

Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners

CLARE E. MILNER¹, REED FERBER², CHRISTINE D. POLLARD³, JOSEPH HAMILL⁴, and IRENE S. DAVIS¹

¹Department of Physical Therapy, University of Delaware, Newark, DE; ²Faculty of Kinesiology, University of Calgary, Calgary, Alberta, CANADA; ³Department of Biokinesiology and Physical Therapy, University of Southern California, Los Angeles, CA; and ⁴Department of Exercise Science, University of Massachusetts, Amherst, MA

ABSTRACT

MILNER, C. E., R. FERBER, C. D. POLLARD, J. HAMILL, and I. S. DAVIS. Biomechanical Factors Associated with Tibial Stress Fracture in Female Runners. *Med. Sci. Sports Exerc.*, Vol. 38, No. 2, pp. 323–328, 2006. **Purpose:** Tibial stress fractures (TSF) are among the most serious running injuries, typically requiring 6–8 wk for recovery. This cross-sectional study was conducted to determine whether differences in structure and running mechanics exist between trained distance runners with a history of prior TSF and those who have never sustained a fracture. **Methods:** Female runners with a rearfoot strike pattern, aged between 18 and 45 yr and running at least 32 km·wk⁻¹, were recruited for this study. Participants in the study were 20 subjects with a history of TSF and 20 age- and mileage-matched control subjects with no previous lower extremity bony injuries. Kinematic and kinetic data were collected during overground running at 3.7 m·s⁻¹ using a six-camera motion capture system, force platform, and accelerometer. Variables of interest were vertical impact peak, instantaneous and average vertical loading rates, instantaneous and average loading rates during braking, knee flexion excursion, ankle and knee stiffness, and peak tibial shock. Tibial varum was measured in standing. Tibial area moment of inertia was calculated from tibial x-ray studies for a subset of runners. **Results:** The TSF group had significantly greater instantaneous and average vertical loading rates and tibial shock than the control group. The magnitude of tibial shock predicted group membership successfully in 70% of cases. **Conclusion:** These data indicate that a history of TSF in runners is associated with increases in dynamic loading-related variables. **Key Words:** GROUND REACTION FORCES, KINEMATICS, TIBIAL SHOCK, AREA MOMENT OF INERTIA

Stress fractures are a common injury in runners. They are consistently among the five most common running injuries, and account for 50% of all injuries sustained by runners and military recruits (13,14,19). The overall incidence of stress fractures ranges from 1.5 to 31% (13,14,19,22,26). Women are reported to be at significantly greater risk, with one study reporting a twofold increase of bilateral stress fractures over men (25). Similarly, the incidence of stress fractures in women college athletes was

double that of men at a Division I institution (1). Others have reported an even greater gender bias in the incidence of stress fractures. An increased incidence of stress reactions, a precursor to stress fracture (8), by a factor of 2.91 in women compared with men has been reported in military recruits (26). The tibia is the most common site of stress fractures in runners, accounting for between 33 and 55% of total stress fractures reported (3,9,18,25,28).

Bone structure is thought to contribute significantly to the overall risk of tibial stress fractures (TSF). This has been shown to be the case in both male military recruits (22) and male runners (5), but not female runners (10). Mediolateral tibial width (9) and tibial area moment of inertia (22) are smaller in those male military recruits who go on to develop a stress fracture. In addition, tibial cross-sectional area, a strong determinant of area moment of inertia, is also smaller in male runners with a history of stress fracture (5). The relationship between tibial area moments of inertia and stress fracture has not been

Address for correspondence: Clare Milner, Department of Physical Therapy, 301 McKinly Lab, University of Delaware, Newark, DE 19716; E-mail: milner@udel.edu.

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determined for female runners. Tibial cross-sectional area, however, was not linked to the occurrence of TSF in a study of 13 female runners with a history of stress fracture (2).

Anatomic alignment has also been implicated in the cause of lower extremity stress fractures. Matheson et al. (18) noted that varus malalignment (genu, tibial, subtalar, and forefoot varus) was often present in athletes with lower extremity stress fractures. During running, the body experiences vertical forces between 2.5 and 2.8 times body weight (23). During this compressive loading, a tibia in varus will likely experience greater bending moments as the vertical force vector projects medial to the tibial shaft. This can result in greater susceptibility to TSF.

