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# Clinical Predictors of Dynamic Lower Extremity Stiffness During Running

Running is an increasingly popular mode of exercise, with more than 48 million participants in the United States in 2015.[30] Running is associated with reduced mortality and disability, but also incurs notable risk for lower extremity injury.[6,19] Runners have to mitigate forces resulting from repetitive single-leg landings, predominantly through eccentric muscle action, and varied passive resistance from skeletal tissues.[35]

During running, the lower extremity can be modeled to have the unique stiffness characteristics of a spring.[3,24] Lower extremity stiffness (Kleg) describes the resistance to general lower extremity joint excursions following ground contact. The most parsimonious method of describing Kleg is the spring mass model, which represents the center of mass on a massless spring. The calculation of Kleg is typically peak vertical ground reaction force (GRF) divided by relative compression of the leg during ground contact,[5] which may serve as a global surrogate for loading rate and the subsequent kinematic response of the lower extremity during running.

**BACKGROUND:** Lower extremity stiffness describes the relative loading and kinematics of the entire lower extremity during ground contact. Previously injured subjects demonstrate altered lower extremity stiffness values. Clinical analysis of lower extremity stiffness is not currently feasible due to increased time and cost.

**OBJECTIVE:** To determine the clinically identifiable contributors to lower extremity stiffness.

**METHODS:** In this cross-sectional controlled laboratory study, 92 healthy runners completed a clinical screening involving passive assessment of hip, knee, and ankle range of motion, along with body anthropometrics. The range of motion was predominantly assessed in the sagittal and frontal planes. In the same session, runners completed an overground kinematic and kinetic running assessment at 3.35 m/s (±5%) to obtain lower extremity stiffness. Correlations between lower extremity stiffness and clinical variables were completed. Modifiable variables were included in an all-possible-linear regressions approach to determine a parsimonious model for predicting lower extremity stiffness.

**RESULTS:** Clinically modifiable measures included in the regression model accounted for 48.4% of the variance of lower extremity stiffness during running. The variables that predicted greater stiffness included greater body mass, less ankle dorsiflexion range of motion with the knee flexed, less hip internal rotation range of motion, and less first-ray mobility.

**CONCLUSION:** Reduced lower extremity range of motion and greater body mass are associated with greater lower extremity stiffness during running. These variables could be addressed clinically to potentially alter lower extremity stiffness and injury risk. *J Orthop Sports Phys Ther 2019;49(2):98-104. Epub 27 Jul 2018. doi:10.2519/jospt.2019.7683*

**KEY WORDS:** *leg stiffness, loading rate, overuse injuries*

A lower Kleg value is associated with greater joint excursion and greater reliance on active muscle contributions to modulate landing tasks,[13,14,25] and a greater Kleg value is associated with reduced joint excursion and increased impulsive loading to bones and cartilage.[33,34] Greater Kleg during hopping has been prospectively linked with greater lower extremity injury occurrence.[32] Additionally, Pruyn et al[28] found that the greater difference in Kleg between legs of Australian rules football players during hopping was also prospectively associated with a greater occurrence of lower extremity injury. These multiple associations suggest a link between Kleg and injury rates during dynamic activities.

Being multifactorial in nature, Kleg may reflect contributions from a variety of active and passive characteristics of the musculoskeletal system.[10,18] Traditionally, Kleg has been assessed by motion capture and inverse dynamics. However, such means of assessment may not be clinically feasible due to the burden of training, time, and cost involved.[5] A clinical method of estimating Kleg is feasible during hopping, however, still requires specific equipment and training.[7,20,23]

It has been demonstrated that Kleg is influenced by the stiffness of the hip,

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knee, and ankle joints, including contributions from both passive and active structures.[26] Given the serial nature of the lower extremity, alterations in stiffness of individual joints can potentially alter overall Kleg. Passive joint structure can also play a role in joint mobility and, subsequently, Kleg. It is often postulated that high-arched runners exhibit a more rigid foot with reduced mobility, whereas low-arched runners have more mobile feet.[31] This link between more restricted motion and arch height is supported by Williams et al,[33] who found that runners with higher, stiffer arches demonstrated greater loading rates and Kleg compared to low-arched runners.[33] Powell et al[27] also found that runners with high arches have significantly greater ankle dynamic joint stiffness during barefoot running.

