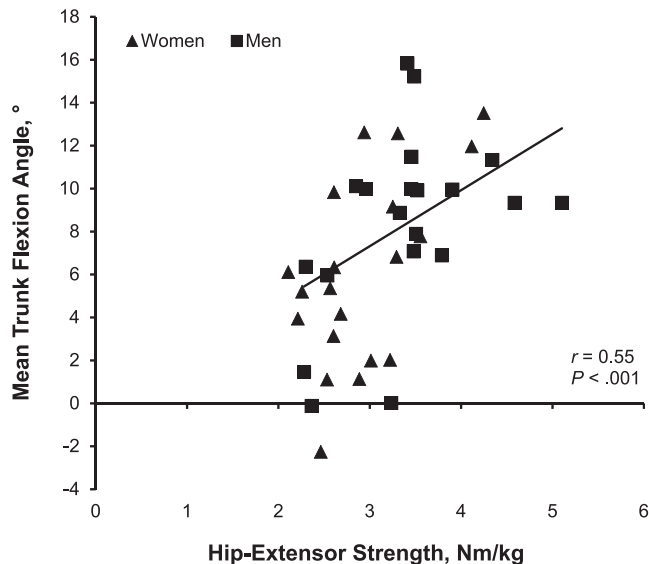
Figure 2. Relationship between the normalized hip-extensor strength and mean trunk-flexion angle during the stance phase of running.

Figure 4. Relationship between the normalized hip-extensor strength and work performed by the knee extensors during the stance phase of running.

extensor strength and sagittal-plane trunk motion. The discrepancy between our study and that of Ford at el[26] may be due to the differences in methods. First, Ford et al[26] quantified trunk motion using range of motion rather than the actual angles that we reported. Whereas range of motion of the trunk may indicate trunk stability, trunk position has been found to be related to lower extremity moments, work, muscle activation, and joint stress[3,4,19,30,34] and, thus, may be a more important variable in lower extremity mechanics. Second, Ford et al[26] evaluated isokinetic hip-extensor strength; we measured isometric strength. Whereas isokinetic strength may better reflect muscle performance during dynamic motion, we used isometric strength testing to obtain a general measure of muscle performance that could be reproduced more readily in a clinical setting without a dynamometer or with inexpensive equipment.
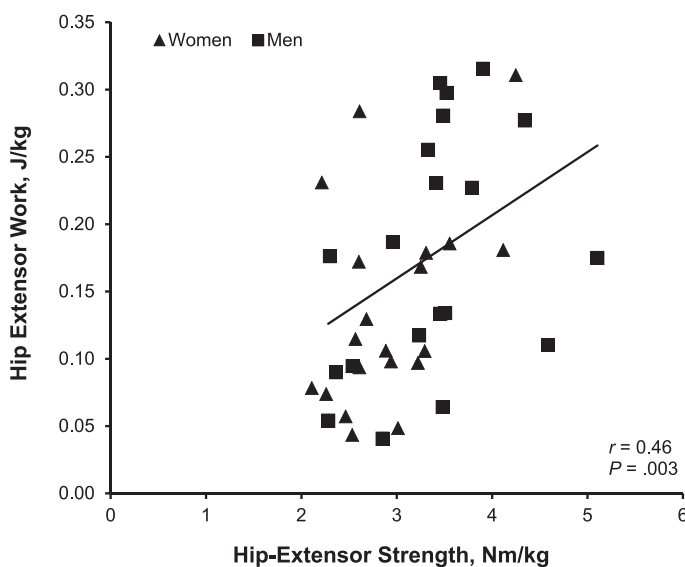

