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Original Research

Fatigue-Induced Hip-Abductor Weakness and Changes in Biomechanical Risk Factors for Running-Related Injuries

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Context: Despite overlap between hip-abductor (HABD) weakness and fatigue-induced changes in running, the interaction of these theorized contributors to running injuries has been underevaluated.

Objective: To assess the effects of a fatiguing run on HABD torque and evaluate the correlation between HABD torque and previously identified running-related injury pathomechanics while participants were rested or fatigued.

Design: Crossover study.

Setting: Laboratory.

Patients or Other Participants: A total of 38 healthy, physically active males (age = 21.61 ± 4.02 years, height = 1.78 ± 0.08 m, body mass = 76.00 ± 12.39 kg).

Intervention(s): Data collection consisted of rested-state collection, a fatiguing treadmill-run protocol, and fatigued-state collection. For the HABD measures, side-lying handheld-dynamometer isometric tests were performed and converted to torque using femur length. For the gait analysis, kinematic (240 Hz) and kinetic (960 Hz) running (4.0 m/s) data were collected for 3 trials. The fatigue protocol involved a graded exercise test and 80% $\dot{V}O_2max$ run to exhaustion. Immediately after the run, fatigued-state measures were obtained.

Main Outcome Measure(s): Variables of interest were HABD torque and peak angles, velocities, and moments for hip and knee adduction and internal rotation. Differences between conditions were compared using paired *t* tests. Pearson correlation coefficients were calculated to evaluate relationships between HABD torque and biomechanical variables.

Results: Fatigue decreased HABD torque and increased hip-adduction angle, knee-adduction velocity, and hip and knee internal-rotation velocities and moments (all P values $< .05$). In the rested state, HABD torque was correlated with hip-adduction velocity (r = –0.322, P = .049). In the fatigued state, HABD torque was correlated with hip-adduction velocity (r = –0.393, P = .015), hip internal-rotation velocity (r = –0.410, P = .01), and knee-adduction angle (r = 0.385, P = .017) and velocity (r = –0.378, P = .019).

Conclusions: Changes in joint velocities due to fatigue and correlations between HABD torque and hip- and knee-joint velocities highlight the need to consider not only the quantity of HABD strength but also the rate of eccentric control of HABDs.

Key Words: knee overuse injuries, gait analysis, hip-abductor strength

Key Points

- A fatiguing run decreased isometric hip-abductor (HABD) torque while increasing peak hip-adduction angle and velocity and internal-rotation velocities and moments at the hip and knee.
- At rest, HABD torque was correlated with hip-adduction velocity. After the fatiguing run, it was also correlated with hip internal-rotation velocity, knee-adduction angle, and knee-adduction velocity.
- Correlations between HABD torque and hip- and knee-joint velocities indicate the need to evaluate the rate of eccentric control of the hip abductors in addition to quantifying strength when exploring the relationship between the HABDs and running-related injuries.

Up to 79% of people who participated in running for fitness or sport sustained a lower extremity overuse injury.[1] In addition, populations who consistently incorporate running into their training programs, such as military members, commonly experience lower extremity overuse injuries.[2–4] Considering the popularity of running and the incorporation of running in physical training programs, the high incidence of overuse injuries has resulted in a substantial need for targeted rehabilitation and injury-prevention strategies. The development of an overuse, running-related injury is multifactorial in nature.[5] A person's training,[6] strength,[7] biomechanical,[6,8,9] and anatomical[6,9] profiles have all been prospectively attributed to injury risk. Modifying training loads provides an easily accessible and direct route to influencing injury risk. However, altering training loads and mileage may not be feasible due to pending personal (eg, marathon entry) or professional (eg, military training) goals. Therefore, pathomechanics and intrinsic risk factors are often investigated as potential intervention points that would augment, or even supersede, training-load modifications. Sufficient strength of the hip abductors (HABDs), including the gluteus medius, gluteus minimus, and tensor fasciae latae, is required to maintain stability during the stance phase of gait. Thus, HABD strength has become an appealing target for rehabilitation and injury-prevention strategies. Motions eccentrically controlled by the HABDs have been established as biomechanical risk factors for lower extremity overuse injuries due to increased hip adduction,[10,11] hip internal rotation,[12] and knee internal rotation[11,13] during running.