Variables that can be easily assessed in clinical settings may also prospectively predict Kleg. Mahieu et al[21] prospectively found that greater dorsiflexion range of motion (ROM) was a significant predictor of greater dorsiflexion during hopping. Man et al[22] also prospectively found that greater passive metatarsophalangeal stiffness was significantly positively correlated with Kleg during running. This demonstrates that clinical variables can potentially predict Kleg during dynamic activities. This improved understanding of the individual musculoskeletal contributions to Kleg could potentially help shape targeted rehabilitation protocols to alter Kleg and subsequently reduce lower extremity injury occurrence.

However, to our knowledge, a comprehensive evaluation of how variables from a clinical assessment relate to Kleg has not been conducted. Therefore, the purpose of this study was to identify clinically measured variables that influence Kleg during running. Emphasis was placed on modifiable clinical variables in order to create a model that more clearly identifies clinical targets for change. We hypothesized that less ROM observed during a clinical exam would be associated with greater Kleg during running.

## METHODS

NINETY-TWO RUNNERS (53 MALE, 39 female; mean ± SD age, 49.7 ± 11.1 years; range, 25-81 years; height, 1.72 ± 0.09 m; mass, 70.6 ± 12.0 kg) volunteered to participate in the study. Subjects were recruited from the local running community population. Subjects were required to be free of lower extremity injury for 6 months and to run a minimum of 16 km per week. The study protocol was approved by the Biomedical Institutional Review Board at East Carolina University. Subjects read and signed an Institutional Review Board–approved informed-consent form prior to participation.

### Procedures

Data collection occurred during 1 session. Initially, a passive analysis of the lower extremities was conducted by a licensed physical therapist with greater than 10 years of experience with sports and orthopaedic patients. The measurements included available passive ROM and resting standing posture at the ankle, knee, and hip, predominantly in the sagittal and frontal planes. A full list of clinical variables and the measurement details are included in the **APPENDIX** (available at www.jospt.org). Results from the clinical assessment were scored as continuous, ordinal, or categorical, depending on test parameters (ie, ROM versus special tests). These clinical assessments were completed bilaterally; however, only the left-leg values were used for this analysis.

Following the clinical exam, subjects were analyzed during overground running using a 9-camera motion-capture system (Qualisys AB, Gothenburg, Sweden). A standing calibration trial was recorded with optoreflective markers placed bilaterally at joint landmarks (anterior superior iliac spines, posterior superior iliac spines, L5-S1, greater trochanters, medial and lateral knee epicondyles, medial and lateral malleoli, bases of the first and fifth metatarsals) and segments (calcaneus, shank, thigh, and pelvis). The markers at joint landmarks were used to establish joint centers and segment coordinate systems, and medial knee and ankle markers were removed before dynamic data collection.

Subjects were instructed to run with their normal running gait and maintain a consistent speed over 2 force plates (Advanced Mechanical Technology, Inc, Watertown, MA) embedded in the 20-m runway. Custom photocells placed 6 m apart allowed containment of subject running speed to 3.35 m/s (±5%). Kinematic data were collected at 240 Hz, while GRF data were synchronously recorded at 1200 Hz. Track Manager (Qualisys AB) software was used to reconstruct 3-D coordinates for each marker.

Subjects were allowed to run along the runway as many times as necessary to feel comfortable with the markers and striking the force plates without aiming or altering their strides. A trial was considered successful when the subject ran with a natural gait over the force plates at a specified speed, and when the entire left foot landed on 1 of the force plates. Subjects were habitual-shod runners and completed the running assessment in self-selected running shoes.

Pelvis, thigh, shank, and foot segments were created from the markers placed on the lower extremities. Marker data were low-pass filtered at 12 Hz and GRF data were low-pass filtered at 50 Hz, each with second-order recursive Butterworth filters. Data were then analyzed during stance phase only, defined between foot strike (vertical GRF greater than 20 N) and toe-off (vertical GRF less than 20 N), and normalized to 101 data points.