Figure 3. Relationship between the normalized hip-extensor strength and work performed by the hip extensors during the stance phase of running.
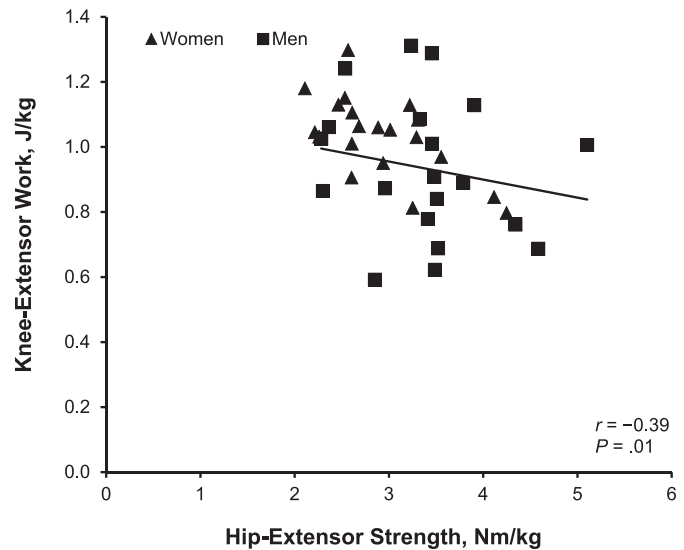
We also noted that individuals with weaker hip extensors demonstrated less hip-extensor and more knee-extensor work during running. This is consistent with the findings of Stearns et al,[25] who reported that individuals with diminished hip-extensor strength relative to knee-extensor strength exhibited higher knee-extensor moments relative to hip-extensor moments during a drop-jump task. Taken together, our observations and those of Stearns et al[25] suggest that diminished hip-extensor strength may contribute to an overreliance on the knee extensors during dynamic activities. An overreliance on the knee extensors indicates higher mechanical loads on the tibiofemoral and patellofemoral joints. For example, increased quadriceps force has been associated with increased patellofemoral-joint stress and patellofemoral pain[4,35–37] and the presence and progression of patellofemoral-joint cartilage lesions.[38,39] Our observations may partially explain the results from previous prospective[40] and retrospective[41] studies in which hip-muscle weakness was found to be associated with the development of various knee injuries.

The findings of our study suggest that strength training of the hip extensors will likely influence the mechanical demands on the hip and knee extensors during running. Further research is warranted to evaluate the effect of hip-extensor strength training on altering trunk posture and reducing knee injuries in runners. However, less than 31% of the variance in trunk posture and hip- and knee-extensor work was explained by hip-extensor strength.

Several limitations need to be considered when interpreting our results. First, given the cross-sectional design of the study, causal relationships cannot be drawn between hip-extensor strength and trunk and lower extremity biomechanics during running. For example, diminished hip-extensor strength may lead to or could result from a more upright trunk posture during running. Second, hip-extensor strength was quantified isometrically. Measures of muscle endurance or isokinetic muscle-performance testing may have yielded stronger correlations among trunk posture and lower extremity biomechanics. Third, we recruited only pain-free volunteers. Given that pain may

influence running biomechanics, caution should be taken when generalizing the results to symptomatic runners. Fourth, participants were all heel strikers and ran at a controlled speed. It is unclear whether the observed correlation would hold true for forefoot and midfoot strikers or different running speeds. Fifth, we did not standardize running shoes because we wanted to ensure that the participants would run with their most natural form. However, the type of running shoe could have influenced knee and hip work.

CONCLUSIONS

Runners with diminished hip-extensor strength exhibited a more upright trunk posture, less work performed by the hip extensors, and more work performed by the knee extensors. In contrast, runners with greater hip-extensor strength exhibited a more forward-leaning trunk, more work performed by the hip extensors, and less work performed by the knee extensors. Our findings suggest that runners with hip-extensor weakness used a more upright trunk posture during running to minimize the demand on the hip extensors. In turn, this strategy appeared to lead to an overreliance on the knee extensors and may contribute to overuse running injuries at the knee.

