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***Original Research***

# Association Between Knee- and Hip-Extensor Strength and Running-Related Injury Biomechanics in Collegiate Distance Runners

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***Context:*** Running-related injuries are common in distance runners. Strength training is used for performance enhancement and injury prevention. However, the association between maximal strength and distance-running biomechanics is unclear.

***Objective:*** To determine the relationship between maximal knee- and hip-extensor strength and running biomechanics previously associated with injury risk.

***Design:*** Cross-sectional study.

***Setting:*** Research laboratory.

***Patients or Other Participants:*** A total of 36 collegiate distance runners (26 men, 10 women; age = 20.0 ± 1.5 years, height = 1.74 ± 0.09 m, mass = 61.97 ± 8.26 kg).

***Main Outcome Measure(s):*** Strength was assessed using the 1-repetition maximum (1RM) back squat and maximal voluntary isometric contractions of the knee extensors and hip extensors. Three-dimensional running biomechanics were assessed overground at a self-selected speed. Running variables were the peak instantaneous vertical loading rate; peak forward trunk-lean angle; knee-flexion, internal-rotation, and -abduction angles and internal moments; and hip-extension, internal-rotation, and -adduction angles and internal moments. Separate stepwise linear regression models were used to examine the associations between strength and biomechanical outcomes ($\Delta R^2$) after accounting for sex, running speed, and foot-strike index.

***Results:*** Greater 1RM back-squat strength was associated with a larger peak knee-flexion angle ($\Delta R^2 = 0.110$, $\Delta P = .045$) and smaller peak knee internal-rotation angle ($\Delta R^2 = 0.127$, $\Delta P = .03$) and internal-rotation moment ($\Delta R^2 = 0.129$, $\Delta P = .03$) after accounting for sex, speed, and foot-strike index. No associations were found between 1RM back-squat strength and vertical loading rate, trunk lean, or hip kinematics and kinetics. Hip- and knee-extensor maximal voluntary isometric contractions were also not associated with any biomechanical variables.

***Conclusions:*** Greater 1RM back-squat strength was weakly associated with a larger peak knee-flexion angle and smaller knee internal-rotation angle and moment in collegiate distance runners. Runners who are weaker in the back-squat exercise may exhibit running biomechanics associated with the development of knee-related injuries.

***Key Words:*** squat, isometric strength, running

**Key Points**

- Greater 1-repetition back-squat strength was weakly associated with larger knee-flexion angles and smaller knee internal-rotation angles during running in collegiate distance runners.
- Isometric knee- and hip-extensor strength were not associated with any biomechanical outcome.
- A smaller knee-flexion angle may contribute to additional knee-joint stiffness, which has been prospectively linked to overuse injuries in runners.
- A larger knee internal-rotation angle during running has been found in runners with a history of iliotibial band syndrome.
- Exercises to enhance the 1-repetition maximum back squat should be considered in resistance-training programs for distance runners to improve performance and reduce the injury risk.

As of 2015, more than 30 000 runners were participating in National Collegiate Athletic Association cross-country running.[1] However, collegiate distance runners are at high risk for overuse injuries. For instance, Kerr et al[2] reported injury rates of 4.66 and 5.85 per 1000 athlete-exposures for males and females in National Collegiate Athletic Association cross-country from 2009–2010 through 2013–2014, respectively. Given the reported injury rates, understanding the risk factors for developing lower extremity injury in runners is important. The cause of running-related injury is multifactorial, and muscle weakness[3] and aberrant running biomechanics[4] may be linked to injury risk.

Strength training is used by competitive distance runners for performance enhancement and injury prevention.[5] In the context of running performance, muscle strength may contribute to improved *running economy* (ie, energy expenditure at a given velocity). For example, Li et al[6] observed that 8 weeks of resistance training using the back-squat exercise improved running economy and 5-km time in competitive runners. The squat is also commonly recommended for injury prevention in young runners[7] because it involves multiple lower extremity muscle groups (eg, hip and knee extensors) while also requiring hip and knee stability from the hip musculature, including the gluteus maximus and medius.[8] Muscle weakness may contribute to an elevated injury risk in distance runners. For example, hip-muscle weakness has been associated with running-related injuries in cross-sectional and prospective observations.[3] Runners with anterior knee pain had weaker knee extensors and flexors than control runners.[9] Furthermore, researchers have linked strength-training interventions to running biomechanics that are associated with increased injury risk. For instance, authors[10] reported that knee-abduction moments were reduced after strength training in recreational runners. However, the association between maximal lower extremity muscle strength and running biomechanics in collegiate competitive distance runners is unclear. Maximal strength has been shown to improve in distance runners in a concurrent endurance and strength-training program.[11] However, few investigators[11] have demonstrated that improvements in strength elicit alterations in running biomechanics.

