Original Research

Leg Stiffness, Joint Stiffness, and Running-Related Injury

Evidence From a Prospective Cohort Study

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Background: The spring-like behavior of the leg and the joints of the lower body during running are thought to influence a wide range of physiologic and mechanical phenomena, including susceptibility to overuse injury. If leg and joint stiffness are associated with running-related injuries, altering joint or leg stiffness may be a useful avenue for injury rehabilitation and injury prevention programs.

Purpose: To test the associations between running-related injury and leg stiffness, knee stiffness, and ankle stiffness in a prospective study of recreational runners.

Study Design: Cohort study; Level of evidence, 2.

Methods: A total of 49 healthy recreational runners took part in a year-long study. Participants completed a 3-dimensional kinematic and kinetic biomechanical assessment at baseline and reported training volume and injury status in a weekly survey during the follow-up period. Relationships between stiffness and injury were assessed at the level of individual legs (n = 98) using spline terms in Cox proportional hazards models.

Results: During follow-up, 23 participants (29 legs) sustained injury. The median time to injury was 27 weeks (53.27 hours of training). Relative injury rate as a function of knee stiffness displayed a weak and nonsignificant *U*-shaped curve (*P* = .187-.661); ankle and leg stiffness displayed no discernable associations with relative injury rate (leg stiffness, *P* = .215-.605; ankle stiffness, *P* = .419-.712).

Conclusion: Leg and joint stiffness may not be important factors in the development of running-related injuries. Moderate changes in leg and joint stiffness are unlikely to substantially alter injury risk.

Keywords: running-related overuse injury; gait mechanics; leg stiffness; joint stiffness

Many aspects of human running can be well approximated using a spring-mass model, in which the legs behave like a spring, storing and releasing mechanical energy during contact with the ground. This mass-spring model has also been extended to consider the spring-like behavior of the ankle and the knee joints during running, which produce greater torques at greater values of angular displacement. Leg and joint stiffness models have successfully explained many facets of human gait, including an individual's energetically optimal stride frequency[13]; how runners maintain similar gait patterns on hard and soft surfaces[12]; and how torque is differentially distributed at the ankle, knee, and hip during forefoot versus rearfoot running.[14] Stiffness may also affect how internal loading is distributed among the components of the musculoskeletal system[36]—if so, leg and joint stiffness may be attractive targets for interventions to prevent or rehabilitate running-related injuries.

Given that leg and joint stiffness are biomechanical constructs that incorporate information about both the motion and the forces encountered by the body, joint and leg stiffness have also been hypothesized to play a role in the development of running-related overuse injury. Previous research has hypothesized that a nonlinear, U-shaped

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curve exists, where "optimal" stiffness levels are associated with the lowest risk of running-related overuse injury.[6,36] Too much stiffness is thought to increase risk of injuries via increased musculoskeletal loading, particularly on bony structures, while stiffness levels that are too low are thought to allow excessive joint motion, thereby increasing the risk of soft tissue injuries.[6] Although injury type was not differentiated, a recent prospective cohort study identified increased knee stiffness as a significant predictor of running-related injury.[22] While these findings were the first prospective evidence linking stiffness to injury, the stiffness-injury relationship was assumed to be strictly linear.

The nature of any potential stiffness-injury association has important implications for injury prevention and rehabilitation interventions beyond those that directly target stiffness. If, for example, greater knee or leg stiffness does indeed increase risk of injury, gait retraining programs that aim to increase stride frequency may lead to an unintentional increase in injury risk, as increasing stride frequency is accomplished in part by an increase in leg stiffness.[11] Likewise, switching from a rearfoot strike to a forefoot strike is known to increase ankle stiffness while decreasing knee stiffness.[14] These alterations in stiffness distribution in the lower leg could have unexpected effects on injury risk, especially if joint stiffness is related to injury risk in a nonlinear fashion.