The role of HABD strengthening in addressing running-related overuse injuries is supported by retrospective findings of HABD weakness in injured participants compared with healthy control participants.[14,15] Furthermore, HABD strengthening during rehabilitation has been shown to decrease patients' pain.[16–18] However, the ability of HABD strengthening programs to produce beneficial biomechanical changes in the running gait is unclear.[19,20] Additionally, patients with symptomatic iliotibial band syndrome did not demonstrate decreases in HABD strength compared with healthy control individuals.[21,22] Although HABD strengthening may be an effective intervention for those with current lower extremity overuse injuries, its role in injury prevention remains largely theoretical and warrants further biomechanical evaluation.

Isokinetic HABD strength has been negatively correlated with hip-adduction range of motion during running in a healthy population, but no other associations with hip or knee biomechanical variables were found.[23] Yet this evaluation was performed with participants in a rested state,[23] despite running-related fatigue being a theorized factor in the development of overuse injury.[24] Isolated fatigue of the HABDs increased frontal-plane hip excursion through loading and the knee-adduction and hip-abduction angles at initial contact during running and jumping tasks.[25] Similarly, a fatiguing run influenced gait in ways that emulated the biomechanics of persons with decreased HABD strength.[26] Therefore, the purpose of our study was to assess the effect of a fatiguing run on HABD torque and to evaluate correlations, in both rested and fatigued states, between HABD torque and gait mechanics previously associated with running-related injuries. We hypothesized that HABD torque would decrease after a fatiguing run and that gait variables previously associated with lower extremity overuse injury would be negatively correlated with HABD torque.

METHODS

Participants

College-aged males who were active participants in the university's Army Reserve Officers' Training Corps were recruited, as running is consistently used in physical training, and lower extremity overuse injuries are prevalent in this population.[2,8] Before data collection, all participants underwent the informed consent process and signed the consent form approved by the university institutional review board, which also approved the study. All participants completed a brief questionnaire that assessed previous lower extremity injury and a medical history form, both of which were evaluated by an athletic trainer. All participants were considered healthy; those with a physician's orders prohibiting them from being involved in physical activity or who had undergone lower extremity surgery within the previous 6 months were excluded from the study. Only those in the low-risk group according to the American College of Sports Medicine Risk Stratification Categories (https://www.acsm.org/blog-detail/acsm-certified-blog/2019/11/11/acsm-risk-stratification-chart-download) were included in the study. All participants reported right-leg dominance.

Experimental Protocol

A single data-collection session consisted of HABD testing and a biomechanical running analysis before and after a fatiguing run. All participants underwent the following sequence: (1) rested-state HABD testing, (2) rested-state running biomechanics, (3) fatiguing-run protocol, (4) fatigued-state running biomechanics, and (5) fatigued-state HABD testing. The data-collection procedures for HABD testing were identical for the rested and fatigued states. The data-collection procedures for running biomechanics were identical for the rested- and fatigued-state gait analyses, except that participants ran, as opposed to walked, back to the starting position during the latter trials.

Hip-Abductor Strength-Testing Procedures

All isometric HABD measures were collected by the same nonauthor researcher. Isometric HABD was measured in the right limb with the participant lying on his contralateral side with a pillow between the knees to align the hip in frontal-plane neutral position.[27] A Microfet (Hogan Industries, Draper, UT) handheld dynamometer was placed on the lateral femoral epicondyle and secured with a nylon strap anchored to the testing table.[27] Each individual was instructed to maximally abduct the hip against the dynamometer for 3 seconds.[19] Five trials were performed: 2 initial practice trials and 3 data-collection trials. The force production during the final 3 trials was averaged for data analysis.[28] A 30-second rest was allowed between trials.[27]

Running Biomechanics Procedures

Recruits wore their personal running shoes during data collection. Retroreflective markers were attached bilaterally on the thorax, pelvis, and lower extremity in accordance with previously published methods.[8] A 3-dimensional motion-capture system situated along an 18-m runway and Nexus software (Vicon Motion Systems Ltd, Centennial, CO) were used to capture kinematic data. Kinetic data were recorded using a force platform (Advanced Mechanical Technology Inc, Watertown, MA) embedded flush with the runway. Kinetic data were collected at 960 Hz and time synchronized with kinematic data collected at 240 Hz.

A static calibration trial was conducted before the dynamic trials. Markers on the medial femoral condyles and medial malleoli were removed for the dynamic trials. Running data-collection trials began after the calibration trial, which enabled participants to become familiar with the collection procedures and running velocity. A trial was considered *successful* if the individual ran at the correct velocity (4.0 m/s ± 10%), as measured by Speedtrap II (Brower Timing Systems, Draper, UT) infrared sensors placed 4 m apart in the middle third of the runway, and landed with the entire foot on the force plate without apparent targeting. Data from 3 successful running trials were collected for the right limb. To assess exertion and fatigue, we obtained ratings of perceived exertion (RPEs) on the Borg scale and ratings of physical fatigue on the fatigue analog scale (FAS) before and after the running trials.