Aberrant running mechanics may contribute to running-related injuries in competitive runners. For instance, greater knee-joint stiffness has been prospectively associated with greater injury incidence in recreational runners.[12] Greater joint loading combined with high running mileage increases the cumulative mechanical stress applied to connective tissues and may contribute to overuse injury.[13] Moreover, ground reaction force characteristics, such as the peak vertical loading rate, have been retrospectively linked to tibial stress fractures in female runners.[14] However, the vertical loading rate has not been prospectively linked to injury in this population.[15,16] Kinematic characteristics may also contribute to the running-related injury risk. For example, males with iliotibial (IT) band syndrome (ITBS) had greater hip internal rotation and knee adduction during early stance compared with control individuals.[4] Therefore, greater frontal- and transverse-plane knee motion may contribute to greater IT band stress.

Strength training improves the strength and stiffness of connective tissue[17] and may increase tissue tolerance to high mechanical loads experienced during running. In a recent review, Bertelsen et al[18] set forth a framework for the causes of running-related injuries and suggested that tissue capacity may be a contributing factor. As such, adding strength training to running programs for distance runners is beneficial because it may improve tissue capacity without the need to increase running exposure. Yet whether maximal strength is associated with running biomechanics that have previously been linked to injury risk in competitive distance runners is unclear. Understanding the role of maximal muscle strength in running biomechanics is critical for developing future training regimens aimed at mitigating lower extremity injuries in competitive distance runners.

The purpose of our study was to determine the relationship between lower extremity strength (1-repetition maximum [1RM] back squat and knee- and hip-extension maximal voluntary isometric contractions [MVICs]) and running biomechanics that have been linked to overuse injury in competitive collegiate distance runners. We hypothesized that greater lower extremity strength would be associated with the following running kinematics: lesser knee-abduction, knee internal-rotation, hip-adduction, and hip internal-rotation angles and greater forward trunk-lean and knee-flexion angles. Similarly, we hypothesized that greater lower extremity strength would be associated with the following running kinetics: lesser vertical loading rate; lesser knee-abduction, knee internal-rotation, hip-adduction, and hip internal-rotation moments; and greater knee- and hip-extension moments.

## METHODS

### Experimental Design

We used a cross-sectional design and collected data during 2 sessions that were conducted in random order and separated by a 1-week washout period. One session consisted of assessments of isometric strength and running biomechanics, and the other session consisted of an assessment of back-squat strength.

### Participants

A total of 36 collegiate distance runners (26 men, 10 women) participated in the study (Table 1). Using an a priori power analysis (G*Power 3; Heinrich Heine Universität, Düsseldorf, Germany[19]), we found that 29 participants would be needed to identify a weak-to-moderate association via stepwise regression ($\Delta R^2 = 0.15$, $\Delta P = .05$, $\beta = .2$, residual variance = 0.50) after accounting for 3 covariates. All participants had a minimum of 6 months of experience in resistance training with the back squat, no injury in the 2 months before the study, and no lower extremity surgery in their lifetime. *Injury* was defined as missing >1 week of training and not returning to a minimum of 50% of their previous training volume.[20,21] All participants provided written informed consent, and the study was approved by the Institutional Review Board of California State University, Fullerton.

### Strength Assessments

One-repetition maximum testing was completed using the back-squat exercise in a single session according to a previously established protocol.[22] The warm-up protocol involved 10 repetitions with an unloaded barbell and 5 repetitions at 50%, 4 repetitions at 70%, 1 repetition at 90%, and 1 repetition at 100% of the participant's estimated 1RM. The test continued with single repetitions until the participant could not visibly reach 90° of knee flexion, dropped the weight, or voluntarily terminated the test. Participants rested 3 minutes between all sets of repetitions, and the number of attempts was 3 ± 1.9.

Maximal knee- and hip-extensor strength of the dominant limb (ie, preferred limb to kick a ball) was evaluated via MVICs on an isokinetic dynamometer (HUMAC NORM, Stroughton, MA). All participants completed a standardized warm-up protocol consisting of two 5-second submaximal contractions at 50% and 75% of self-perceived maximal effort, followed by 1 practice MVIC at 100% effort. All participants completed 3 MVIC attempts after the warm-up protocol, received oral encouragement and visual feedback on the torque output, and rested 30 seconds between attempts. Knee-extension MVICs were performed with participants seated and the hip (determined as the trunk relative to the thigh) and knee flexed to 110° and 60°,

