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Free moment as a predictor of tibial stress fracture in distance runners

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Abstract

Stress fractures are a common and serious overuse injury in runners, particularly female runners. They may be related to loading characteristics of the lower extremity during running stance. Some tibial stress fractures (TSFs) are spiral in nature and, therefore, may be related to torque. Free moment (FM) is a measure of torque about a vertical axis at the interface with the shoe and ground. Increases in FM variables may be related to a history of TSF in runners. The purpose of this cross-sectional study was to investigate differences in FM between female distance runners with and without a history of TSF and, additionally, to investigate the relationship between absolute FM and the occurrence of TSF. A group of 25 currently uninjured female distance runners with a history of TSF (28 ± 10 years, $46 \pm 15\,\mathrm{km\,week^{-1}}$) and an age- and mileage-matched control group of 25 healthy runners with no previous lower extremity fractures (26 ± 9 years, $46 \pm 19\,\mathrm{km\,week^{-1}}$) participated in this study. Ground reaction forces and foot placement on the force platform were recorded during running at $3.7\,\mathrm{m\,s^{-1}}$ ($\pm 5\%$). Peak adduction, braking peak and absolute peak FM and impulse were compared between groups using one-tailed *t*-tests. The predictive value of absolute peak FM was investigated via a binary logistic regression. All variables, except impulse, were significantly greater in runners with a history of TSF. Absolute peak FM had a significant predictive relationship with history of TSF. There is a significant relationship between higher values for FM variables and a history of TSF.

Keywords: Ground reaction forces; Running; Female

1. Introduction

Overuse injuries occur frequently in runners, with incidence rates as high as 85% being reported in the literature (Bovens et al., 1989). The most serious overuse injury in terms of recovery time is a stress fracture. Lower extremity stress fractures typically require 6–8 weeks rest from running to allow the bone to heal. Stress fractures are one of the five most common injuries in the running population, accounting for between 6% and 14% of all injuries sustained by runners (James et al., 1978; McBryde, 1985). The most commonly injured bone is the tibia, with tibial stress fractures (TSFs) accounting for between 35% and 49% of all stress fractures in runners (Matheson et al., 1987; McBryde, 1985). There is also a gender bias in the occurrence of stress fractures, with women reported consistently as being at twice the risk of sustaining stress fracture than men (Arendt et al., 2003). Reasons for this gender bias are unclear: it may be partly related to lower bone density or differences in bone geometry in females compared to males, although existing studies are inconclusive (Beck et al., 2000; Bennell et al., 2004).

Recent studies of TSFs have suggested that their occurrence may be related to higher loading of the lower extremity (Milner et al., 2005). Additionally, there is evidence that some TSFs are spiral fractures (Spector et al, 1983). This suggests that, in addition to vertical and shear forces, torques may be involved in the development of a TSF. However, the frequency of

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occurrence of spiral TSF is unknown, since they are usually classified according to their anatomical location on the tibia (Spector et al., 1983). Furthermore, Ekenman et al. (1998) reported that the tibia is exposed to a combination of bending, shearing and torsion simultaneously during activities such as running. The free moment (FM) is the torque about a vertical axis due to friction between the foot and the ground during stance (Holden and Cavanagh, 1991). While FM has been linked to pronation (Holden and Cavanagh, 1991), its potential role in running injuries has not been widely investigated. Although FM is not a direct measure of the torque acting on the tibia, higher FM is likely to contribute to higher torque. As an indicator of the torque about a vertical axis experienced at the point of contact between the foot and the ground, FM is worthy of further investigation in relation to stress fracture.

Preliminary work in our laboratory showed a higher peak adduction FM (resistance to toeing out) and trends towards greater FM at peak braking force and net angular impulse in 13 runners with a history of TSF, compared to runners with no previous lower extremity bony injuries (Milner et al., 2004). FM at peak braking force may be important if both shear and torque are high at the same time. These trends suggest that there might be significant differences in FM variables between the groups if a larger subject pool were analyzed. Furthermore, the preliminary study did not consider the absolute magnitude of peak FM. Since this study indicated that some runners may have an abduction bias in FM (more than 50% stance with abduction FM), considering only their peak adduction FM would not indicate the greatest torque acting on their lower extremity. Therefore, an absolute measure (peak regardless of direction) may better represent the magnitude of the torque acting on the lower extremity.