Total Kleg during running for the left leg was calculated using the formula Kleg = $F_{max}/\Delta L$, where $F_{max}$ is peak vertical GRF; and $\Delta L = \Delta y + L\,(1 - \cos\theta)$, where L is initial leg length, $\Delta y$ is vertical displacement of the body's center of mass, and $\theta = \sin^{-1}(vT_c/2L)$, where $v$ is forward velocity and $T_c$ is contact time.[24] Initial leg length was defined at the vertical distance of the greater trochanter to the floor during standing calibration.

Body center-of-mass position was estimated from the L5-S1 kinematic marker. Forward velocity was calculated from the average center-of-mass forward velocity (determined via the first derivative of the L5-S1 position data) during stance phase.

### Statistical Methods

Descriptive statistics were reported as means and standard deviations for continuous variables, or as frequencies for categorical variables. Simple Pearson correlations and 1-way analyses of variance were computed for continuous and categorical variables, respectively, to determine the relationships of Kleg separately for each clinically assessed variable. Multiple regression analyses were then performed to determine which set of clinical variables best predicted Kleg. A series of multiple regression models were developed to determine a parsimonious model, including forward and backward selection along with an all-possible-regressions approach. A multiple regression model containing all 13 modifiable clinical variables was also developed to ensure the coefficient of determination ($R^2$) was not meaningfully reduced in the parsimonious model. In an effort to focus on modifiable clinical contributions, nonmodifiable variables (eg, leg and foot lengths, arch height) were excluded from the regression analyses.

## RESULTS

Descriptive statistics for each of the clinical variables of interest are reported in **TABLE 1.** Average ± SD left Kleg during running was 11.09 ± 2.37 kN/m. The association between Kleg and each clinical variable is reported in **TABLE 2.** The forward selection approach to multiple regression yielded significant predictors of hip internal rotation, subject body mass, and first-ray mobility ($R^2$ = 46.4%). The backward selection approach to multiple regression yielded significant predictors of hip internal rotation, subject body mass, and ankle dorsiflexion with the knee in 90° of flexion ($DF_{flex}$) ($R^2$ = 44.2%). The all-possible-regressions approach for 4 predictors included hip internal rotation, subject body mass, $DF_{flex}$, and first-ray mobility and was considered the final model (**TABLE 3**). This model accounted for 48.4% of the variance in Kleg during running ($P$<.001). The individual predictors revealed that less $DF_{flex}$, less hip internal rotation, a hypomobile first ray, and greater body mass were associated with greater Kleg. This multiple regression equation for Kleg (kiloNewtons per meter) is estimated as [12.23 + (−0.09 × $DF_{flex}$ ROM) + (−0.07 × hip internal ROM) + (0.05 × body mass) + (first-ray mobility)], where mobility was defined as hypomobile (0), normal (0.09), or hypermobile (1.27).

The multiple regression model containing all 13 modifiable variables explained only slightly more of the variance associated with Kleg during running ($R^2$ = 54.0%). This indicates that this study's parsimonious model with 4 terms captures nearly all of the variance of Kleg that was explained by the 13 modifiable variables.

## DISCUSSION

The purpose of this study was to identify clinical variables that contribute to Kleg during running. In the current study, Kleg was similar to previously reported values of stiffness.[9,12] Nearly half (48.4%) of the variance in Kleg was explained by a brief clinical evaluation. More importantly, these variables are clinically modifiable. This is surprising, given that a large portion of dynamic Kleg is modulated through active eccentric muscle action during