**Table 1. Participants' Descriptive Statistics**

| Characteristic | No. |
|---|---|
| Sex, males/females | 26/10 |
| | Mean (95% Confidence Interval) |
| Age, y | 20.02 (19.54, 20.51) |
| Height, m | 1.74 (1.71, 1.77) |
| Mass, kg | 61.97 (59.27, 64.67) |
| Running distance, km/wk | 84.56 (79.54, 89.58) |
| Running speed, m/s | 4.12 (4.01, 4.22) |
| Strength characteristics | |
| Isometric extensor strength, Nm/kg | |
| Knee | 3.75 (3.49, 4.01) |
| Hip | 3.00 (2.77, 3.23) |
| 1-Repetition maximum back-squat strength, BW | 1.30 (1.24, 1.36) |
| Running kinematics, angle° | |
| Peak knee flexion | −51.53 (−53.45, −49.62) |
| Peak knee abduction | −3.56 (−4.88, −2.26) |
| Peak knee internal rotation | 5.69 (3.72, 7.67) |
| Peak hip extension | −4.02 (−6.03, −2.01) |
| Peak hip adduction | 11.97 (10.46, 13.47) |
| Peak hip internal rotation | 2.15 (0.03, 4.26) |
| Trunk lean | 13.13 (11.98, 14.29) |
| Running kinetics | |
| Peak knee moment, BW × height | |
| Extensor | 0.21 (0.20, 0.22) |
| Abduction | −0.039 (−0.047, −0.033) |
| Internal rotation | 0.042 (0.038, 0.046) |
| Peak hip moment, BW × height | |
| Extensor | −0.11 (−0.12, −0.10) |
| Abduction | −0.14 (−0.15, −0.13) |
| Internal rotation | 0.08 (−0.04, 0.20) |
| Peak vertical loading rate, BW/s | 69.46 (64.46, 74.45) |

Abbreviation: BW, body weight.

respectively. Hip-extension MVICs were performed with participants positioned prone and the hip and knee flexed to 60° and 90°, respectively.[23] The dynamometer pad was placed 2 fingerwidths from the medial malleolus and femoral condyles for the knee- and hip-joint MVICs, respectively, and the axis of the arm was visually aligned with the joint center.

## Running Biomechanics

Running biomechanics were analyzed after the MVICs were completed and approximately 10 minutes of rest. The warm-up consisted of a 10-minute treadmill (Star Trac model 8TR; Core Health & Fitness, LLC, Vancouver, WA) run at the participant's self-selected speed. Participants wore laboratory-standard neutral-cushion running shoes (model Pegasus 32; Nike, Inc, Beaverton, OR) and tight-fitting clothing. Static retroreflective markers were placed on the first thoracic vertebra and lumbosacral joint and bilaterally on the iliac crest, anterior-superior iliac spine, posterior-superior iliac spine, greater trochanter, and acromioclavicular joints. Unilateral markers were placed medially and laterally on the femoral condyles and malleoli, the first and fifth metatarsal heads, and the heel counter of the dominant limb. Dynamic tracking clusters containing 4 retroreflective markers were placed on the thigh, shank, and foot of the dominant limb to track segment motion. The markers on the first thoracic vertebra, lumbosacral joint, and acromioclavicular joints were kept in place to track trunk motion, and markers on the anterior-superior iliac spine and posterior-superior iliac spine were kept in place to track the pelvis.[23] All lower extremity static markers except at the heel counter were removed before the running trials began. All static and dynamic trials were recorded at 240 Hz by using a Qualisys (Gothenburg, Sweden) 9-camera motion-capture system.

Participants performed 5 overground practice running trials on a 20-m runway and through 2 timing gates (model TF100; TrackTronix, Lenexa, KS) to establish a consistent self-selected speed. The participants then performed 5 trials at their self-selected speed (±5%), contacting 1 force plate (Advanced Mechanical Technology, Inc, Watertown, MA) sampling at 2400 Hz. Trials were recorded if the dominant foot contacted the plate under each speed condition. Trials were repeated if the running speed was not within 5% of the previously established speed, the foot missed the force plate, or the participant visually changed his or her gait to contact the force plate.

## Data Reduction

The 1RM back squat was also normalized to body mass, and the maximal weight lifted was used for analysis. The MVIC torque data were gravity corrected and normalized to body mass, and the peak torque of the 3 trials was used for analysis. Marker position and force data were low-pass filtered at 20 Hz.[24] We calculated the hip-joint center as 25% of the distance between greater trochanter markers[25] and subsequent joint centers as the center point between the lateral and medial static markers. Joint angles and moments were determined using Visual3D software (C-Motion, Inc, Germantown, MD). Vertical loading rate was computed using a custom LabView program (National Instruments, Austin, TX).