The purpose of this cross-sectional study was to investigate differences in FM between female distance runners with and without a history of TSF and, additionally, to investigate the relationship between absolute FM and the occurrence of TSF. We hypothesized that maximum adduction FM (ADDFM), FM at peak braking force (FMBRAK), net angular impulse (IMP) and absolute peak FM (|FM|) would be greater in runners with a history of TSF compared to those who had never sustained a lower extremity bony injury. In addition, we hypothesized that |FM| would be predictive of group membership.

2. Methods

2.1. Subjects

All subjects gave their written informed consent prior to participation in the study. All procedures were approved by the Institution's Human Subjects Review Board prior to the commencement of this study. Participants were recruited from local races, running clubs and teams. Subjects were excluded if they were currently injured, had abnormal menses (missed more than three consecutive monthly periods in the previous 12 months), were pregnant or suspected they were pregnant. A group of 25 currently uninjured female distance runners with a history of TSF (28 ± 10 years, 46 ± 15 km week^{-1}) and an age- and mileage-matched control group of 25 healthy runners with no previous lower extremity fractures (26 ± 9 years, 46 ± 19 km week^{-1}: CTRL) participated in this study. The TSF group was an average of 48 months post-injury (range 3–120 months). The majority (23/25) had one previous TSF; one subject had two previous TSFs and another had four previous TSFs. It was not known how many subjects had spiral TSFs. A priori power calculations were based on data from a preliminary study conducted in our laboratory (Milner et al., 2004). Based on an α level of 0.05, β of 0.20 and effect sizes of 0.78 for FMBRAK and 0.48 for IMP, 24 subjects were needed to detect a twofold difference between groups (Lieber, 1990). ADDFM was significantly different between groups in the preliminary study. On entry into the study, the TSF group had reported a previous TSF, which had been confirmed by a medical professional and diagnostic imaging tests (bone scan, MRI or X-ray). All subjects were rearfoot strikers, having a strike index of $\leqslant 0.33$ (Cavanagh and LaFortune, 1980). This was to ensure that they had a similar loading pattern, since there are differences in ground reaction force patterns between rearfoot, midfoot and forefoot strikers.

2.2. Experimental protocol

Ground reaction force data were collected at 960 Hz using a strain-gaged force platform (Bertec Corporation, Columbus, OH) as the subjects ran overground along a 23 m runway at 3.7 m s^{-1} ($\pm 5\%$). Running speed was monitored via two photocells placed 2.88 m apart and linked to a timer. Footwear was standardized with all subjects wearing the same make and model of a commercially available neutral shoe. Data were collected for a single stance phase per trial, as the subject contacted the force platform located in the center of the runway. Five acceptable trials were collected. Trials in which the subject appeared to change their gait or target the force platform were discarded. Prior to data collection, subjects performed practice trials to ensure that they would achieve the required speed and correct foot placement on the force platform without modifying their gait. Holden and Cavanagh (1991) noted differences between FM on the right and left sides of an individual. Therefore, foot contact on the force platform was on the involved side in the TSF group, to capture the appropriate FM data. Since neither side had a previous TSF in the CTRL group, there was no reason to prefer one side over the other; therefore, foot contact was made on the right side.

Kinematic data were collected, using a six camera motion capture system (Vicon, Oxford, UK) sampling at 120 Hz, for the calculation of strike index (Cavanagh and LaFortune, 1980). Retroreflective tracking markers were placed proximally and distally on the vertical bisection of the heel counter of the shoe and on the lateral part of the heel. In addition to marker position data collection during the running trials, a standing trial was collected with an additional anatomical marker placed on the tip of the toe box. This marker was used to determine the position of the long axis of the foot and its position and orientation in the global coordinate system during stance.