Fatiguing-Run Protocol Procedures

After completing the rested-state running trials, participants began the fatiguing-run protocol, which consisted of a graded exercise test, 5-minute seated rest, and exhaustive run. The protocol was performed on a treadmill (model Quinton Medtrack T65; Cardiac Science Corp, Bothell, WA). Retroreflective markers on the shoes and anterior-superior iliac spines were removed for the treadmill protocol. Metabolic data were collected using a metabolic cart via open-circuit indirect calorimetry (model TrueOne 2400; ParvoMedics, Inc, Sandy, UT). Calibration was conducted before each data-collection session according to the manufacturer's instructions.

The treadmill protocol began with a speed-blinded modified Astrand graded exercise test (GXT) to determine maximum oxygen consumption ($\dot{V}O_2$max).[29] Standardized instructions were given before the GXT, with an emphasis on the importance of maximum effort. The GXT was stopped when the participant reached the point of volitional exhaustion, and $\dot{V}O_2$max was confirmed based on his meeting 1 of the following criteria: respiratory exchange ratio $>$1.15, plateau in maximum oxygen output with an increase in work rate, blood lactate $>$8 mmol, or RPE $>$17 on termination of the GXT.[29] After the GXT, the individual rested while seated for 5 minutes; blood lactate was collected via finger prick during the final minute of the rest period. The RPE and FAS data were collected immediately at the point of volitional exhaustion on the GXT and after the 5-minute rest period.

After the seated rest, the breathing apparatus was refitted, and the participant began the exhaustive run at a speed calculated to elicit 80% of $\dot{V}O_2$max at a 1% grade. Metabolic data were collected during the first 3 minutes of the run to confirm attainment of 80% $\pm$ 5% $\dot{V}O_2$max. If this metabolic threshold was not met, the speed was increased until it was achieved, and then the breathing apparatus was removed. To gauge the individual's fatigue level, RPE and FAS measurements were collected during the exhaustive run at 5 minutes, the GXT time, twice the GXT time, and the end of the exhaustive run. Participants were encouraged to continue running at the prescribed treadmill speed for twice the length of the GXT or until each reported an RPE $>$17 or an FAS score $>$7, whichever came second. Those who met the RPE and FAS criteria but thought they could not maintain the running pace for twice the length of the GXT were allowed to decrease the pace, within a 5–8 mph (8–13 kph) range, as long as the RPE and FAS criteria were maintained until the time criterion was achieved. If the participant needed to discontinue due to volitional exhaustion, the exhaustive run was ended.

Fatigued-State Data Collection

Immediately after the fatiguing-run protocol, the retroreflective markers were replaced as needed, a static calibration trail was repeated, and data collection for the fatigued-state biomechanics began, followed by the isometric HABD measures. Collection of the fatigued-state running biomechanical, RPE, FAS, and isometric HABD measures was performed using the same methods as for the rested state, with the addition of running between gait trials. Water was available to each person during all aspects of data collection.

Data Reduction and Statistical Analysis

Data from participants who did not meet at least 1 of the criteria for $\dot{V}O_2$max were excluded from analysis. The kinematic and kinetic data were filtered using a low-pass, fourth-order Butterworth filter with a 10-Hz cutoff frequency. Kinematic variables of interest were peak angles and velocities for hip adduction, hip internal rotation, knee adduction (varus), and knee internal rotation. Kinetic data used for joint moments were filtered before moment calculations. Kinetic variables of interest were peak hip and knee adduction and internal-rotation moments. All moments were expressed as external moments and normalized to body mass. Variables of interest were identified from each of the 3 successful trials, and an ensemble mean was used for analysis. Isometric HABD measures were normalized to body mass (N/kg) and then converted to torque (Nm/kg) by multiplying by the length of the lever arm.[17,28] The *lever arm* was the distance (meters) from the greater trochanter to the lateral femoral epicondyle, where the dynamometer was placed.[28]

We analyzed the data using SPSS (version 24.0; IBM Corp, Armonk, NY) with the α level set a priori at $P < .05$. Differences in HABD torque, biomechanical variables, and the RPE and FAS measures between conditions (rested versus fatigued) were compared using paired *t* tests. Pearson correlation coefficients were calculated to evaluate correlations between (1) rested isometric HABD torque and rested biomechanical variables, (2) fatigued-state isometric HABD torque and fatigued-state biomechanical variables, and (3) percentage change in isometric HABD torque and the biomechanical variables due to fatigue.