Heel contact and toe-off were identified when the vertical ground reaction force exceeded 20 N and fell below 20 N, respectively, and indicated the length of the stance phase. Joint kinematics were computed as the motion of the distal relative to the proximal segment using the Cardan sequence of flexion-extension, abduction-adduction, and internal-external rotation. Trunk angle was calculated as motion of the trunk segment relative to the global vertical axis. Peak angles and moments (knee flexion, abduction, and internal rotation and hip flexion, adduction, and internal rotation) during the stance phase were extracted for analysis. *Vertical loading rate* was defined as the peak derivative during the first 13% of the stance phase and normalized to body weight.[26] Internal joint moments were determined using inverse dynamics and were normalized to a product of body weight and height. We time normalized all kinematic and kinetic waveforms to 100% of the stance phase and plotted them as ensemble averages for descriptive purposes (Figures 1 and 2). The foot-strike index[27] was used to quantify the footfall pattern, which may influence knee and hip biomechanics during running.[28] Briefly, the foot-strike index quantifies the footfall pattern via the position of the center of pressure at heel contact expressed as a percentage of the foot-segment length (rearfoot = 0%–33%, midfoot = 33%–67%, forefoot = 67%–100%). Foot-

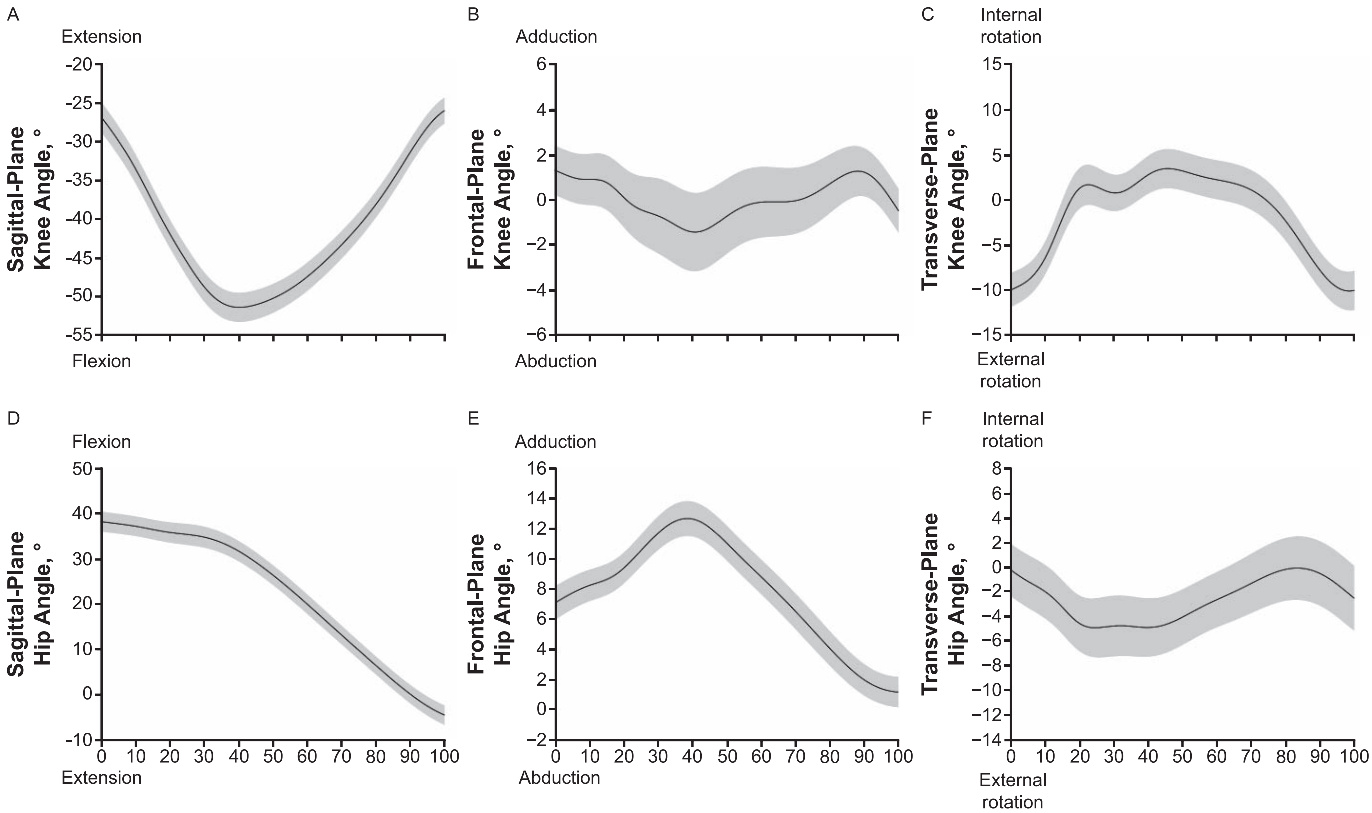


**Figure 1. Ensemble averages and 95% confidence intervals for, A, sagittal-, B, frontal-, and, C, transverse-plane knee kinematics and, D, sagittal-, E, frontal-, and, F, transverse-plane hip kinematics.**