Leg and joint stiffness themselves are also possible targets for gait retraining interventions, especially in light of recent advances in calculating stiffness using research-grade or commercially available wearable sensors.[5,17] With such devices, protocols for monitoring or altering stiffness could be efficiently implemented in clinical settings on large numbers of patients. However, before interventions to monitor or change leg and joint stiffness can be implemented, it is necessary to confirm the previously hypothesized relationships between injury risk and stiffness.

As such, we sought to determine the relationship between running-related injury and leg, knee, and ankle stiffness using data from a prospective cohort study of recreational runners. We hypothesized that leg, knee, and ankle stiffness would have a significant and nonlinear association with running-related injury risk.

METHODS

Study Design and Participants

We recruited a convenience sample of recreational runners for a prospective cohort study with a maximum follow-up of 1 year. Participants were recruited between November 2015 and June 2016 using flyers, emails, a research recruiting web page on institutional websites, and word of mouth. We aimed to recruit at least 38 runners for follow-up of at least 6 months to ensure that at least 10 injuries were observed (based on expected annual injury rates) because approximately 10 events per variable are necessary for univariate analysis of time-to-event data.[26,35] Our ultimate sample size and number of events observed surpassed this threshold.

Volunteers were eligible to participate if they were between the ages of 18 and 65 years, had run at least 16 km per week for at least 2 years, and had no history of injury in the previous 3 months. Participants who had experienced an injury in the past were required to have returned to their typical training volume and intensity. Volunteers were ineligible if they had any history of surgery to the back or lower extremities. The study was approved by the university's institutional review board, and all participants provided written informed consent.

Biomechanical Gait Data

Upon enrollment into the study, all participants completed an in-laboratory overground kinematic and kinetic gait assessment. Gait data were captured at 240 Hz using a 9-camera motion capture system (Oqus 400; 500 Qualisys AB) synchronized with three 1200-Hz force plates (OR-6-2000; AMTI Inc). Each individual was outfitted with retroreflective markers in a bilateral modified Cleveland Clinic lower-body configuration.

Participants completed 2 sets of gait trials: 1 set at a criterion speed of 4.0 m/s and 1 set at the individual's self-reported preferred training speed. At both speeds, a minimum of 5 successful trials on both legs was collected. A trial was deemed successful if the participant's speed was within ±5% of the target speed, the participant's foot made full contact with a force plate, and the participant did not modify his or her gait to target the force plate. To ensure that interparticipant differences in stiffness were a function of gait mechanics and not footwear, individuals wore a standardized neutral running shoe during the gait collection protocol (One X CrossFit Cushion 3.0; Reebok).

Marker data were filtered using a fourth-order zero-lag low-pass Butterworth filter with a cutoff frequency of 12 Hz for marker data and 50 Hz for force data. Joint kinematics and kinetics were calculated using Visual3D software (C-motion Inc) using segment masses from Dempster and segment inertial properties from the geometric model of Hanavan.[9,15] Joint centers were defined at the midpoint between the medial and lateral malleoli (ankle), at the midpoint between the medial and lateral junctions of the tibia and femur (knee), and using the regression equations of Bell et al[1,2] (hip). Sagittal plane internal joint moments were calculated using force data filtered at 12 Hz to avoid impact-related artifacts in joint moment data[19] and expressed in their respective joint coordinate systems.[10]

Leg stiffness was calculated using the equations of McMahon and Cheng[21]:

$$k_{leg} = \frac{F_{\max}}{\Delta L}$$

where k_{leg} is leg stiffness, ΔL is the change in vertical leg length from initial contact to the instant of maximal vertical ground reaction force, and F_{max} is the maximum vertical ground reaction force. In turn, ΔL was calculated as follows:

$$\Delta L = \Delta y + L_0(1 - \cos(\theta))$$

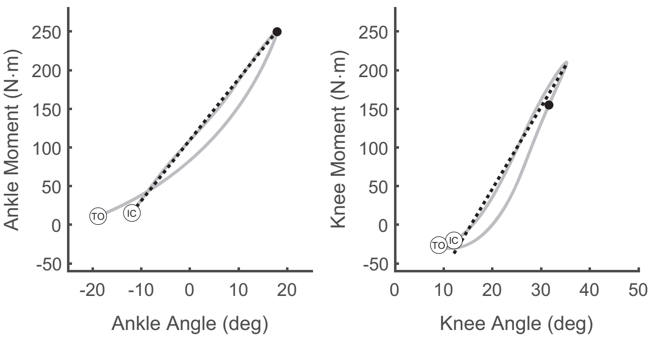

Figure 1. Plotting joint moment against joint angle from initial contact (IC) to toe-off (TO) illustrates the characteristic torsion spring-like function of the knee and ankle during running. Joint stiffness was calculated as the slope of a least squares line (black dashes) fit to the angle-moment data from IC to the end of the absorption phase, defined as the instant of maximum ankle dorsiflexion and depicted as a black dot.[14]

$$\theta = \sin^{-1}\left(\frac{vt_c}{2L_0}\right)$$

where Δy is the maximum change in vertical position of the body's center of mass during stance, L_0 is the standing leg length, θ is half the angle of the arc swept by the leg during stance, v is horizontal velocity at initial contact, and t_c is the ground contact time. In addition, Δy was calculated using double-integration of the vertical ground-reaction force assuming equal and opposite initial and final vertical velocities of the body's center of mass during stance, L_0 was calculated using height of the greater trochanter during the standing calibration trial, and v was calculated using the velocity of the center of mass of the pelvis.

Ankle and knee joint stiffness was calculated using the method of Hamill et al,[14] in which a linear regression equation is fit to the joint moment/joint angle plot using data from initial contact until the end of the absorption phase, which is defined as the instant of maximum ankle dorsiflexion during stance. This same instant is used for the calculation of ankle stiffness and knee stiffness (ie, knee stiffness is calculated using data from initial contact to the instant of maximum ankle dorsiflexion). The slope of this line gives the joint stiffness (Figure 1). Although this calculation does not represent true mechanical stiffness, it can be considered a measure of "quasi-stiffness."[20] Stiffness data were calculated using kinetic and kinematic data for each step and averaged across trials within a condition and a leg.

Follow-up and Outcomes

Study participants completed a weekly survey distributed via email (Qualtrics) that inquired about training volume, nonrunning physical activity, and any running-related pain or injuries that occurred. Participants were asked to report "any pain, injury, or problem with your legs, feet, joints, pelvis, and/or back." If any potential injury was reported, individuals were asked whether they reduced or cancelled training sessions due to the problem, and if so, how many days of planned training were reduced or cancelled. These responses were used to measure the primary outcome, which was the emergence of a running-related injury. Running-related injury was defined using the consensus-based definition of running-related injury proposed by Yamato et al[39] as any running-related pain that caused a cancellation or reduction in volume or intensity of at least 3 planned running sessions.

Participants were also asked to report the location of the injury in a free-response question and on a series of graphics of a human figure (a "pain manikin").[34] These responses were used to determine the location of the injury and assign it to either the left or the right leg. A licensed, experienced physical therapist reviewed the free-text responses to confirm that the description of pain was consistent with a running-related injury rather than nonrunning pain or injury (eg, work-related injury).

Stiffness variables often differ from leg to leg, and, as a result, each leg may be exposed to a different level of injury risk. To account for these differences, we recorded injuries at the level of individual legs. Each leg contributed person-time to the study until the occurrence of injury, the end of the study, or the participant was lost to follow-up. In this way, if a participant sustained an injury on the left side of the body, his or her right leg would continue to accrue time spent in the study until injury on the right side, loss to follow-up, or study conclusion. This approach follows previous research and provides a valid way to incorporate biomechanical data from both legs.[4] One individual sustained a back injury during follow-up, which was assigned to both legs; however, this participant had already sustained injury on 1 side of the body, so potential ambiguities regarding which leg to assign to a back injury were not an issue with our data.