RESULTS

A total of 38 males successfully completed the study protocol, and their data were analyzed. Five participants terminated the exhaustive run due to volitional exhaustion, and the exhaustive runs of 33 participants were ended because the termination criteria outlined in the "Methods" were met. Participant demographics and data-collection metrics are reported in Table 1. Rested- and fatigued-state HABD torque and the biomechanical variables of interest are provided in Table 2. The HABD torque decreased from the rested to the fatigued state. Hip-adduction angle, hip internal-rotation velocity, hip internal-rotation moment, knee-adduction (varus) velocity, knee internal-rotation velocity, and knee internal-rotation moment increased from the rested to the fatigued state.

In the rested state, HABD torque was significantly correlated with maximum hip-adduction velocity (r = –0.322, P = .049). In the fatigued state (Figure), HABD torque was correlated with maximum hip-adduction velocity (r = –0.393, P = .015), hip internal-rotation velocity (r = –0.410, P = .01), maximum knee-adduction (r = 0.385, P = .017), and maximum knee-adduction velocity (r = –0.378, P = .019). The percentage change in HABD torque was not significantly correlated ($P \geq .05$) with the percentage change in any of the biomechanical variables.

Table 1. Participants' Descriptive Data (n = 38)

Variable	Mean ± SD
Age, y	21.61 ± 4.02
Height, m	1.78 ± 0.08
Body mass, kg	76.00 ± 12.39
Body fat, %	13.18 ± 5.70
Resting heart rate, beats/min	68.53 ± 10.05
Femur length, m	0.41 ± 0.03
$\dot{V}O_2$max, mL/kg/min	53.11 ± 6.39
Blood lactate, mmol	12.53 ± 2.50
Exhaustive run pace, mph	7.43 ± 0.64
Time of exhaustive run, min:s	19:38 ± 4:09
Rating of perceived exertion at run termination (scale = 6–20)	16.76 ± 1.99
Rating of fatigue at run termination (scale = 0–10)	7.66 ± 1.40

DISCUSSION

In healthy, physically active males, an exhaustive running bout at 80% of $\dot{V}O_2$max produced a 15% decrease in HABD torque. In addition, we observed fatigue-induced changes in biomechanical variables that were previously associated with running-related injury,[8,10,11] including increased hip-adduction angle and knee-adduction (varus) and internal-rotation velocities. The fatigued state also elicited significant correlations that were not present during the rested state between HABD torque and the biomechanical variables of interest. Use of the fatigued state to uncover underlying, potentially injurious metrics is endorsed. Compared with control individuals, patients with iliotibial band syndrome displayed increased knee adduction after 30 minutes of running but not at the onset of running.[30] Collectively, these findings support the need to evaluate theoretical frameworks for the development of running injuries in a fatigued state.

The influence of fatigue on HABD torque and, subsequently, the relationship between HABD torque and the biomechanical variables previously associated with running-related injury, were our primary interest in the current study. The decrease we noted in HABD torque (15%) was similar to that reported earlier after an exhaustive run (11%).[10] Although HABD torque was correlated with peak hip adduction in participants with patellofemoral pain syndrome,[10] we observed no correlation between these variables in our population of healthy males (rested state: $r = -0.263$, $P = .10$; fatigued state: $r = -0.189$, $P = .24$). Our findings support the healthy control group findings reported by Dierks et al[10] (before a prolonged run: $r = 0.017$, $P = .472$; after a prolonged run: $r = 0.051$, $P = .208$). Thus, HABD weakness, which resulted from a fatiguing run in our investigation, was not related to the increased hip-adduction angle. Similarly, Pohl et al[31] demonstrated no compensatory patterns in walking after a nerve block to simulate HABD weakness. Previous associations between HABD weakness and hip adduction in those with running-related injuries may not have been due to muscle weakness alone; pain may be related to compensatory patterns for increased hip adduction, not strength.[21,22] Muscle weakness and pain from lower extremity overuse injury occur over an extended period, allowing compensatory patterns to develop.[31,32] Decreases in strength from fatigue may not persist long enough for compensatory patterns to develop,[31] which may explain the absence of a correlation between HABD torque and hip-adduction angle in our research.