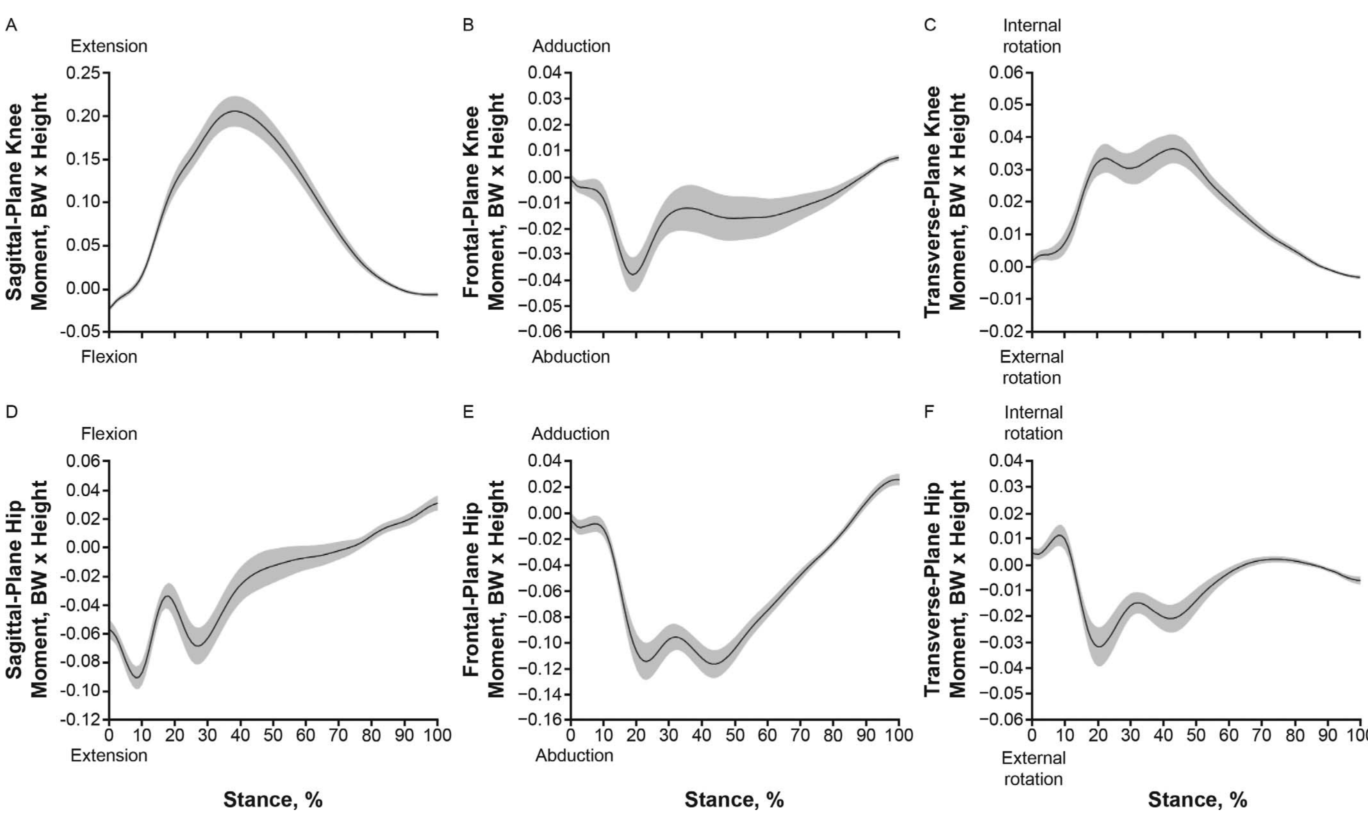


**Figure 2. Ensemble averages and 95% confidence intervals for, A, sagittal-, B, frontal-, and, C, transverse-plane internal knee-joint moments and, D, sagittal-, E, frontal-, and, F, transverse-internal hip-joint moments. Abbreviation: BW, body weight.**

Table 2. Association Between 1-Repetition Maximum Back-Squat Strength and Running Biomechanics After Accounting for Sex, Self-Selected Speed, and Foot-Strike Index

| Variable | Value | | |
|---|---|---|---|
| | Unstandardized β | Δ$R^2$ | Δ$P$ |
| Kinematic measure, angle, °[a] | | | |
| Peak | | | |
| Knee flexion | −14.07 | 0.110 | .045[b] |
| Knee abduction | 2.12 | 0.006 | .65 |
| Knee internal rotation | −14.21 | 0.127 | .03[b] |
| Hip extension | 9.27 | 0.037 | .28 |
| Hip adduction | 6.14 | 0.038 | .28 |
| Hip internal rotation | 0.04 | 0.029 | .31 |
| Trunk lean | −5.70 | 0.054 | .18 |
| Kinetic measure[a] | | | |
| Peak moment, BW × height | | | |
| Knee extensor | 0.035 | 0.026 | .32 |
| Knee abduction | 0.032 | 0.044 | .19 |
| Knee internal rotation | 0.014 | 0.129 | .03[b] |
| Hip extensor | 0.027 | 0.013 | .54 |
| Hip abduction | −0.004 | 0.001 | .88 |
| Hip internal rotation | 0.015 | 0.042 | .24 |
| Peak vertical loading rate, BW/s | −12.831 | 0.015 | .49 |

Abbreviation: BW, body weight.