Stress fractures are thought to be related to some quantity, or “dose” of loading, where dose may be a measure of some combination of peak shock, ground reaction force loading rates, peaks, and repetitions. Some researchers, however, have reported no difference in vertical impact and active peak ground reaction forces between runners with and without a history of TSF (2,5). Conversely, Grimston et al. (10) reported significantly greater vertical impact and active forces in female runners with a history of tibial or femoral stress fractures compared with those without such a history. Increased ground reaction forces would likely result in greater bending moments experienced by the tibia. Furthermore, Hennig et al. (12) and Laughton et al. (16) both reported that vertical ground reaction force-loading rates were significantly and positively correlated to peak tibial accelerations during running. Therefore, if loading rates are increased, it is likely that tibial shock is also increased. Whether the increased loading rates are directly related to strain rates experienced by the bone is yet to be determined. However, preliminary work in our laboratory (6) suggests, that increased loading rates can be related to tibial stress fracture in female distance runners.

Although smaller in magnitude, anterior–posterior ground reaction forces applied to the lower extremity during the loading phase of stance may also influence loading of the tibia. Previous studies have again produced conflicting results. Runners with a history of TSF have demonstrated increased (10) and normal (2,5) peak braking force. Based on our preliminary work, which suggests that loading rates are significantly different between these groups with respect to vertical ground reaction forces (6), we expect loading rates during braking to also be increased in runners with a history of stress fracture.

The total range of motion the lower extremity undergoes during the loading phase of the gait cycle may influence the forces experienced by the body. Assuming a given impulse, greater excursions will likely result in lower peak ground reaction forces and possibly lower loading rates. McNitt-Gray et al. (21) demonstrated this principle by reporting that lower peak ground reaction forces and loading rates were associated with greater hip and knee flexion excursions in controlled landings in gymnasts. These increased excursions may, therefore, reduce the risk for stress fractures. McMahan et al. (20) have shown that

running with exaggerated knee flexion (Groucho running) reduces the effective vertical stiffness of the lower extremity and causes the runner to attenuate more shock between the shank and head, compared with normal running. Conversely, if knee joint excursion is decreased, greater lower extremity stiffness will likely result. A “stiff” runner has been shown to spend less time in contact with the ground (7) and attenuate less shock (20). This may also increase their risk of TSF. The torsional stiffness of an individual joint may provide additional insight into the differences between runners with and without a history of TSF.

This cross-sectional study was conducted to determine whether differences in structure and mechanics existed between trained female distance runners with a history of a prior TSF and those who had not sustained a fracture. We hypothesized that runners who had a prior TSF would have increased vertical loading rates, increased vertical impact peak, increased loading rates during braking, and increased knee and ankle joint torsional stiffness in the sagittal plane, compared with those who had not sustained a fracture. Furthermore, we hypothesized that runners who had sustained a TSF would have increased tibial acceleration and decreased knee flexion excursion, compared with those who had not sustained a fracture. Structurally, they would have increased tibial varum during standing and decreased tibial area moment of inertia. Additionally, we hypothesized that the magnitude of tibial shock would discriminate between runners with and without a history of TSF.

METHODS

Subjects. Approval for all procedures was obtained from the human subjects review board of the University of Delaware before commencing this study. All subjects gave their written informed consent before participation in the study. Participants aged between 18 and 45 yr, who typically ran at least $32 \text{ km}\cdot\text{wk}^{-1}$, were recruited from local races, running clubs, and university cross-country teams by direct contact with study personnel or via flyers outlining the study. Subjects were excluded if they were currently injured, had a history of cardiovascular pathology, had abnormal menses (defined as missing more than three consecutive monthly periods in the last 12 months), or were pregnant or suspected they were pregnant. Runners with abnormal menses were excluded to reduce the likelihood of stress fractures being related to reduced bone density, rather than factors associated with running. A total of 20 rearfoot strikers with a history of tibial stress fracture (TSF: age 26 ± 9 yr, $46 \pm 11 \text{ km}\cdot\text{wk}^{-1}$, 35 ± 28 months after injury) and 20 age- and mileage-matched rearfoot striking control subjects with no previous lower extremity bony injuries (CTRL: age 25 ± 9 yr, $47 \pm 16 \text{ km}\cdot\text{wk}^{-1}$) participated in this study. These data are part of a larger study of distance runners, and those with a rearfoot strike pattern, confirmed by calculation of the strike index (4), were selected from the subject pool. On entry into the study, subjects reported their injury history. The TSF group had reported a previous TSF, which had been confirmed at

the time by a medical professional using diagnostic imaging tests (bone scan, magnetic resonance imaging (MRI), or x-ray study). Control runners had not reported any previous lower extremity bony injuries.