The only peak angle significantly correlated with HABD torque was knee adduction in the fatigued state ($r = 0.385$, $P = .017$); in contrast, Dierks et al[10] observed no relationship. However, different populations might have contributed to the contradictory findings, as Dierks et al[10] studied a mixed-sex population (5 males, 15 females). Movement patterns associated with running-related injuries have differed between sexes.[33,34] Furthermore, knee adduction was greater in males with patellofemoral pain syndrome than in male control participants and females with patellofemoral pain syndrome.[34] Our fatigued-state findings occurred in a healthy population; future investigators should continue to evaluate knee adduction in relation to running-related injury in males.

We assessed HABD torque in relation to not only the magnitude of movement (peak angle) but also the rate of

Table 2. Differences Between Rested and Fatigued States (n = 38)

Variable	State, Mean ± SD		*P* Value
	Rest	Fatigue	
Isometric strength measure			
Hip-abductor torque, Nm/kg	1.78 ± 0.28	1.50 ± 0.31	<.001 [a]
Kinematic gait maximum			
Hip adduction, °	10.37 ± 3.33	11.43 ± 3.89	.007 [a]
Hip-adduction velocity, °/s	140.8 ± 46.39	150.23 ± 56.53	.294
Hip internal rotation, °	9.32 ± 10.25	9.65 ± 10.01	.832
Hip internal-rotation velocity, °/s	307.92 ± 117.07	352.24 ± 134.04	.037 [a]
Knee varus, °	10.58 ± 11.68	9.53 ± 5.37	.528
Knee varus velocity, °/s	188.27 ± 74.45	232.18 ± 98.50	.003 [a]
Knee internal rotation, °	19.62 ± 13.57	20.53 ± 5.59	.716
Knee internal-rotation velocity, °/s	453.63 ± 111.63	604.62 ± 412.06	.022 [a]
Kinetic gait			
Vertical ground reaction force, N/kg	25.65 ± 1.91	25.38 ± 2.00	.152
Maximum hip-adduction moment, Nm/kg	1.61 ± 0.35	1.58 ± 0.37	.576
Maximum hip internal-rotation moment, Nm/kg	0.03 ± 0.03	0.04 ± 0.03	.046 [a]
Maximum knee-adduction moment, Nm/kg	1.91 ± 0.44	1.86 ± 0.43	.423
Maximum knee internal-rotation moment, Nm/kg	0.21 ± 0.11	0.23 ± 0.12	.034 [a]

[a] Different at the $P < .05$ level.