Missing Data and Loss to Follow-up

Participants were considered lost to follow-up when they ceased responding to the automated weekly survey emails. In a few cases, long periods of nonresponse were punctuated by occasional survey responses. To limit the effect of these long periods of nonresponse, we implemented an iterative procedure where the final survey from participants with <75% compliance (defined as proportion of surveys completed from enrollment until loss to follow-up) was excluded until compliance met or exceeded 75%. For the remaining missed surveys, missing training volume data were handled using multiple imputation as implemented in the 2-level predictive mean matching method in the R packages "mice" (Version 3.8.0) and "miceadds" (Version 3.7-6).[7,28,33] All statistical analyses were conducted in R Version 4.0.2 (R Core Team, Vienna, Austria). Five imputed data sets were created, and models were pooled using Rubin's Rules as described by Van Buuren.[33]

Statistical Analysis

Estimates and 95% confidence intervals (CIs) for the association between running-related injury and leg stiffness,

TABLE 1
Participant Characteristics (30 Women, 19 Men)[a]

	Min	First Quartile	Median	Third Quartile	Max
Age, y	18	23	29	37	58
Height, m	1.58	1.66	1.72	1.80	1.93
Weight, kg	49.82	60.10	66.89	71.90	103.80
BMI	18.06	20.57	22.24	24.20	31.98
Training volume at enrollment, km/wk	16.09	20.12	32.19	44.26	120.70
Running experience at enrollment, y	2	4.5	7	15	22
Preferred running speed, m/s	2.42	3.21	3.70	3.92	4.48
Ankle stiffness, N·m/deg	4.13	7.38	8.79	10.57	16.45
Knee stiffness, N·m/deg	4.37	5.56	6.92	8.92	13.10
Leg stiffness, kN/m	7.19	8.90	10.07	12.83	16.30

[a] Stiffness values are for the right leg at a standard criterion speed of 4.0 m/s; stiffness data from both legs and at both the criterion speed and the runner's preferred running speed were used in the analyses. BMI, body mass index; Min, minimum; Max, maximum.

ankle stiffness, and knee stiffness were assessed using 3 separate extended Cox proportional hazards models with Peto correction for ties. In each model, the stiffness-related changes in injury rate were allowed to vary in a smooth, nonlinear fashion by using restricted cubic splines with 10 knots dispersed evenly throughout the data and smoothness selected using restricted maximum likelihood fitting.[29] This approach allows the model to accommodate possible nonlinear associations between stiffness and injury risk. Because the smoothing penalty was chosen using restricted maximum likelihood, the number and placement of spline knots had minimal effect on the results.[16]

Given that stiffness and injury occur at the level of legs, which are nested within people, we addressed the correlated nature of these observations by including a Gaussian random effect (or "frailty") at the participant level in each model.[32] In this way, we accounted for factors that are shared among legs within the same individual—while 1 individual's left and right legs may differ in their stiffness, they share the same genetics, lifetime physical activity history, and other variables that may affect injury risk (including training volume). Allowing legs to cluster within individuals also provides a valid method of continuing follow-up for the uninjured contralateral limb after an injury, which is important when a biomechanical mechanism of injury is thought to act at the level of the leg versus at the level of the individual.[4] All statistical analyses were conducted using R Version 4.0.2 using the "survival" (Version 3.2-3) and "mgcv" packages (Version 1.8-31).[27,31,37,38]

TABLE 2
Distribution of Injury Locations Within the 29 Legs (23 Participants) Injured During Follow-up

Injury Location	No. of Legs
Foot	5
Ankle	3
Shank	4
Knee	4
Thigh	5
Hip/pelvis	4
Back	1
Multiple locations	3
Total	29