**TABLE 1** All Variables Assessed During Clinical Screening for the Left Limb*

| Clinical Variable | Value |
|---|---|
| Anthropometrics | |
| Leg length, cm | 88.4 ± 5.5 |
| Foot length, cm | 26.1 ± 1.7 |
| Q angle, deg | 9.9 ± 6.5 |
| Truncated foot length, cm | 19.8 ± 1.3 |
| Dorsum height of foot at 50% foot length during WB, cm | 6.5 ± 0.6 |
| Dorsum height of foot at 50% foot length during NWB, cm | 7.2 ± 0.6 |
| Dorsum height difference (NWB − WB), cm | 0.7 ± 0.2 |
| Body mass, kg | 70.6 ± 12.0 |
| Height, m | 1.72 ± 0.09 |
| Joint ROM, deg | |
| Ankle DF with knee in full extension | 19.8 ± 4.5 |
| Ankle DF with knee in 90° of flexion | 25.4 ± 4.9 |
| Ankle DF difference (flexion − extension) | 5.6 ± 3.0 |
| Hip internal rotation | 39.8 ± 7.6 |
| Hip external rotation | 40.3 ± 6.8 |
| Hip total transverse ROM | 80.1 ± 10.0 |
| Subtalar inversion | 18.9 ± 5.5 |
| Subtalar eversion | 8.3 ± 3.3 |
| Subtalar total ROM | 27.3 ± 7.0 |
| Hallux DF | 80.4 ± 12.5 |
| Foot posture | |
| Subtalar neutral position, deg | 5.4 ± 2.8 |
| Forefoot/rearfoot angle, deg† | 4.1 ± 3.6 |

*Table continues on page 101.*

ground contact.[35] The multiple regression equation generated from these data could lay the initial groundwork for a clinical tool to estimate Kleg in the absence of expensive 3-D biomechanical systems.

The current study demonstrates that less lower extremity joint ROM (ie, hip internal rotation, ankle dorsiflexion, first-ray mobility) is associated with greater Kleg. This supports our hypothesis that reduced mobility observed during a clinical exam would be associated with greater Kleg during running. These reductions in ROM may result in reduced joint excursions during ground contact that would potentially be associated with greater stiffness.

Previous work concurs that greater body mass and reduced lower extremity joint mobility in the foot are associated with greater Kleg during running.[8,22] This relationship of both body mass and joint mobility to Kleg is expected, given that it comprises $F_{max}/\Delta L$, where greater body mass is associated with greater $F_{max}$ and reduced lower extremity joint mobility is likely associated with less potential for lower extremity compression ($\Delta L$).[22,27,33] These clinical variables could serve as a targeted rehabilitation protocol to potentially alter stiffness during running.

For example, by increasing ankle dorsiflexion through a targeted stretching protocol, reductions in Kleg during running may be achieved. Conversely, a runner with a lower level of Kleg and with a history of Achilles tendinopathy may increase his or her Kleg value through targeted plyometric training focused on ankle, knee, and hip muscle strength and joint control.[29]

However, some degree of caution should be taken in regard to the clinical utility of this current regression model. This is an initial attempt at defining a predictive model for Kleg in a clinical sense. We have not conducted testing by targeting 1 variable (eg, increasing $DF_{flex}$ with calf stretching) and the subsequent effects on additional variables and overall Kleg. It is highly likely that a targeted rehabilitation protocol would require all variables to be addressed simultaneously for effective changes in Kleg. Additionally, the current regression model is more heavily weighted toward fluctuations in foot mobility, particularly with first-ray mobility. How foot mobility affects overall Kleg during running warrants further research.

Previous studies have demonstrated that Kleg is predominantly modulated by the neuromechanical properties of a multitude of joints, including the hip, knee, and ankle.[1,11,15,16,26] Our parsimonious clinical model consisted of 1 foot measurement, 1 ankle measurement, 1 hip measurement, and body mass, which demonstrates both the proximal and distal nature of modulating dynamic Kleg during running. These variables demonstrate the ability of the lower extremity to modulate stiffness in a variety of patterns. For example, reduced stiffness about the ankle joint could be compensated for with increased stiffness about the knee joint.[17]

While the current study did not include any kinetic or kinematic predictor variables, commonly measured clinical variables were useful in predicting a dynamic measure. It is important to note that roughly half of the variance of Kleg is still unexplained through this model, and further investigations should focus