Data were processed using custom LabView programs (National Instruments Corporation, Austin, TX). FM is the torque about a vertical axis due to friction between foot and ground during stance. Following the sign convention of Holden and Cavanagh (1991), positive FM acts to resist toeing out (ADDFM) and negative FM acts to resist toeing in (ABDFM) (Fig. 1). To preserve this sign convention, the FM calculation that follows was negated for the right foot. FM was calculated from the components of moment and force output from the force platform. FM is one of two components of the moment, M_z, acting about a vertical axis at the center of the force platform. The second component is the moment due to the resultant shear force acting through the center of pressure. Detailed examples of the relationship between FM and the moment about a vertical axis at the center of the force platform were provided by Holden and Cavanagh (1991). The equation describing the contributions of these two components to the vertical moment was used to derive FM from force platform output (Bertec Corporation, 2003). All force platform channels were baseline adjusted to a zero offset when unloaded prior to calculating FM.

$$\mathrm{FM} = Mz - (\mathrm{CP}x \cdot Fy) + (\mathrm{CP}y \cdot Fx),$$
$$\mathrm{CP}x = -My/Fz \text{ and } \mathrm{CP}y = Mx/Fz,$$

where M_z is the moment about the z-axis, CP_x the x-coordinate of center of pressure, F_y the ground reaction force in y-direction, CP_y the y-coordinate of center of pressure, F_x the ground reaction force in x-direction, M_y the moment about y-axis, F_z the ground reaction force in z-direction and M_x the moment about x-axis. Positive y-axis was in the direction of progression, positive z-axis was vertically downwards and positive x-axis was to the left when facing the direction of progression, following the right-hand rule. FM was normalized by dividing by body weight and height, making the reported FM dimensionless (and IMP in seconds). This reduces the effects of differences in weight and height between subjects on the magnitude of FM and facilitates meaningful comparisons between subjects.

Each variable was averaged over five trials per subject. ADDFM was the maximum adduction value of FM during stance; FMBRAK was the FM at peak braking force during stance; Impulse was the net area under the FM curve during stance; |FM| was the maximum absolute value of FM during stance.

Strike index was calculated as the position of the center of pressure at foot strike, relative to the long axis of the foot at foot flat. In the current study, it was determined by the point of intersection of a perpendicular from the center of pressure to the long axis of the foot. This position of this point along the long axis is calculated as a proportion of the overall length of the long axis away from the heel. Rearfoot striking is defined as a strike index $\leqslant 0.33$ (Cavanagh and LaFortune, 1980). Strike index was determined using custom Visual Basic programs (Microsoft Corp) and Visual 3D software (C-Motion, Rockville, MD). All subjects were rearfoot strikers, with mean values for strike index of 0.08 ± 0.05 for the TSF group, and 0.09 ± 0.05 for the CTRL group.

Independent t-tests were used to test for significant differences between groups. Since we were only interested in whether the values of FM variables would be greater than normal in the TSF group, one-tailed tests were used. Lower values for FM variables in the TSF group were interpreted in the same way as no difference between groups.

A binary logistic regression was carried out to determine whether |FM| predicted group membership.

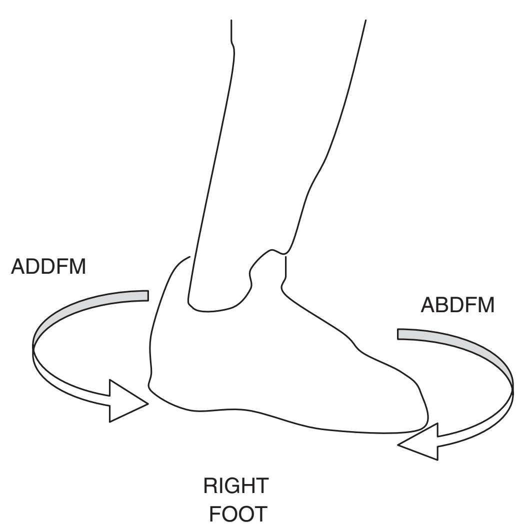

Fig. 1. Representation of adduction free moment resisting toe out and abduction free moment resisting toe in of the foot during contact with the ground.

The alpha level for all statistical tests was 0.05. In addition, effect sizes were determined for all variables, to aid the interpretation of any differences found. Ensemble average curves are also presented, both for the TSF and CTRL groups as a whole, and for subdivisions of subjects with adduction and abduction FM bias. FM bias was determined from the percent of stance with adduction FM for each subject. Subjects with adduction FM for more than 50% of stance are designated as having an adduction FM bias and others as having a abduction FM bias. This subdivision of subjects was conducted to further explore whether |FM| was more appropriate than ADDFM as a representative FM variable.