Sensitivity Analysis

In time-to-event analysis of sports injury, multiple definitions of "time" are defensible.[25] We focused our primary analysis on hours of running until injury but also conducted a parallel analysis using weeks of training until injury. Likewise, the in-laboratory biomechanical assessments included gait data collected at both a standardized speed of 4.0 m/s and at each participant's self-reported preferred running speed; we again conducted parallel analyses—while a runner's preferred speed better reflects his or her gait patterns during typical training sessions, a standardized speed ensures that differences among individuals are the result of inherent gait mechanics without confounding by variations in running speed. Furthermore, because training speed may be an independent risk factor for injury, any stiffness-injury associations may reflect the effects of speed and not inherent stiffness per se. Given that researchers may come to different conclusions on the appropriateness of assessing gait at a preferred versus a standardized speed, we present the results of both analyses here for transparency.

RESULTS

A total of 55 individuals were enrolled for participation. Of these, 2 participants were excluded for ongoing and preexisting injury, 1 was excluded for completing no weekly surveys, and 3 were excluded for not including training volume in their survey responses. A total of 32 weekly surveys from 10 different individuals were excluded via the iterative right-censoring procedure to ensure $\geq$75% compliance during the study duration. These iterative exclusions accounted for approximately 2.1% of all surveys received. A total of 49 participants (98 legs) contributed a total of 2742 person-weeks and 6379.6 hours of running (mean, 27.98 weeks of training and 65.10 hours of total running per leg) to the final analysis (Table 1).

A total of 29 legs across 23 individuals (29.6% of legs; 46.9% of individuals) sustained an injury during follow-up. Median time to injury on either leg, as determined using Kaplan-Meier estimates, was 27 weeks or 53.27 hours of training. The most common location of injury was the foot, but injuries occurred throughout the lower body (Table 2).