**TABLE 1** All Variables Assessed During Clinical Screening for the Left Limb* (continued)

| Clinical Variable | Value |
|---|---|
| First-ray position, n | |
| PF | 22 |
| Normal | 70 |
| DF | 0 |
| First-ray mobility, n | |
| Hypomobile | 6 |
| Normal | 71 |
| Hypermobile | 15 |
| Resting calcaneal stance angle, deg‡ | -2.7 ± 4.3 |
| Standing rearfoot angle, deg‡ | -7.7 ± 5.2 |
| Hallux valgus, deg | 10.3 ± 4.1 |
| Tibial varum, deg† | 4.2 ± 4.3 |
| AHI during WB | 0.36 ± 0.02 |
| AHI during NWB | 0.32 ± 0.02 |
| AHI: difference (WB – NWB) | 0.03 ± 0.01 |
| Clinical tests/muscle length | |
| Hamstring ROM (supine, 90°/90° position), deg§ | -18.8 ± 10.4 |
| Quadriceps ROM (prone, heel-to-buttock distance), cm | 1.5 ± 2.8 |
| Ober test, n | |
| Positive | 10 |
| Negative | 82 |
| Thomas test, n | |
| Positive | 25 |
| Negative | 67 |

*Abbreviations: AHI, arch height index; DF, dorsiflexion; NWB, non-weight bearing; PF, plantar flexion; ROM, range of motion; WB, weight bearing.*
**Values are mean ± SD unless otherwise indicated.*
*†Varus is positive.*
*‡Valgus is negative.*
*§Knee flexion angle from full extension.*

**TABLE 2** PEARSON CORRELATION COEFFICIENTS BETWEEN CONTINUOUS CLINICAL VARIABLES OF INTEREST AND LOWER EXTREMITY STIFFNESS

| Clinical Variable | r | P Value* |
|---|---|---|
| Nonmodifiable: continuous | | |
| AHI: NWB | 0.36 | .003† |
| AHI: WB | 0.36 | .003† |
| AHI: difference (WB – NWB) | -0.01 | .9 |
| Dorsum height of the foot at 50% foot length in NWB | 0.6 | <.001† |
| Dorsum height of the foot at 50% foot length in WB | 0.62 | <.001† |
| Dorsum height difference (NWB -WB) | 0.02 | .79 |
| Foot length | 0.37 | <.001† |
| Forefoot/rearfoot angle | -0.03 | .76 |
| Hallux valgus | -0.14 | .16 |
| Height | 0.47 | <.001† |
| Leg length | 0.39 | <.001† |
| Q angle | 0.03 | .76 |
| Resting calcaneal stance | 0.17 | .09 |
| Standing rearfoot angle | 0.12 | .22 |
| Subtalar neutral | 0.05 | .58 |
| Tibial varum | -0.07 | .48 |
| Truncated foot length | 0.2 | .07 |
| Nonmodifiable: categorical | | |
| First-ray position | | .43 |
| Modifiable: continuous | | |
| Ankle DF with knee in full extension, deg‡ | -0.31 | .002† |
| Ankle DF with knee in 90° of flexion, deg‡ | -0.43 | <.001† |
| Ankle DF difference (flexion – extension) | -0.15 | .12 |
| Hallux DF‡ | -0.14 | .15 |
| Hamstring ROM (supine, 90°/90° position)‡ | -0.17 | .08 |
| Hip external rotation‡ | -0.09 | .37 |
| Hip internal rotation‡ | -0.53 | <.001† |
| Hip total transverse ROM | -0.41 | <.001† |
| Body mass‡ | 0.54 | <.001† |
| Quadriceps ROM (prone, heel-to-buttock distance)‡ | 0.21 | .06 |
| Subtalar eversion‡ | -0.16 | .1 |
| Subtalar inversion‡ | -0.26 | .012† |
| Subtalar total ROM | -0.26 | .009† |
| Modifiable: categorical | | |
| First-ray mobility‡ | | <.001† |
| Ober test‡ | | .27 |
| Thomas test‡ | | .47 |

*Abbreviations: AHI, arch height index; DF, dorsiflexion; NWB, non-weight bearing; ROM, range of motion; WB, weight bearing.*
**Overall P values from 1-way analyses of variance were reported for categorical variables and lower extremity stiffness.*
*†Statistically significant (P<.05).*
*‡Clinically modifiable variables utilized in the regression analysis (n = 13).*

on different neuromechanical factors that may add to the predictive model.