[a] Joint moments are expressed as internal measures.

[b] Δ$P < .05$.

Table 3. Association Between Knee-Extension Maximal Voluntary Isometric Contraction and Running Biomechanics After Accounting for Sex, Self-Selected Speed, and Foot-Strike Index

| Variable | Value | | |
|---|---|---|---|
| | Unstandardized β | Δ$R^2$ | Δ$P$ |
| Kinematic measure, angle, ° | | | |
| Peak | | | |
| Knee flexion | 0.48 | 0.003 | .76 |
| Knee abduction | 1.77 | 0.084 | .07 |
| Knee internal rotation | −1.64 | 0.032 | .29 |
| Hip extension | 0.51 | 0.002 | .78 |
| Hip adduction | −0.18 | 0.001 | .89 |
| Hip internal rotation | 2.56 | 0.080 | .09 |
| Trunk lean | 0.76 | 0.020 | .41 |
| Kinetic measure[a] | | | |
| Peak moment, BW × height | | | |
| Knee extensor | −0.003 | 0.003 | .75 |
| Knee abduction | 0.003 | 0.008 | .56 |
| Knee internal rotation | 0.001 | 0.001 | .95 |
| Hip extensor | −0.001 | 0.002 | .81 |
| Hip abduction | −0.001 | 0.001 | .85 |
| Hip internal rotation | 0.001 | 0.001 | .95 |
| Peak vertical loading rate, BW/s | −3.461 | 0.022 | .39 |

Abbreviation: BW, body weight.

[a] Joint moments are expressed as internal measures.

strike index was calculated using a modified foot segment[16] and was a continuous variable.

## Statistical Analyses

Descriptive statistics (means and standard deviations) were computed for all outcome variables. Outcomes were assessed for normality using the Shapiro-Wilk test and via inspection of skewness and kurtosis (ratio of standard error to statistic). Outliers were examined using boxplots. We performed separate forward stepwise linear regression models to address the unique association between each strength (predictor) and biomechanical (criterion) outcome after accounting for sex (male = 0; female = 1), running speed (m/s), and foot-strike index (%). Covariates were included because previous research[28,29] indicated that running biomechanics differed between males and females, forefoot and rearfoot runners, and faster and slower speeds. Covariates were entered first (step 1), and the strength variable of interest was entered second. The change in the coefficient of determination ($\Delta R^2$, $\Delta P$) from step 1 to step 2 was used to represent the magnitude of association ($\alpha = .05$, $\beta = .2$). All analyses were conducted using SPSS (version 26; IBM Corp, Armonk, NY).

## RESULTS

All data were normally distributed, and no outliers were identified. Descriptive statistics are presented in Table 1; the sample was predominately male. One participant did not complete the 1RM back-squat assessment (ie, did not return for the second session), so the analyses were limited to 35 participants for this outcome. Similarly, a technical problem arose for 1 participant during the hip-extension MVIC, and the analyses were limited to 35 participants for this outcome. Covariates explained 1.2% to 22.7% of the variance in the running kinematic variables (Supplemental Table 1) and 4.75% to 24.7% of the variance in the running kinetic variables (Supplemental Table 2).

## Back-Squat Strength

Greater 1RM back-squat strength was associated with a larger peak knee-flexion angle ($\Delta R^2 = 0.110$, $\Delta P = .045$, total $R^2 = 0.13$), smaller peak knee internal-rotation angle ($\Delta R^2 = 0.127$, $\Delta P = .03$, total $R^2 = 0.36$), and smaller peak knee internal-rotation moment ($\Delta R^2 = 0.129$, $\Delta P = .03$, total $R^2 = 0.38$) after accounting for sex, speed, and foot-strike pattern (Table 2). No associations were found between 1RM back-squat strength and hip kinematics or kinetics, trunk-lean angle, or vertical loading rate (all $\Delta P$ values $>$ .05).

## Isometric Strength

No associations were present between maximal isometric knee-extension strength and any biomechanical variable (all $\Delta P$ values $> .05$; Table 3). Similarly, no associations were observed between maximal isometric hip-extensor strength and any running biomechanical variable after accounting for sex, speed, and foot-strike index (all $\Delta P$ values $> .05$; Table 4).