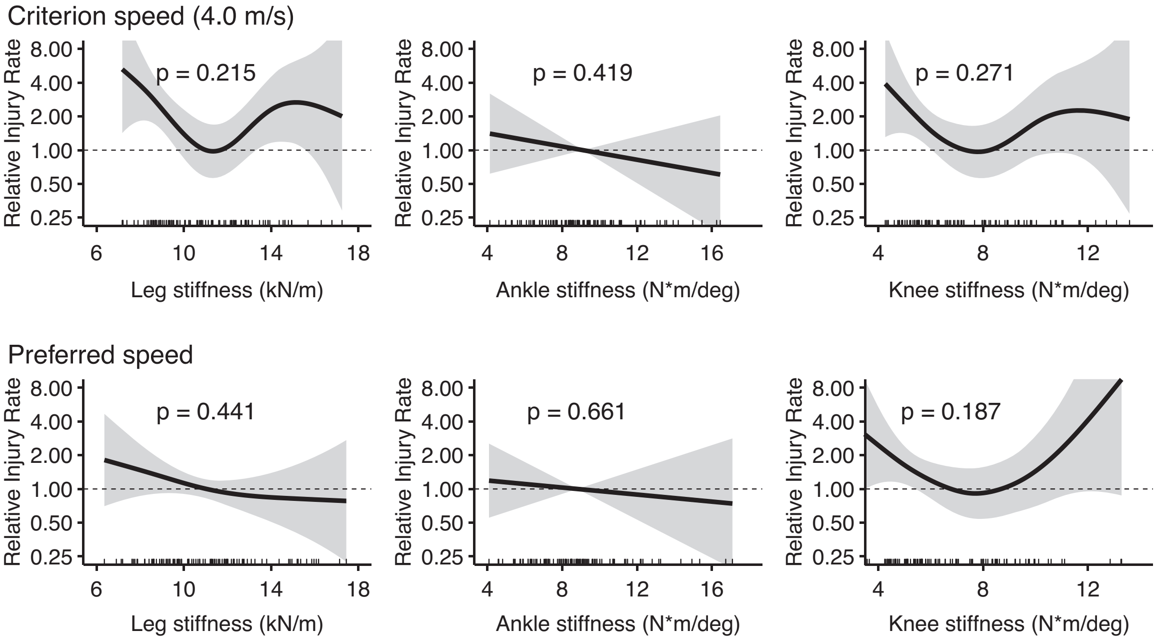

Figure 2. Relative injury rate as a function of leg, ankle, and knee stiffness when injuries were assessed using weeks of training until injury. Black lines show relative injury rate (HR) estimates for various levels of each stiffness metric compared with an individual of average stiffness (where HR = 1.0). Gray shaded bands show pointwise 95% CIs, and dashed lines show null hypothesis of no association (ie, HR = 1.0 for all levels of stiffness). Rug ticks show the distribution of individual stiffness values for all 98 legs. HR, hazard ratio; kN/m, kilo-Newtons per meter; N*m/deg, Newton-meters/degree.

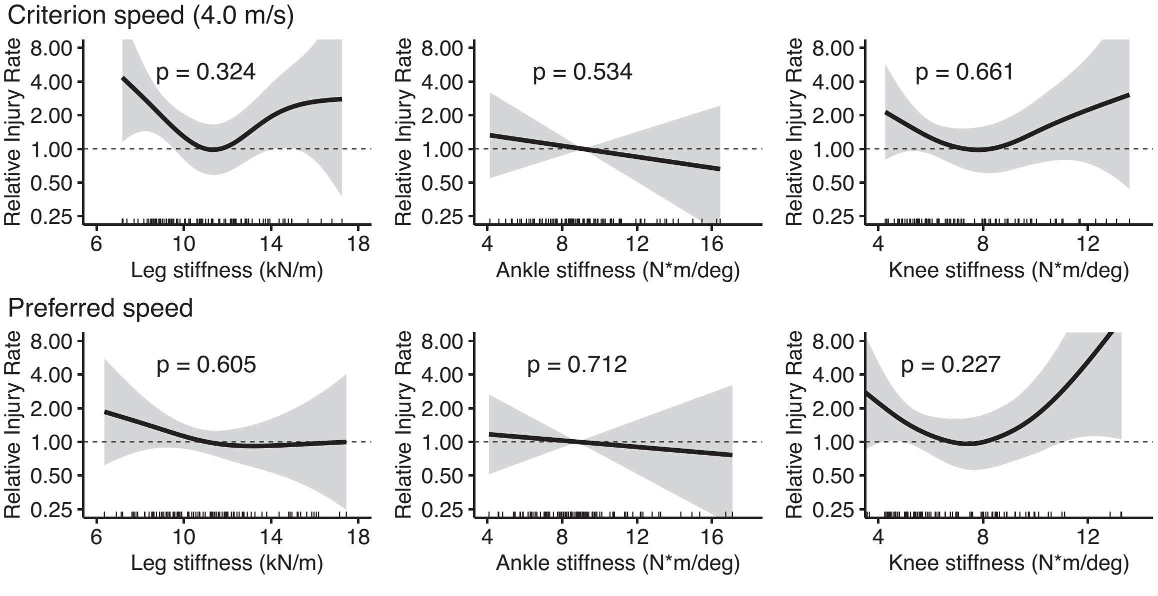

Figure 3. Relative injury rate as a function of leg, ankle, and knee stiffness when injuries were assessed using hours of training until injury. Black lines show relative injury rate (HR) estimates for various levels of each stiffness metric compared with an individual of average stiffness (where HR = 1.0). Gray shaded bands show pointwise 95% CIs, and dashed lines show null hypothesis of no association (ie, HR = 1.0 for all levels of stiffness). Rug ticks show the distribution of individual stiffness values for all 98 legs. HR, hazard ratio; kN/m, kilo-Newtons per meter; N*m/deg, Newton-meters/degree.

We found weak and nonsignificant ($P = .187\text{-}.712$) associations between stiffness measures and injury (Figures 2 and 3). Relative injury rates tended to be equal across different levels of ankle stiffness and showed weak U-shaped associations for knee and leg stiffness. The greatest degree of nonlinearity in estimated relative injury rates was found for knee stiffness at preferred running speed (*P* = .187 and .227 for weeks and hours of training until injury, respectively), with proportionally greater increases in relative injury rates at knee stiffness levels greater than approximately 10 N·m/deg. However, 95% CIs were compatible with associations ranging from beneficial to injurious for both high and low stiffness levels.