REFERENCES

1. van Gent RN, Siem D, van Middelkoop M, et al. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *Br J Sports Med*. 2007;41(8):469–480.
2. Taunton JE, Ryan MB, Clement DB, McKenzie DC, Lloyd-Smith DR, Zumbo BD. A retrospective case-control analysis of 2002 running injuries. *Br J Sports Med*. 2002;36(2):95–101.
3. Teng HL, Powers CM. Influence of trunk posture on lower extremity energetics during running. *Med Sci Sports Exerc*. 2015;47(3):625–630.
4. Teng HL, Powers CM. Sagittal plane trunk posture influences patellofemoral joint stress during running. *J Orthop Sports Phys Ther*. 2014;44(10):785–792.
5. Goss DL, Gross MT. A comparison of negative joint work and vertical ground reaction force loading rates in Chi runners and rearfoot-striking runners. *J Orthop Sports Phys Ther*. 2013;43(10):685–692.
6. Arendse RE, Noakes TD, Azevedo LB, Romanov N, Schwellnus MP, Fletcher G. Reduced eccentric loading of the knee with the pose running method. *Med Sci Sports Exerc*. 2004;36(2):272–277.
7. Schache AG, Blanch PD, Dorn TW, Brown NA, Rosemond D, Pandy MG. Effect of running speed on lower limb joint kinetics. *Med Sci Sports Exerc*. 2011;43(7):1260–1271.
8. Schache AG, Brown NA, Pandy MG. Modulation of work and power by the human lower-limb joints with increasing steady-state locomotion speed. *J Exp Biol*. 2015;218(15):2472–2481.
9. Ferber R, Davis IS, Williams DS. Gender differences in lower extremity mechanics during running. *Clin Biomech (Bristol, Avon)*. 2003;18(4):350–357.
10. Novacheck T. The biomechanics of running. *Gait Posture*. 1998;7(1):77–95.
11. Devita P, Hortobagyi T, Barrier J. Gait biomechanics are not normal after anterior cruciate ligament reconstruction and accelerated rehabilitation. *Med Sci Sports Exerc*. 1998;30(10):1481–1488.
12. Reiman MP, Bolgla LA, Lorenz D. Hip functions influence on knee dysfunction: a proximal link to a distal problem. *J Sport Rehabil*. 2009;18(1):33–46.
13. Willson JD, Davis IS. Lower extremity strength and mechanics during jumping in women with patellofemoral pain. *J Sport Rehabil*. 2009;18(1):76–90.
14. Cinchanowski HR, Schmitt JS, Johnson RJ, Niemuth PE. Hip strength in collegiate female athletes with patellofemoral pain. *Med Sci Sports Exerc*. 2007;39(8):1227–1232.
15. Sled EA, Khoja L, Deluzio KJ, Olney SJ, Culham EG. Effect of a home program of hip abductor exercises on knee joint loading, strength, function, and pain in people with knee osteoarthritis: a clinical trial. *Phys Ther*. 2010;90(6):895–904.
16. Hinman RS, Hunt MA, Creaby MW, Wrigley TV, McManus FJ, Bennell KL. Hip muscle weakness in individuals with medial knee osteoarthritis. *Arthritis Care Res*. 2010;62(8):1190–1193.
17. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther*. 2010;40(2):42–51.
18. Leteneur S, Simoneau E, Gillet C, Dessery Y, Barbier F. Trunk's natural inclination influences stance limb kinetics, but not body kinematics, during gait initiation in able men. *PLoS One*. 2013;8(1): e55256.
19. Oberländer KD, Brüggemann G-P, Höher J, Karamanidis K. Reduced knee joint moment in ACL deficient patients at a cost of dynamic stability during landing. *J Biomech*. 2012;45(8):1387–1392.
20. Asay JL, Mündermann A, Andriacchi TP. Adaptive patterns of movement during stair climbing in patients with knee osteoarthritis. *J Orthop Res*. 2009;27(3):325–329.
21. Geiser CF, O'Connor K, Earl JEE. Effects of isolated hip abductor fatigue on frontal plane knee mechanics. *Med Sci Sports Exerc*. 2010; 42(3):535–545.
22. Jacobs CA, Uhl TL, Mattacola CG, Shapiro R, Rayens WS. Hip abductor function and lower extremity landing kinematics: sex differences. *J Athl Train*. 2007;42(1):76–83.
23. Hollman JH, Ginos BE, Kozuchowski J, Vaughn AS, Krause DA, Youdas JW. Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. *J Sport Rehabil*. 2009;18(1):104–117.
24. Patrek MF, Kernozek TW, Willson JD, Wright GA, Doberstein ST. Hip-abductor fatigue and single-leg landing mechanics in women athletes. *J Athl Train*. 2011;46(1):31–42.
25. Stearns KM, Keim RG, Powers CM. Influence of relative hip and knee extensor muscle strength on landing biomechanics. *Med Sci Sports Exerc*. 2013;45(5):935–941.
26. Ford KR, Taylor-Haas JA, Genthe K, Hugentobler J. Relationship between hip strength and trunk motion in college cross-country runners. *Med Sci Sports Exerc*. 2013;45(6):1125–1130.
27. Worrell TW, Karst G, Adamczyk D, et al. Influence of joint position on electromyographic and torque generation during maximal voluntary isometric contractions of the hamstrings and gluteus maximus muscles. *J Orthop Sports Phys Ther*. 2001;31(12):730–740.
28. Stratford P, Bruulsema A, Maxwell B. The effect of inter-trial rest interval on the assessment of isokinetic thigh muscle torque. *J Orthop Sports Phys Ther*. 1990;11(8):362–366.
29. Belli A, Kyröläinen H, Komi PV. Moment and power of lower limb joints in running. *Int J Sports Med*. 2002;23(2):136–141.
30. Mündermann A, Asay JL, Mündermann L, Andriacchi TP. Implications of increased medio-lateral trunk sway for ambulatory mechanics. *J Biomech*. 2008;41(1):165–170.
31. Wu G, Siegler S, Allard P, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion: part I. Ankle, hip, and spine. International Society of Biomechanics. *J Biomech*. 2002;35(4):543–548.
32. Winter DA. Mechanical work, energy, and power. In: Winter DA. *Biomechanics and Motor Control of Human Movement*. 4th ed. Hoboken, NJ: Wiley; 2009:139–175.
33. Sorenson SC, Arya S, Souza RB, Pollard CD, Salem GJ, Kulig K. Knee extensor dynamics in the volleyball approach jump: the