## DISCUSSION

The purpose of our study was to determine the associations between knee- and hip-extensor strength (1RM back-squat and isometric knee- and hip-extensor strength) and running biomechanics that have previously been associated with overuse injuries in competitive distance runners. The 1RM back squat was used as a global assessment of lower extremity strength that involves similar muscles and biomechanics to those involved in running.[30] We selected knee- and hip-extensor isometric

Table 4. Association Between Hip-Extension Maximal Voluntary Isometric Contraction and Running Biomechanics After Accounting for Sex, Self-Selected Speed, and Foot-Strike Index

| Variable | Value | | |
|---|---|---|---|
| | Unstandardized β | $\Delta R^2$ | $\Delta P$ |
| Kinematic measure, angle, ° | | | |
| Peak | | | |
| Knee flexion | −2.66 | 0.098 | .08 |
| Knee abduction | 0.11 | 0.001 | .91 |
| Knee internal rotation | −2.28 | 0.063 | .14 |
| Hip extension | 2.54 | 0.059 | .16 |
| Hip adduction | 2.26 | 0.103 | .07 |
| Hip internal rotation | 0.03 | 0.024 | .34 |
| Trunk lean | 0.27 | 0.003 | .77 |
| Kinetic measure, [a] | | | |
| Peak moment, BW × height | | | |
| Knee extensor | 0.006 | 0.024 | .34 |
| Knee abduction | 0.001 | 0.002 | .78 |
| Knee internal rotation | 0.001 | 0.009 | .57 |
| Hip extensor | 0.004 | 0.020 | .43 |
| Hip abduction | 0.006 | 0.035 | .24 |
| Hip internal rotation | 0.011 | 0.009 | .53 |
| Peak vertical loading rate, BW/s | 1.080 | 0.003 | .75 |

Abbreviation: BW, body weight.

[a] Joint moments are expressed as internal measures.

strength tests because they are clinical assessments of strength that are often used to assess distance runners.[23] The primary finding was that greater 1RM back-squat strength was associated with a larger peak knee-flexion angle, smaller peak knee internal-rotation angle, and smaller knee internal-rotation moment after adjusting for sex, running speed, and foot-strike index. However, 1RM back-squat strength was not associated with other kinematic variables or running kinetics. Furthermore, isometric strength was not associated with running kinematics or kinetics. Finally, sex, running speed, and foot-strike index were included as covariates and were associated with a variety of running kinematics and kinetics. As such, future researchers should consider these factors when analyzing relationships between strength and running biomechanics.

We hypothesized that greater 1RM back-squat strength would be related to greater peak knee-extensor moments because greater strength may allow runners to produce a larger torque at the knees during running. Although our findings did not support this hypothesis, we noted a relationship between 1RM strength and greater peak knee-flexion angle during the stance phase. Stronger runners may be able to use greater knee flexion without an increased joint moment, thereby creating a more favorable landing strategy during the early stance phase of running. Sagittal-plane knee-joint stiffness is derived from the change in moment divided by the change in angle and has been prospectively linked to overuse injury in recreational runners.[12] Therefore, less knee flexion may contribute to additional knee-joint stiffness and may be partially attributable to lower 1RM back-squat strength.

We also found that greater 1RM back-squat strength was associated with smaller peak knee internal-rotation angle and internal-rotation moment. Peak knee internal-rotation angle and internal-rotation moment are associated with overuse knee conditions in runners. For example, female runners with ITBS displayed a larger peak knee internal-rotation angle than did uninjured controls.[31] The IT band originates on the gluteus maximus and tensor fascia lata muscles and inserts onto the Gerdy tubercle at the tibia. Thus, it can assist with rotary and frontal-plane stabilization of the knee joint,[8,32] and gluteus maximus muscle weakness may contribute to lowest knee-joint stability during running.

Contrary to our hypothesis, we identified no relationship between 1RM back-squat strength and hip kinematics or kinetics during running. The back squat is an exercise used to target the knee extensors rather than the hip extensors.[33] Conversely, the deadlift exercise is hip dominant, and greater sagittal-plane hip-joint moments and power occur during the deadlift than during the back squat.[33] We found a substantial proportion of unexplained variance in knee kinematics despite associations between 1RM back-squat strength and knee-flexion and internal-rotation angles. Distance running is a submaximal activity, and maximal strength may not characterize the task demands. Similarly, movement velocity is slower during a 1RM back squat than during running. Other factors, such as muscular endurance and the rate of force development, may be better indicators of muscle function during running, and future investigators should comprehensively evaluate these characteristics.

We also demonstrated no association between any strength measurement and hip frontal-plane running biomechanics. Iliotibial band syndrome has been linked to altered hip frontal-plane kinematics. Ferber et al[31] determined that runners with ITBS had larger peak hip-adduction angles than uninjured control participants. Furthermore, the hip-adduction angle has been linked to other knee-joint injuries, such as patellofemoral pain syndrome.[34] The squat and the isometric hip-extensor tests used in our study primarily occur in the sagittal plane. Brund et al[35] also observed no relationship between hip-abductor eccentric strength and frontal-plane hip or knee kinematics during running. Similarly, the bilateral squat test and non–weight-bearing isometric test likely do not reflect the biomechanical demands of running, which is unilateral and weightbearing.