A priori power calculations for this study were done using preliminary data from our laboratory for peak tibial shock, instantaneous and average vertical loading rates, and knee flexion excursion. Sample sizes were determined based on predicted power to detect a difference of 15% between the groups with an alpha 0.05 and 80% power. We consider a difference of $\geq 15\%$ to be clinically relevant. Based on the formula of Lieber (17), minimal sample sizes of between 9 and 20 subjects per group were determined from our existing data for these variables. Inclusion of 20 subjects per group, therefore, should provide adequate power to detect clinically relevant differences in all variables between groups.

Kinematic and kinetic measurements. Lower extremity position data were collected at 120 Hz using a six-camera Vicon 512 motion capture system (Oxford Metrics, Oxford, UK). Markers were placed on the lower extremity and pelvic region to enable three-dimensional kinematics to be determined for the stance phase of running. A Bertec force platform (Bertec Corporation, Columbus, OH) synchronized with the motion capture system was used to collect ground reaction force data at 960 Hz. Additionally, a uniaxial accelerometer (PCB Piezotronics Inc, Depew, NY), also sampling at 960 Hz, was attached over the anteromedial portion of the distal tibia, as described by Lughton et al. (16). Running velocity was monitored via two photocells linked to a timer.

Markers were attached at L5S1, iliac crest and anterior superior iliac spine to track the pelvic segment. Molded thermoplastic shells with four noncollinear markers attached were secured on the posterolateral proximal thigh and posterolateral distal shank. Three markers were attached to the heel portion of the running shoe to approximate rearfoot motion: two marking the vertical bisection of the heel and a third on the lateral side of the heel. Several additional markers were attached to the subject initially to define the anatomic coordinate systems and inertial parameters of each segment. These markers were removed following the standing calibration trial. Anatomic markers were placed over the greater trochanter, lateral and medial knee at the level of the lateral femoral epicondyle, lateral and medial ankle at the level of the lateral malleolus, first and fifth metatarsal heads, and the tip of the toe box.

Subjects wore standard, neutral laboratory running shoes and ran overground along a 23-m runway at a velocity of $3.7 \text{ m}\cdot\text{s}^{-1}$ ($\pm 5\%$). Data were collected for a single stance phase as the runner traversed the force plate located in the center of the runway. Five acceptable trials were collected. Trials in which the subject appeared to change gait to target the force platform, as determined subjectively by the investigators, were discarded. Subjects performed practice trials to ensure that they could maintain a consistent running speed and make contact with the central portion of the force platform without modifying their gait.

Data were processed in Visual 3D (C-Motion, Rockville, MD). Three-dimensional ankle and knee angles were resolved about a joint coordinate system (11). Kinetic data, used in the calculation of joint stiffness, were calculated about XYZ rotation Cardan angles referenced to coordinate systems embedded in the distal segment. All other variables were calculated using custom LabView (National Instruments Corporation, Austin, TX) programs. Ground reaction force variables (vertical instantaneous and average loading rate (VILR, VALR), impact peak, (IPEAK), and anterior-posterior instantaneous and average loading rates during initial braking (BILR, BALR)) were determined. Loading rates were calculated between 20 and 80% of the period between footstrike and impact peak (vertical) or braking peak (anterior-posterior). This portion of the curve was chosen because it is the most linear portion of the initial loading part of the curve (Fig. 1). Average loading rate was calculated as the total change in force divided by the total change in time over this period. Instantaneous loading rate was the peak sample-to-sample loading rate occurring during this period. Tibial shock (peak positive acceleration (PPA)) was calculated after the average value and any linear trend in the acceleration signal were removed, as described by Shorten and Winslow (27). Peak positive acceleration was determined as the highest acceleration measurement during the stance phase. Knee flexion excursion (KEXC) was calculated as knee flexion range of motion from foot strike to peak knee flexion.