While the findings of the current study are unique and clinically useful, further research should focus on determining "ideal" Kleg values that may be used as "cutoffs" to minimize injury risk or improve performance. Previous research has indicated that there is an optimal Kleg value that maximizes performance during jumping,[2] and there is likely a trade-off between performance and injury risk. Additional clinical tests and variables should be included in future studies that incorporate neuromuscular factors (eg, knee extension strength and/or rate of torque development) in an attempt to explain a substantially greater proportion of the variance in Kleg.

## Limitations

The subjects in the current study ran at a fixed pace, which may not reflect the normal training pace of all subjects. Further information could be gleaned by having subjects run at varying velocities to analyze changes in Kleg and to determine additional associations with clinical variables.

Furthermore, subjects' foot-strike patterns were not controlled. The large majority of the subjects in the current study were rearfoot strikers. Delineating subjects based on foot-strike pattern could provide additional or different variables to be included in the model. For example, runners with rearfoot- and midfoot-strike patterns have been shown to exhibit different levels of overall leg stiffness.[4]

History of a lower extremity injury can also alter running biomechanics, which can alter Kleg. The subjects in this study were injury free at the time of testing; however, given the advanced age of this cohort (nearly 50 years), many subjects demonstrated at least 1 running-related injury in their running careers. Additional studies should more closely control previous injuries, and this analysis could be expanded to include currently injured runners.

## CONCLUSION

Alterations in Kleg have been linked with musculoskeletal injury.[28,32] However, clinical assessment of Kleg is currently neither feasible nor efficient. The current investigation provides initial data for a relevant clinical tool to assist clinicians in predicting Kleg as well as identifying modifiable characteristics that may be targets for interventions designed to alter Kleg. Such a tool would allow for actionable adaptations of training and rehabilitation programs in an attempt to minimize injury risk. These variables (hip internal rotation ROM, $DF_{flex}$, first-ray mobility, and body mass) are clinically important, as they account for nearly half of the observed variance of Kleg, and all the variables except body mass are modifiable passive characteristics of structures in the lower extremities. Moreover, body mass is modifiable over longer-term interventions (eg, diet, exercise). The remaining variance of Kleg may likely be explained by other passive anatomical contributions (eg, joint ROM, anatomical structure) and active neuromuscular contributions at the ankle, knee, and hip. ◉

## KEY POINTS

**FINDINGS:** This study found that nearly half of the variance associated with lower extremity stiffness could be explained by 4 clinical variables commonly used in physical therapy. Reductions in lower extremity mobility found on a clinical exam and greater body mass are associated with greater lower extremity stiffness during running.

**IMPLICATIONS:** Patients who have reductions in passive mobility on a clinical exam and/or greater body mass may be at greater risk for lower extremity running-related injuries.

**CAUTION:** Subjects were habitual runners who were injury free at the time of data collection. These findings may not be applicable to those in the general population who do not participate in regular running, or to individuals with ongoing running-related injuries.