These associations were unaffected by changes in modeling choices. Sensitivity analysis across both measures for time (hours of training until injury, weeks of training until injury) and across both the criterion running speed of 4.0 m/s and preferred running speed showed that only high levels of knee stiffness had any consistent trends with regard to estimated relative injury rates, displaying a U-shaped curve in all 4 analyses.

DISCUSSION

The objective of this study was to test the association between running-related injuries and leg, knee, and ankle stiffness. In this prospective cohort study, leg, ankle, and knee stiffness were not significantly associated with relative injury rates. Contrary to our hypothesis, we did not find sufficient evidence to support the argument that stiffness is an important factor in the development of injury.

These findings contrast with those of previous work suggesting that excessively high or low stiffness levels should increase injury risk.[6,22,36] Butler et al[6] proposed the existence of "optimal" levels of stiffness, linking the greater incidence of bony and soft tissue injuries in high- and low-arched runners, respectively, with higher levels of leg stiffness observed in high-arched runners and lower levels of leg stiffness observed in low-arched runners.

Messier et al[22] found that odds of injury increased in individuals with greater knee stiffness, but they did not specifically address the potential for nonlinear associations between knee stiffness and injury. The direction of our findings coincides with those of Messier et al for runners with very high levels of knee stiffness (ie, greater risk for high levels of stiffness) but disagree in regard to injury risk at lower than average stiffness levels. The differences in findings are not likely to be explained by differences in participant population, as the knee stiffness values seen in the present study when running at preferred training pace (mean ± SD, 6.78 ± 2.24 N·m/deg) cover a similar range as the stiffness values seen in Messier et al[22] in injured and uninjured individuals (6.89 ± 2.65 and 6.72 ± 2.03 N·m/deg, respectively), running at modestly faster preferred speeds (3.60 ± 0.48 m/s in the present study; approximately 2.9 ± 0.4 and 3.0 ± 0.4 m/s in injured and uninjured individuals, respectively, in Messier et al). Both Messier et al and Carruthers and Farley[8] noted that knee and leg stiffness are moderately correlated with body weight; we observed this trend as well ($\rho = 0.49$ for the right leg at preferred training pace). From a causal perspective, if greater stiffness is a consequence of greater body mass, it would be inappropriate to adjust for body weight during analysis—doing so would diminish the potential causal effect of stiffness on injury.[3] As such, we chose not to adjust for body weight in our analyses.

Gait mechanics are just 1 potential cause of running-related injury. While leg stiffness may modulate the structure-specific load on the body during training, training-related factors (eg, weekly mileage) influence the overall cumulative loading experienced by any given runner, and factors such as muscular strength and diet may influence that athlete's capacity to withstand cumulative loading.[23] Our analysis used stiffness measures as a proxy for structural loading and compared athletes after equivalent amounts of training using time-to-event analysis, which accounts for differences in weekly training volume. However, we did not measure or adjust for factors that could affect load-bearing capacity, such as lifetime physical activity history, diet, or sleep; as such, our results should be interpreted cautiously.

Except for legs with the most extreme values of knee and leg stiffness (ie, leg stiffness >13 kN/m or <7.5 kN/m; knee stiffness >9 N·m/deg or <5 N·m/deg), the 95% CIs for relative injury rates did not exceed 2.0, suggesting that moderate changes in leg, ankle, and knee stiffness are unlikely to lead to large changes in injury risk. These findings should give more confidence to clinicians employing stride frequency-based or footstrike-based gait retraining programs, as the changes in stiffness associated with these interventions are relatively small (eg, an increase in leg stiffness of 1.37 kN/m for a 10% increase in stride frequency)[11] and are thus not likely to result in unintentional increases in injury risk for most runners.