Joint torsional stiffness was calculated as the change in joint moment divided by the change in joint angle (7). It is recognized that these stiffness measures represent the sum of many individual stiffness measures and may, more accurately, be referred to as measures of quasistiffness (15). For the purposes of this report, however, the term stiffness will be used. Sagittal plane average knee joint stiffness (KSTIF) was determined from foot strike to peak knee

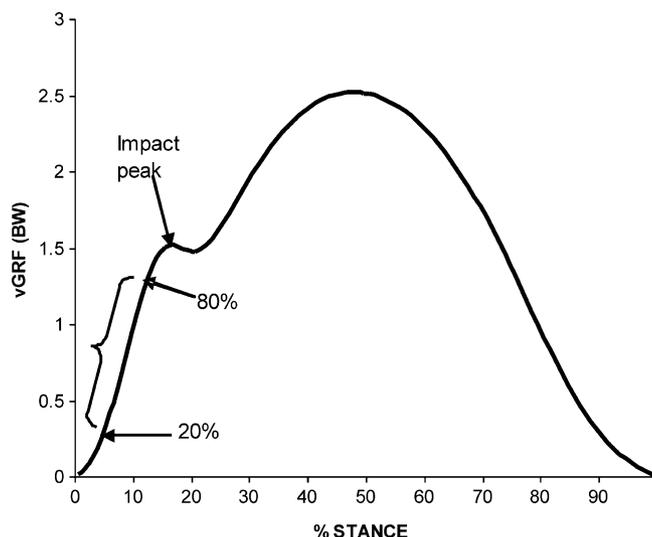


FIGURE 1—Instantaneous and average vertical loading rates calculated over the portion of the vertical ground reaction force curve between 20 and 80% of the time to impact peak. See text for full description.

flexion (i.e., the loading phase) during stance (Fig. 2). Sagittal plane average ankle joint stiffness (ASTIF) was determined from initial peak plantarflexion to peak dorsiflexion during stance (Fig. 2).

Strike index was calculated to confirm that all subjects were rearfoot strikers, having a strike index <33%, as defined by Cavanagh and Lafortune (4). Strike index is described by the point of intersection of a perpendicular drawn from the center point of pressure at footstrike and the long axis of the foot. This point of intersection is reported as a percentage of foot length from the heel.

All variables were determined for each of five trials per subject, averaged within the subject and then averaged across groups.

Structural measurements. Tibial x-ray studies were done for a subset of 33 subjects (18 TSF and 15 CTRL). The x-ray studies of both tibiae were taken from anterior and lateral views while standing with feet internally rotated 15° to account for the natural external rotation of the frontal plane of the tibia (22). A foot template was used to ensure consistency of foot placement between subjects. Tibial area moment of inertia (TIBAMI) was calculated from measurements made on the x-ray films, according to Milgrom et al. (22). As described by Milgrom et al. (22), the tibial cross-section was represented as an elliptical ring with an elliptical hole offset within it. Both the anterior-posterior and medial-lateral axes of rotation passed through the ring's centroid. Tibial varum was measured by an experienced physical therapist as the angle subtended by the bisection of the tibia in the frontal plane and a vertical reference.

Statistical analysis. Boxplots were used to identify outliers, defined as values >1.5 times the interquartile range away from the median. Identified outliers were removed from the data before statistical analysis of the differences between groups. A total of six data points fell outside this defined range and were removed as follows: two from the RTSF group for BALR, one from the CTRL group for ASTIF, one from each group for KSTIF, and one from the

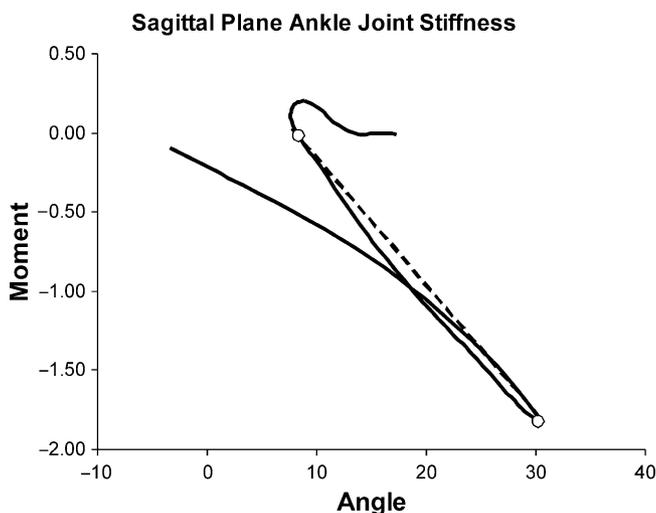


FIGURE 2—Calculation of average sagittal plane joint stiffness, depicting the ankle joint. See text for full description.

TABLE 1. Mean (SD) ground reaction force variables for retrospective tibial stress fracture (TSF) group and control (CTRL) group.