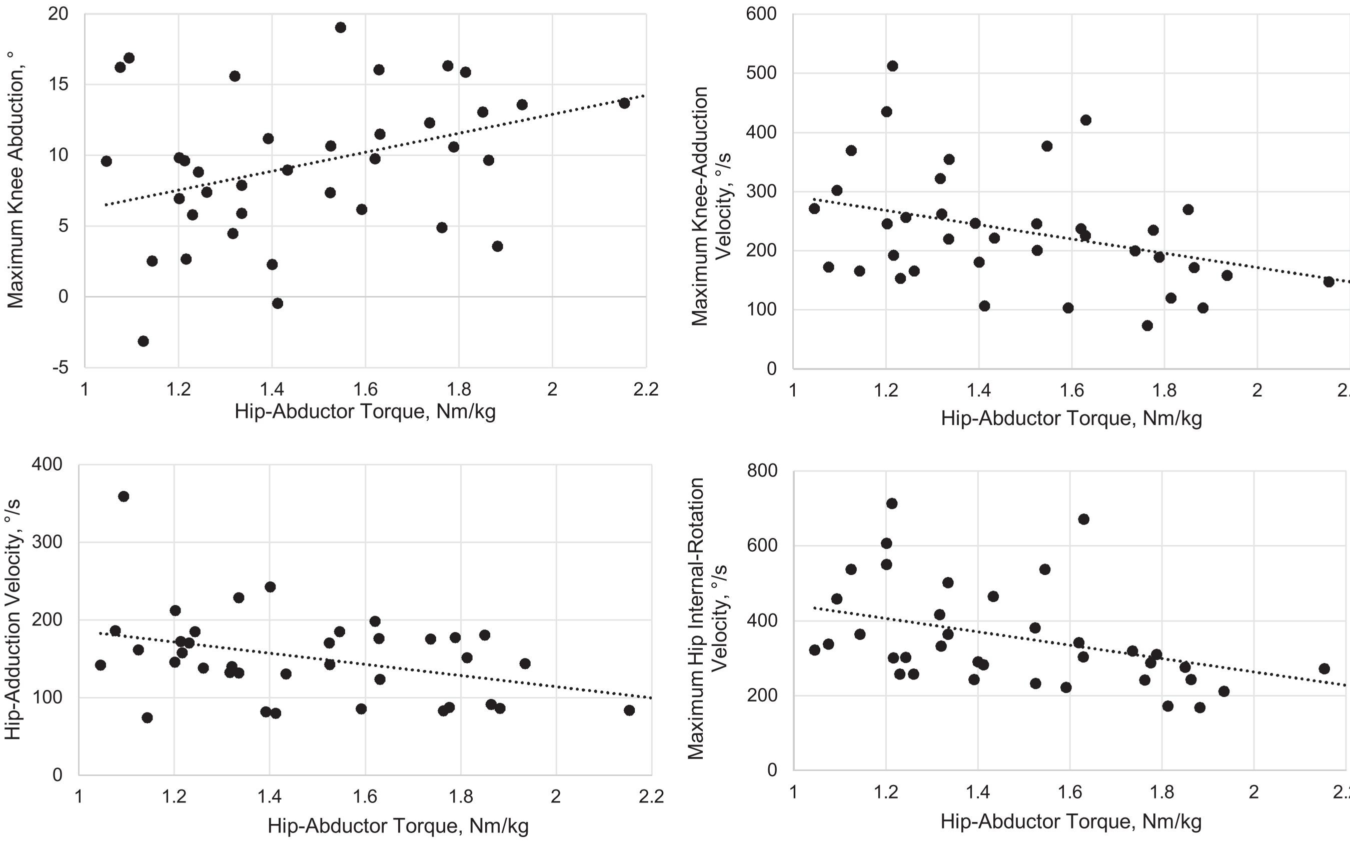

Figure. Significant correlations with hip-abductor torque in the fatigued state.

movement (velocity). The relationship between HABD torque and velocities at the hip and knee was examined because prospective findings[8,35] indicated that rate of motion may be a better variable for determining injury risk than joint angles alone. Hip-adduction velocity was significantly correlated with HABD torque in both the rested and fatigued states. In addition, knee adduction and hip internal-rotation velocity were negatively correlated with HABD torque. These results, in relation to evidence supporting the importance of the rate of movement in the development of running-related injuries,[8,35] have applications for clinical injury prevention. In a randomized, controlled trial, Toresdahl et al[36] evaluated how a home-exercise strength-training intervention influenced injury rates in first-time marathon participants. The study design allowed the effects of the intervention to be appropriately assessed because the strength-training and non–strength-training groups did not differ in training loads or finishing times.[36] Despite 12 weeks of strength training by the experimental group, no difference in injury rate was reported between groups.[36] Our findings suggest that the velocity of a task performed for injury-prevention purposes must be considered. Exercises performed in the Toresdahl et al[36] intervention were primarily focused on sagittal-plane movements (eg, squats, lunges, and single-legged toe touches) or isometric stability (eg, plank and side plank). Although additional work is needed to identify the role of HABD strength in running-related injury prevention,[37] clinicians should take into account both the magnitude and rate of force development when incorporating HABD strength training.

A primary limitation of our research was the use of isometric handheld dynamometry to evaluate HABD torque. During gait, the HABDs are required to act eccentrically to stabilize the pelvis. Thus, isometric measures may lack construct validity.[23,38] Eccentric isokinetic measures may have more ecologic validity; however, we chose isometric testing due to its clinical utility. Significant correlations between HABD torque and joint velocities warrant further investigations using measures of eccentric HABD capabilities. Another measure of muscle performance that we did not explore but which may be related to injury is hip power. Authors[39] of a prospective investigation noted that decreased average hip external-rotator power predicted lower extremity injury in females; however, HABD peak torque was not predictive. Including only male participants may have been a further limitation of our study, yet because increasing evidence[33,34] indicates that sex may play a role in pathomechanics, we excluded females. Future researchers should evaluate the effects of fatigue on HABD torque and gait mechanics in females and, ideally, should compare sexes.

In summary, we demonstrated that a fatiguing run resulted in decreased HABD torque and changes in biomechanical variables that were previously associated with running-related injury. The biomechanical variables increased by fatigue were hip adduction, knee-adduction (varus) velocity, and knee internal-rotation velocity. Although HABD torque and peak hip-adduction angle had earlier been associated with running-related injury and were negatively affected by fatigue in our analysis, no relationship between these variables was present. Our investigation was performed in healthy males, but our findings support the growing body of literature indicating that HABD weakness and increased hip-adduction angle during gait may be secondary to injury and not causal. The HABD torque was not correlated with peak hip adduction, yet it was associated with knee adduction in the fatigued state. This result may be unique due to our all-male population. Finally, changes in joint velocities due to fatigue and correlations between HABD torque and hip- and knee-joint velocities highlight the clinical need to consider not only the quantity of HABD strength but also the quality of motion and eccentric control provided by the HABDs.