We encourage future work specifically focused on runners with knee stiffness greater than approximately 9 N·m/deg (approximately the top 75th percentile or ≥1 standard deviation above average), as our models indicated the possibility for substantial increases in injury risk above this threshold. However, we emphasize that confidence intervals for these extreme values of stiffness were wide, allowing for the possibility of substantial increases or decreases in injury risk compared with stiffness values in runners with average stiffness in our study (eg, a relative injury rate as low as 0.78 or as high as 3.66 for a runner with knee stiffness of 10 N·m/deg compared with a runner with average knee stiffness) (Figure 3). Larger studies, particularly those with a larger number of participants at these extreme levels of stiffness, will be necessary to determine whether runners with very high levels of knee stiffness are indeed more prone to injury. The evidence from this study does not, on the whole, support a strong association between extreme values of leg, knee, or ankle stiffness and running-related injury.

The strengths of this study included its prospective nature, assessment of stiffness at the level of individual legs, and accounting for the possibility of nonlinear associations between stiffness and injury. Like most prospective studies to date on running-related injury, our findings were based on a modestly sized convenience sample of runners, which may not be representative of the broader population of runners. Although convenience samples are widely used in running injury research, these samples tend to have a lower body mass index and be younger, healthier, more predominantly male, and more likely to train at faster speeds.[30] Although our study population included runners across a wide range of ages and body mass indicess and was not predominantly male, all participants in our study had at least 2 years of running experience. Thus, our findings may not be generalizable to novice runners.

While our sample size was adequate for univariate time-to-event analysis, the limited sample size of our study precluded conducting detailed stratified or adjusted analyses to examine the contributions of multiple risk factors for running-related injury and may have limited our power to detect small or moderate associations between stiffness and injury, especially at extreme values.[35] As such, we encourage future work with larger participant pools, particularly at extreme values of stiffness.

We relied on self-reported training data to investigate associations between stiffness and hours of training until injury. Self-reported training volume may not reliably estimate true training volume, which may have biased our results.[24] However, because we also assessed the relationship between stiffness and weeks of training until injury and observed no major changes in our findings, any unreliability in training volume likely had a minimal influence on our results.

Self-reported injury data provide only limited information on the anatomic structures affected by individual injuries—uncovering any potential relationships between leg or joint stiffness and specific types of running injuries would likely require injury diagnoses confirmed by a clinician. While stiffness has been associated with greater overall injury risk in previous work,[22] emerging research suggests that some biomechanical risk factors are only relevant for certain injury locations.[18] Although our results suggest stiffness may not be a major factor in overall injury risk, further research using clinician-confirmed injuries may be warranted to identify tissue-specific associations between stiffness and injuries to specific load-bearing tissues (e.g., patellofemoral joint, tibia).

As with all laboratory-based biomechanical research, gait patterns adopted during a 1-time in-laboratory assessment may not be reflective of gait mechanics during typical training. Stiffness may affect injury in a location-specific manner, but because only a small number of participants sustained injury at any given anatomic location, we were not able to assess location-specific associations between stiffness and injury. Runners with extreme stiffness values are, by definition, rare—in our study, only about 25% of participants had knee stiffness levels >9 N·m/deg—so our ability to detect increases in injury risk at very high or very low stiffness values was limited, as we did not specifically recruit runners with unusually high or low stiffness levels, which may be a target population for future observational studies or randomized controlled trials.

CONCLUSION

Our findings suggest that leg, knee, and ankle stiffness levels observed most commonly in runners may not be clinically relevant factors in the development of running-related injury. While discouraging from the perspective of identifying runners at high risk for developing injury, these results indicate that small to moderate changes in stiffness brought about by gait retraining or modification are not likely to lead to unintentional increases in injury risk.

We could not exclude the possibility that runners with unusually high knee stiffness are at an increased risk for injury. Additional research on these runners could pave the way for more individualized and subject-specific interventions to reduce injury risk.

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