Ground Reaction Force	TSF	CTRL	Effect Size	P Value
IPEAK (BW)	1.84 (0.21)	1.70 (0.32)	0.51	0.057
VILR (BW·s ⁻¹)*	92.56 (24.74)	79.65 (18.81)	0.59	0.036
VALR (BW·s ⁻¹)*	78.97 (24.96)	66.31 (19.52)	0.56	0.041
BILR (BW·s ⁻¹)	20.35 (6.17)	19.29 (4.70)	0.19	0.272
BALR (BW·s ⁻¹)	8.54 (3.10)	8.37 (2.25)	0.07	0.420

* Significant at $P \leq 0.05$.

CTRL group for TIBAMI. One-tailed independent *t*-tests were used to test for significant differences between groups, based on the directional hypotheses stated previously. Bonferroni adjustments for multiple comparisons were not made as the hypotheses tested were developed *a priori* and, therefore, should be considered independent of each other (24). A binary logistic regression was carried out to determine whether PPA predicted group membership. The alpha level for all statistical tests was 0.05. We considered P values $0.05 < P \leq 0.10$ to be trends within the data. In addition, effect sizes were determined for all variables to aid in the interpretation of any trends found.

RESULTS

Instantaneous and average vertical loading rates were increased in the TSF group, compared with the control group (Table 1). A trend was also noted toward a higher impact peak ($P = 0.057$, moderate effect size = 0.51) in the TSF group. Loading rates during braking, however, were not different between the groups. The TSF group also showed a large increase in peak tibial shock compared with controls. A trend was also seen toward higher knee joint stiffness in the TSF group ($P = 0.054$, moderate effect size = 0.54), but ankle joint stiffness was not greater in the TSF group (Table 2). Knee flexion excursion also showed no differences between the two groups. The structural measure tibial varum also did not differ between the groups. The decrease in tibial area moment of inertia in the TSF group was small and not significant. A *post hoc* power analysis indicated that the study was underpowered to detect a 9% difference in TIBAMI, the magnitude of the difference between groups found by Milgrom et al. (22). The effect size in the present study was the same as that reported by Milgrom et al. (22).

The results of the binary logistic regression suggest that increased PPA is related to an increased likelihood of being in the TSF group. The model indicates that for every 1-g increase in PPA, the likelihood of having a history of TSF increases by a factor of 1.361 (95% confidence interval

TABLE 2. Mean (SD) joint excursion, stiffness, and structural variables for retrospective tibial stress fracture (TSF) group and control (CTRL) group.

	TSF	CTRL	Effect Size	P Value
KEXC	33.1 (5.0)	34.8 (5.2)	0.34	0.147
ASTIF ($\times 10^{-2}$)*	4.31 (0.59)	4.59 (0.61)	-0.46	†
KSTIF ($\times 10^{-2}$)	4.88 (0.88)	4.46 (0.68)	0.54	0.054
PPA*	7.70 (3.21)	5.81 (1.66)	0.74	0.014
TIBAMI	11312 (2883)	12224 (2387)	-0.34	0.174
TIBVAR	6 (2)	6 (2)	-0.36	0.128

* Significant at $P \leq 0.05$. † In opposite direction to hypothesized difference.

1.020–1.816, $P = 0.036$). According to the model chi-square statistic, the model is significant ($P = 0.020$). It also predicts group membership correctly in 70% of cases. The Nagelkerke R square value is 0.169, suggesting that 17% of the variance between the two groups is explained by PPA.

DISCUSSION

We investigated the biomechanical and structural differences between female distance runners with and without a history of TSF. Runners with a history of TSF exhibited greater instantaneous and average vertical loading rates, but no difference in loading rates during braking, compared with healthy controls. Differences in loading rates between these two groups have not been considered previously. Indications in our preliminary study (6) that both vertical and anterior–posterior loading rates are associated with a history of TSF were only partially supported by this more comprehensive study. The small net differences in loading rates during braking between groups (BILR 6%, BALR 2%) account for their lack of association with a history of stress fracture. In terms of peak ground reaction forces, runners who had sustained a previous TSF showed a small, nonsignificant (8% increase, $P = 0.057$) increase in the magnitude of the vertical impact peak compared with those who had never sustained a fracture. The moderate effect size (0.51) suggests, however, that impact peak may be an important factor in the cause of TSF. Although it is recognized that these are small increases, the cumulative effect of these slightly higher impacts in the TSF group may become important in injury development when repeated over thousands of foot strikes.