## REFERENCES


1. Arampatzis A, Brüggemann GP, Metzler V. The effect of speed on leg stiffness and joint kinetics in human running. *J Biomech*. 1999;32:1349-1353. https://doi.org/10.1016/S0021-9290(99)00133-5
2. Arampatzis A, Schade F, Walsh M, Brüggemann GP. Influence of leg stiffness and its effect on myodynamic jumping performance. *J Electromyogr Kinesiol*. 2001;11:355-364. https://doi.org/10.1016/S1050-6411(01)00009-8
3. Blickhan R. The spring-mass model for running and hopping. *J Biomech*. 1989;22:1217-1227. https://doi.org/10.1016/0021-9290(89)90224-8
4. Breine B, Malcolm P, Van Caekenberghe I, Fiers P, Frederick EC, De Clercq D. Initial foot contact and related kinematics affect impact loading rate in running. *J Sports Sci*. 2017;35:1556-1564. https://doi.org/10.1080/02640414.2016.1225970
5. Butler RJ, Crowell HP, 3rd, Davis IM. Lower extremity stiffness: implications for performance and injury. *Clin Biomech (Bristol, Avon)*. 2003;18:511-517. https://doi.org/10.1016/S0268-0033(03)00071-8
6. Chakravarty EF, Hubert HB, Lingala VB, Fries JF. Reduced disability and mortality among aging runners: a 21-year longitudinal study. *Arch Intern Med*. 2008;168:1638-1646. https://doi.org/10.1001/archinte.168.15.1638
7. Dalleau G, Belli A, Viale F, Lacour JR, Bourdin M. A simple method for field measurements of leg stiffness in hopping. *Int J Sports Med*. 2004;25:170-176. https://doi.org/10.1055/s-2003-45252
8. Farley CT, Glasheen J, McMahon TA. Running springs: speed and animal size. *J Exp Biol*. 1993;185:71-86.
9. Farley CT, González O. Leg stiffness and stride frequency in human running. *J Biomech*. 1996;29:181-186. https://doi.org/10.1016/0021-9290(95)00029-1
10. Farley CT, Houdijk HH, Van Strien C, Louie M. Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. *J Appl Physiol (1985)*. 1998;85:1044-1055. https://doi.org/10.1152/jappl.1998.85.3.1044
11. Farley CT, Morgenroth DC. Leg stiffness primarily depends on ankle stiffness during human hopping. *J Biomech*. 1999;32:267-273. https://doi.org/10.1016/S0021-9290(98)00170-5
12. Ferris DP, Liang K, Farley CT. Runners adjust leg stiffness for their first step on a new running surface. *J Biomech*. 1999;32:787-794. https://doi.org/10.1016/S0021-9290(99)00078-0
13. Granata KP, Padua DA, Wilson SE. Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *J Electromyogr Kinesiol*. 2002;12:127-135. https://doi.org/10.1016/S1050-6411(02)00003-2
14. Granata KP, Wilson SE, Padua DA. Gender differences in active musculoskeletal stiffness. Part I. Quantification in controlled measurements of knee joint dynamics. *J Electromyogr Kinesiol*. 2002;12:119-126. https://doi.org/10.1016/S1050-6411(02)00002-0
15. Hobara H, Inoue K, Muraoka T, Omuro K, Sakamoto M, Kanosue K. Leg stiffness adjustment for a range of hopping frequencies in humans. *J Biomech*. 2010;43:506-511. https://doi.org/10.1016/j.jbiomech.2009.09.040
16. Hobara H, Muraoka T, Omuro K, et al. Knee


**TABLE 3** Multiple Regression Model Results for the Final Model Containing the 4 Predictor Variables

| | Estimated Unstandardized Coefficient | Standard Error | *t* Statistic | *P* Value | Variance Inflation Factor |
|---|---|---|---|---|---|
| Intercept | 12.23 | 2.22 | 5.50 | <.001* | |
| First-ray mobility (hypomobile versus normal) | 0.09 | 0.31 | −0.30 | .76 | 1.80 |
| First-ray mobility (hypomobile versus hypermobile) | 1.27 | 0.52 | 2.36 | .02* | 2.03 |
| Ankle dorsiflexion with knee in 90° of flexion | −0.09 | 0.04 | -2.14 | .03* | 1.25 |
| Hip internal rotation | −0.07 | 0.02 | -2.36 | .02* | 1.54 |
| Body mass | 0.05 | 0.01 | 3.25 | .001* | 1.41 |

**Statistically significant (P<.05).*

stiffness is a major determinant of leg stiffness during maximal hopping. *J Biomech*. 2009;42:1768-1771. https://doi.org/10.1016/j.jbiomech.2009.04.047

**17.** Kuhman D, Melcher D, Paquette MR. Ankle and knee kinetics between strike patterns at common training speeds in competitive male runners. *Eur J Sport Sci*. 2016;16:433-440. https://doi.org/10.1080/17461391.2015.1086818

**18.** Latash ML, Zatsiorsky VM. Joint stiffness: myth or reality? *Hum Mov Sci*. 1993;12:653-692. https://doi.org/10.1016/0167-9457(93)90010-M