influence of patellar tendinopathy. *J Orthop Sports Phys Ther*. 2010; 40(9):568–576.

34. Blackburn JT, Padua DA. Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech (Bristol, Avon)*. 2008;23(3):313–319.

35. Ho KY, Blanchette MG, Powers CM. The influence of heel height on patellofemoral joint kinetics during walking. *Gait Posture*. 2012; 36(2):271–275.

36. Farrokhi S, Keyak JH, Powers CM. Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: a finite element analysis study. *Osteoarthr Cartil*. 2011;19(3):287–294.

37. Heino Brechter J, Powers CM. Patellofemoral stress during walking in persons with and without patellofemoral pain. *Med Sci Sports Exerc*. 2002;34(10):1582–1593.

38. Teng HL, MacLeod TD, Kumar D, Link TM, Majumdar S, Souza RB. Individuals with isolated patellofemoral joint osteoarthritis exhibit higher mechanical loading at the knee during the second half of the stance phase. *Clin Biomech (Bristol, Avon)*. 2015;30(4):383–390.

39. Teng HL, MacLeod TD, Link TM, Majumdar S, Souza RB. Higher knee flexion moment during the second half of the stance phase of gait is associated with magnetic resonance imaging progression of patellofemoral joint osteoarthritis. *J Orthop Sports Phys Ther*. 2015; 45(9):656–664.

40. Leetun DT, Ireland ML, Willson JD, Ballantyne BT, Davis IS. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc*. 2004;36(6):926–934.

41. Nadler SF, Malanga GA, DePrince M, Stitik TP, Feinberg JH. The relationship between lower extremity injury, low back pain, and hip muscle strength in male and female collegiate athletes. *Clin J Sport Med*. 2000;10(2):89–97.

Address correspondence to Hsiang-Ling Teng, PhD, PT, Department of Physical Therapy, Engineering Technology 130, California State University, Long Beach, 1250 Bellflower Boulevard, Long Beach, CA 90840. Address e-mail to hsiang-ling.teng@csulb.edu.