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REFERENCES

1. Lun V, Meeuwisse WH, Stergiou P, Stefanyshyn D. Relation between running injury and static lower limb alignment in recreational runners. *Br J Sports Med*. 2004;38(5):576–580.
2. Radzak K, Sufton JM, Timmons MK, Lopp R, Stickley CD, Lam KC. Patient and injury demographics of athletic training medical care for Reserve Officer Training Corps (ROTC): a report from the Athletic Training Practice-Based Research Network [abstract]. *J Athl Train*. 2019;54(6 suppl):S-125.
3. Bulzacchelli MT, Sulsky SI, Zhu L, Brandt S, Barenberg A. *The Cost of Basic Combat Training Injuries in the US Army: Injury-Related Medical Care and Risk Factors*. Amherst, MA: US Army Research Institute of Environmental Medicine; 2017.
4. Kaufman KR, Brodine S, Shaffer R. Military training-related injuries: surveillance, research, and prevention. *Am J Prev Med*. 2000;18(3 suppl):54–63.
5. Hreljac A. Etiology, prevention, and early intervention of overuse injuries in runners: a biomechanical perspective. *Phys Med Rehabil Clin N Am*. 2005;16(3):651–667, vi.
6. Winter SC, Gordon S, Brice SM, Lindsay D, Barrs S. A multifactorial approach to overuse running injuries: a 1-year prospective study. *Sports Health*. 2020. doi:1941738119888504
7. Luedke LE, Heiderscheit BC, Williams DS, Rauh MJ. Association of isometric strength of hip and knee muscles with injury risk in high school cross country runners. *Int J Sports Phys Ther*. 2015;10(6):868–876.
8. Stickley CD, Presuto MM, Radzak KN, Bourbeau CM, Hetzler RK. Dynamic varus and the development of iliotibial band syndrome. *J Athl Train*. 2018;53(2):128–134.
9. Messier SP, Martin DF, Mihalko SL, et al. A 2-year prospective cohort study of overuse running injuries: The Runners and Injury Longitudinal Study (TRAILS). *Am J Sports Med*. 2018;46(9):2211–2221.
10. Dierks TA, Manal KT, Hamill J, Davis IS. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J Orthop Sports Phys Ther*. 2008;38(8):448–456.
11. Ferber R, Noehren B, Hamill J, Davis IS. Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics. *J Orthop Sports Phys Ther*. 2010;40(2):52–58.
12. Verrelst R, De Clercq D, Vanrenterghem J, Willems T, Palmans T, Witvrouw E. The role of proximal dynamic joint stability in the development of exertional medial tibial pain: a prospective study. *Br J Sports Med*. 2014;48(5):388–393.
13. Noehren B, Davis I, Hamill J. ASB Clinical Biomechanics Award Winner 2006: Prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech (Bristol, Avon)*. 2007;22(9):951–956.
14. Fredericson M, Cookingham CL, Chaudhari AM, Dowdell BC, Oestreicher N, Sahrmann SA. Hip abductor weakness in distance runners with iliotibial band syndrome. *Clin J Sport Med*. 2000;10(3):169–175.
15. Niemuth PE, Johnson RJ, Myers MJ, Thieman TJ. Hip muscle weakness and overuse injuries in recreational runners. *Clin J Sport Med*. 2005;15(1):14–21.
16. Khayambashi K, Mohammadkhani Z, Ghaznavi K, Lyle MA, Powers CM. The effects of isolated hip abductor and external rotator muscle strengthening on pain, health status, and hip strength in females with patellofemoral pain: a randomized controlled trial. *J Orthop Sports Phys Ther*. 2012;42(1):22–29.
17. Dolak KL, Silkman C, Medina McKeon J, Hosey RG, Lattermann C, Uhl TL. Hip strengthening prior to functional exercises reduces pain sooner than quadriceps strengthening in females with patellofemoral pain syndrome: a randomized clinical trial. *J Orthop Sports Phys Ther*. 2011;41(8):560–570.
18. Ferber R, Kendall KD, Farr L. Changes in knee biomechanics after a hip-abductor strengthening protocol for runners with patellofemoral pain syndrome. *J Athl Train*. 2011;46(2):142–149.
19. Willy RW, Davis IS. The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. *J Orthop Sports Phys Ther*. 2011;41(9):625–632.
20. Snyder KR, Earl JE, O'Connor KM, Ebersole KT. Resistance training is accompanied by increases in hip strength and changes in lower extremity biomechanics during running. *Clin Biomech (Bristol, Avon)*. 2009;24(1):26–34.
21. Grau S, Krauss I, Maiwald C, Best R, Horstmann T. Hip abductor weakness is not the cause for iliotibial band syndrome. *Int J Sports Med*. 2008;29(7):579–583.
22. Foch E, Reinbolt JA, Zhang S, Fitzhugh EC, Milner CE. Associations between iliotibial band injury status and running biomechanics in women. *Gait Posture*. 2015;41(2):706–710.
23. Taylor-Haas JA, Hugentobler JA, DiCesare CA, et al. Reduced hip strength is associated with increased hip motion during running in young adult and adolescent male long-distance runners. *Int J Sports Phys Ther*. 2014;9(4):456–467.
24. Milgrom C, Radeva-Petrova DR, Finestone A, et al. The effect of muscle fatigue on in vivo tibial strains. *J Biomech*. 2007;40(4):845–850.
25. Geiser CF, O'Connor KM, Earl JE. Effects of isolated hip abductor fatigue on frontal plane knee mechanics. *Med Sci Sports Exerc*. 2010;42(3):535–545.
26. Radzak KN, Putnam AM, Tamura K, Hetzler RK, Stickley CD. Asymmetry between lower limbs during rested and fatigued state running gait in healthy individuals. *Gait Posture*. 2017;51:268–274.
27. Nakagawa TH, Moriya ET, Maciel CD, Serrao AF. Frontal plane biomechanics in males and females with and without patellofemoral pain. *Med Sci Sports Exerc*. 2012;44(9):1747–1755.
28. Pohl MB, Kendall KD, Patel C, Wiley JP, Emery C, Ferber R. Experimentally reduced hip-abductor muscle strength and frontal-plane biomechanics during walking. *J Athl Train*. 2015;50(4):385–391.
29. Heyward VH, Gibson A. *Advanced Fitness Assessment and Exercise Prescription*. 7th ed. Champaign, IL: Human Kinetics; 2014.
30. Baker RL, Souza RB, Rauh MJ, Fredericson M, Rosenthal MD. Differences in knee and hip adduction and hip muscle activation in runners with and without iliotibial band syndrome. *PM R*. 2018;10(10):1032–1039.