**19.** Lee DC, Pate RR, Lavie CJ, Sui X, Church TS, Blair SN. Leisure-time running reduces all-cause and cardiovascular mortality risk. *J Am Coll Cardiol*. 2014;64:472-481. https://doi.org/10.1016/j.jacc.2014.04.058

**20.** Lloyd RS, Oliver JL, Hughes MG, Williams CA. Reliability and validity of field-based measures of leg stiffness and reactive strength index in youths. *J Sports Sci*. 2009;27:1565-1573. https://doi.org/10.1080/02640410903311572

**21.** Mahieu NN, Witvrouw E, Stevens V, Van Tiggelen D, Roget P. Intrinsic risk factors for the development of Achilles tendon overuse injury: a prospective study. *Am J Sports Med*. 2006;34:226-235. https://doi.org/10.1177/0363546505279918

**22.** Man HS, Lam WK, Lee J, Capio CM, Leung AKL. Is passive metatarsophalangeal joint stiffness related to leg stiffness, vertical stiffness and running economy during sub-maximal running? *Gait Posture*. 2016;49:303-308. https://doi.org/10.1016/j.gaitpost.2016.07.004

**23.** Maquirriain J. Leg stiffness changes in athletes with Achilles tendinopathy. *Int J Sports Med*. 2012;33:567-571. https://doi.org/10.1055/s-0032-1304644

**24.** McMahon TA, Cheng GC. The mechanics of running: how does stiffness couple with speed? *J Biomech*. 1990;23 suppl 1:65-78. https://doi.org/10.1016/0021-9290(90)90042-2

**25.** Milner CE, Ferber R, Pollard CD, Hamill J, Davis IS. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc*. 2006;38:323-328. https://doi.org/10.1249/01.mss.0000183477.75808.92

**26.** Padua DA, Carcia CR, Arnold BL, Granata KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *J Mot Behav*. 2005;37:111-125. https://doi.org/10.3200/JMBR.37.2.111-126

**27.** Powell DW, Williams DS, 3rd, Windsor B, Butler RJ, Zhang S. Ankle work and dynamic joint stiffness in high- compared to low-arched athletes during a barefoot running task. *Hum Mov Sci*. 2014;34:147-156. https://doi.org/10.1016/j.humov.2014.01.007

**28.** Pruyn EC, Watsford ML, Murphy AJ, et al. Relationship between leg stiffness and lower body injuries in professional Australian football. *J Sports Sci*. 2012;30:71-78. https://doi.org/10.1080/02640414.2011.624540

**29.** Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol*. 2003;89:1-7. https://doi.org/10.1007/s00421-002-0741-y

**30.** Statista. Number of participants in running/jogging and trail running in the U.S. from 2006 to 2017 (in millions). Available at: https://www.statista.com/statistics/190303/running-participants-in-the-us-since-2006/. Accessed January 3, 2019.

**31.** Subotnick SI, Sisney P. Treatment of Achilles tendinopathy in the athlete. *J Am Podiatr Med Assoc*. 1986;76:552-557. https://doi.org/10.7547/87507315-76-10-552

**32.** Watsford ML, Murphy AJ, McLachlan KA, et al. A prospective study of the relationship between lower body stiffness and hamstring injury in professional Australian rules footballers. *Am J Sports Med*. 2010;38:2058-2064. https://doi.org/10.1177/0363546510370197

**33.** Williams DS, 3rd, Davis IM, Scholz JP, Hamill J, Buchanan TS. High-arched runners exhibit increased leg stiffness compared to low-arched runners. *Gait Posture*. 2004;19:263-269. https://doi.org/10.1016/S0966-6362(03)00087-0

**34.** Williams DS, 3rd, McClay IS, Hamill J. Arch structure and injury patterns in runners. *Clin Biomech (Bristol, Avon)*. 2001;16:341-347. https://doi.org/10.1016/S0268-0033(01)00005-5

**35.** Zhang SN, Bates BT, Dufek JS. Contributions of lower extremity joints to energy dissipation during landings. *Med Sci Sports Exerc*. 2000;32:812-819. https://doi.org/10.1097/00005768-200004000-00014

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