Based on our findings, TSF, which are fatigue fractures of the bone, appear to be most related to loading rates. Loading rate is one of the factors associated with its fatigue limit. The fatigue limit of a tissue is related to the type of load applied, its peak magnitude, loading rate, and the total dose. When comparing these two groups of runners, the type of load is similar (a combination of compression and bending), because both groups were rearfoot strikers. The total dose was assumed to be similar, because the groups were matched for mileage, although this method did not account for differences in absolute number of steps caused by the likely differences in stride length between subjects. The comparison of structure and alignment of the tibia also indicated that these were similar between the groups. Differences in load characteristics between the two groups, therefore, likely were reflected in the peak magnitude and loading rate. We hypothesized that both types of variables would be increased in the stress fracture group. Our results, combined with those of Crossley et al. (5) and Bennell et al. (2), however, suggest that the differences are in the vertical loading rate, rather than the impact peak or anterior–posterior loading rates during braking.

Peak tibial shock is another measure of the load applied to the lower extremity. Because a strong correlation has

been reported between vertical loading rates and tibial shock (17), we expected that shock would also be increased in the TSF group. As expected, we found a large increase in tibial shock in the stress fracture group, along with the increases in vertical loading rates. Additionally, tibial shock was found to predict a history of stress fracture in the binary logistic regression. Although it is a surrogate measure of bone loading, tibial shock actually provides a more direct estimate of the load acting on the tibia itself than ground reaction forces. Ground reaction forces represent the net forces acting on the center of mass of the whole body (27). Tibial shock, therefore, may be a more sensitive discriminator of runners at higher risk of TSF. While this needs to be confirmed with prospective studies, it may provide a means of screening for high-risk individuals. This measure is particularly amenable to mass screening because minimal preparation time is associated with its use, compared with a full kinematic and kinetic analysis of running gait.

The magnitudes of loading rates and peak tibial shock experienced during running are affected by the body's response to the applied load, as well as the magnitude of the load itself. The extreme example of Groucho running (20), in which the runner exaggerates knee flexion, provides a good illustration of this. When running with an extreme degree of knee flexion, the runner reduces the effective vertical stiffness of the lower extremity. The opposite is also true: running with reduced knee flexion increases the effective vertical stiffness of the lower extremity. We had expected to find significantly greater knee and ankle joint stiffness, accompanied by reduced knee joint excursion, in the TSF group. However, this was not supported by our results, which indicated only a trend toward increased knee stiffness in the TSF group ($P = 0.054$) for a 9% increase. The effect size, however, was moderate (0.54), indicating that stiffness may be an important factor. No difference was seen in excursion between the groups.

The decrease in TIBAMI in the TSF group was small, but showed the same small effect size (0.34) as found in 295 male infantry recruits who sustained a stress fracture during basic training (22). These recruits had a statistically smaller TIBAMI than those who did not fracture (22). In another study, however, several measures of tibial geometry showed no difference from normal in a group of 13 female runners with a history of TSF (2). It remains inconclusive whether decreases in TIBAMI are related to a history of TSF in female distance runners. Furthermore, tibial varum was no different between groups. This was unexpected, as Matheson (18) noted that varus malalignment was often present in male and female athletes with a history of stress fracture. We found that, in female distance runners, dynamic biomechanical characteristics of running gait associated with vertical loading show the greatest differences between groups.

The standardization of running speed and footwear reduces the number of extraneous variables contributing to differences between subjects during the laboratory-based comparison of running mechanics. During the follow-up

period, however, footwear and running speed were not monitored. This is a limitation of the study because the running mechanics recorded in the laboratory may differ slightly from those that the subject experiences during normal running. Differences in footwear and running speed may affect the magnitude of lower extremity loading experienced. Furthermore, the conclusions drawn from this study should be interpreted with caution because the study was retrospective and cross-sectional. Prospective studies of runners who sustain a TSF are needed to determine cause and effect with respect to loading rates and fracture occurrence.

In conclusion, based on the results of this study, a history of TSF in female runners is associated with increases in several dynamic loading-related variables:

instantaneous and average vertical loading rate and peak tibial shock. A trend toward higher knee stiffness and impact peak, indicated by a moderate effect size for history of TSF, but not statistically significant differences, was also found. No significant differences were found in the structural measures of tibial area moment of inertia and tibial varum angle in this group of runners with a history of TSF compared with a healthy control group. The magnitude of peak tibial shock predicted group membership successfully in 70% of cases.

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