31. Pohl MB, Kendall KD, Patel C, Wiley JP, Emery C, Ferber R. Experimentally reduced hip-abductor muscle strength and frontal-plane biomechanics during walking. *J Athl Train*. 2015;50(4):385–391.
32. Henriksen M, Aaboe J, Simonsen EB, Alkjaer T, Bliddal H. Experimentally reduced hip abductor function during walking: Implications for knee joint loads. *J Biomech*. 2009;42(9):1236–1240.
33. Phinyomark A, Osis S, Hettinga BA, Leigh R, Ferber R. Gender differences in gait kinematics in runners with iliotibial band syndrome. *Scand J Med Sci Sports*. 2015;25(6):744–753.
34. Willy RW, Manal KT, Witvrouw EE, Davis IS. Are mechanics different between male and female runners with patellofemoral pain? *Med Sci Sports Exerc*. 2012;44(11):2165–2171.
35. Hamill J, Miller R, Noehren B, Davis I. A prospective study of iliotibial band strain in runners. *Clin Biomech (Bristol, Avon)*. 2008;23(8):1018–1025.
36. Toresdahl BG, McElheny K, Metzl J, Ammerman B, Chang B, Kinderknecht J. A randomized study of a strength training program to prevent injuries in runners of the New York City Marathon. *Sports Health*. 2020;12(1):74–79.
37. Rathleff MS, Rathleff CR, Crossley KM, Barton CJ. Is hip strength a risk factor for patellofemoral pain? A systematic review and meta-analysis. *Br J Sports Med*. 2014;48(14):1088.
38. Baldon Rde M, Lobato D FM, Carvalho LP, Santiago P RP, Benze BG, Serrão FV. Relationship between eccentric hip torque and lower-limb kinematics: gender differences. *J Appl Biomech*. 2011;27(3):223–232.
39. Verrelst R, Van Tiggelen D, De Ridder R, Witvrouw E. Decreased average power of the hip external muscles as a predictive parameter for lower extremity injury in women: a prospective study. *Clin J Sport Med*. 2018;28(6):533–537.

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