The discordance in our findings between the 1RM back-squat and isometric strength assessments may be due to contraction type. The 1RM back squat uses a dynamic eccentric muscle action, followed by a concentric muscle action similar to the muscle-contraction demands during running. Conversely, isometric strength may not accurately characterize muscle function during dynamic tasks, such as running. The back squat is a commonly used exercise for strengthening the knee and hip extensors in collegiate distance runners,[36] and our results indicated that the 1RM back squat was associated with favorable knee-joint kinematics (ie, greater peak flexion angle and smaller peak internal-rotation angle).

No relationship was evident between strength outcomes and trunk-lean angle during running, which was contrary to earlier findings[23] of a relationship between greater isometric hip-extensor strength and a larger forward trunk lean in recreational runners. The lack of associations in this investigation may have reflected the experience and running speed of the participants. Our competitive runners ran an average of 84.56 km/week at a speed of 4.12 m/s (collapsed across sex). In contrast, the recreational runners studied by Teng and Powers[23] ran an average of 35 to 37 km/wk and were analyzed at a predetermined speed of 3.4 m/s. Peak trunk-lean angle is altered when runners are instructed to run at a speed different from their preferred speed.[37] Therefore, the predetermined speed used by Teng and Powers[23] may not have accurately represented the runners' preferred trunk-lean angle. Our hypothesis was based on the work of previous authors[38] who identified an association between greater trunk lean and lower patellofemoral contact stress. However, excessive trunk lean may be detrimental to performance and optimal running mechanics, and an optimal trunk lean angle is unknown and should be addressed in future research.

The weak associations between strength and running biomechanics should not detract from other benefits of strength training for collegiate distance runners. Improvements in force-production capabilities of the propulsive muscles (hip and knee extensors and plantar flexors) improve tissue tolerance to mechanical loading[17] and performance in competition.[39] Bertelsen et al[18] suggested that injury occurs after the load capacity of a runner is exceeded. Strength training may be an intervention to increase runners' capacity and reduce their future injury risk.[18] Moreover, weight training contributes to large improvements in performance, and the benefits are more profound for well-trained than recreational athletes.[39] In a recent meta-analysis, Trowell et al[11] indicated that strength training in runners contributed to minimal adaptations in running biomechanics but did improve knee-extensor, knee-flexor, and plantar-flexor strength. In another meta-analysis, Lum and Barbosa[39] showed that strength training was associated with faster performances in Olympic time-based sports. Future authors need to examine the associations between other metrics of muscle function (eg, muscular endurance, fatigability, and the rate of force development) and running biomechanics.

Limitations should be considered when interpreting the results of our study. First, the population was predominately male, and running biomechanics may differ by sex.[29] However, to account for the unequal sex distribution, sex was a covariate in the regression analyses. Second, our collegiate distance runners were not analyzed at the same point within their competitive seasons. Most runners were analyzed during the offseason and preseason phase for either cross-country or track and field. Thus, the preparation stage and strength-training schedule may have influenced strength capacity. Third, the foot segment we used in our biomechanical analyses resulted in a truncated foot because the distal endpoint was represented by the midpoint of the first and fifth metatarsal markers. Consequently, foot-strike index values can exceed 100%, and the dichotomous classification of runners into footfall pattern categories (ie, rearfoot, midfoot, and forefoot) may not be accurate. Hence, we used the foot-strike index as a continuous variable (%), for which a larger value still represents more of a forefoot than rearfoot position at ground contact. Fourth, we chose the back squat as an assessment of overall lower body strength; it may not reflect performance of all exercises (eg, deadlift) included in a distance-runner's strength-training program. Future researchers should investigate the association between alternative strength-training exercises and distance-running biomechanics. Fifth, the runners were free of injury within the 2 months before testing; however, 4 participants reported a history of stress fracture, and 15 participants described various soft tissue injuries in the year before the study, which may have influenced running biomechanics.[14] Nevertheless, it would be impractical to recruit collegiate distance runners with no history of injury given the high incidence of running-related injuries.

## CONCLUSIONS

Greater 1RM back-squat strength was weakly associated with a larger peak knee-flexion angle, smaller peak knee internal-rotation angle, and smaller peak knee internal-rotation moment in collegiate distance runners. Conversely, maximal knee- and hip-extensor isometric strength was not associated with any running biomechanical variable. Maximal strength was not strongly related to distance-running biomechanics. However, strength may play a greater role in overall performance and tissue resilience in collegiate distance runners.

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