3. Results

All variables indicated that FM was greater in the TSF group (Table 1, Fig. 2). While the magnitude of FM was significantly greater in the TSF group for both ADDFM and FMBRAK, the highest values in both groups were found for |FM|. |FM| also had a larger effect size (0.99) than ADDFM (0.80). The higher value of |FM|, compared to ADDFM, indicates that in some runners ABDFM (resistance to toeing in) is greater in magnitude than ADDFM (resistance to toeing out). Mean ABDFM was smaller than both ADDFM and |FM| and not different between the groups (TSF: 2.9 ± 4.3; CTRL: 2.9 ± 2.7), confirming that ABDFM was high in only a few subjects. There was no difference in IMP between the groups. The group average curves provide an indication of the general pattern of FM during stance (Fig. 2), but as can be seen from the large spread indicated by the standard deviation in Table 1, the shape of the FM curve was quite variable between subjects. This is partly due to some runners having an abduction FM bias (7 in TSF and 9 in CTRL), illustrated in Figs. 3 and 4.

Results of the binary logistic regression suggested that higher |FM| was related to an increased likelihood of being in the TSF group. The model indicated that for every 1.0×10^{-3} increment in |FM|, the likelihood of having a history of TSF increased by a factor of 1.365 (95% confidence interval 1.099–1.695, $p = 0.005$). According to the model χ^2 statistic, the model is significant ($p = 0.001$). It also predicted group membership correctly in 66% of the cases. The Nagelkerke R^2 value was 0.274, suggesting that 27% of the variance between the two groups is explained by |FM|.

Table 1
Average normalized free moment variables in female runners with (TSF) and without (CTRL) a history of tibial stress fracture

	ADDFM	FMBRAK	IMP (s)	|FM|
TSF	7.7 ± 4.7	4.6 ± 5.7	4.5 ± 9.9	9.3 ± 4.3
CTRL	4.7 ± 2.5	1.6 ± 3.7	1.6 ± 5.5	5.9 ± 2.1
Effect size	0.80	0.62	0.36	0.99
P	0.004	0.017	0.105	<0.001

All variables are $\times 10^{-3}$, except IMP which is $\times 10^{-4}$.

4. Discussion

We investigated the differences in FM between female distance runners with a history of TSF and those who

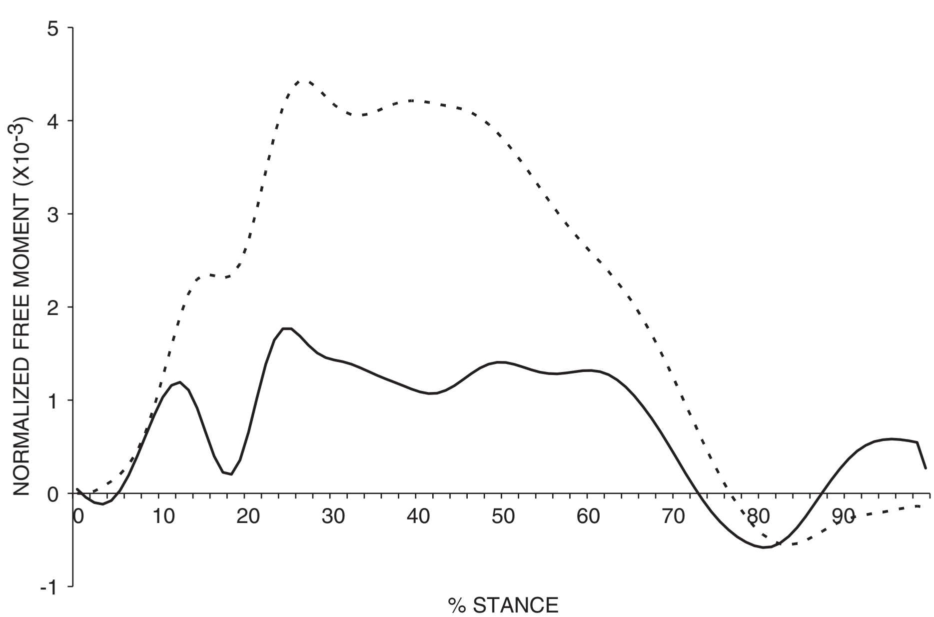

Fig. 2. Average normalized free moment during stance in female runners with (TSF; dashed line) and without (CTRL; solid line) a history of TSF.

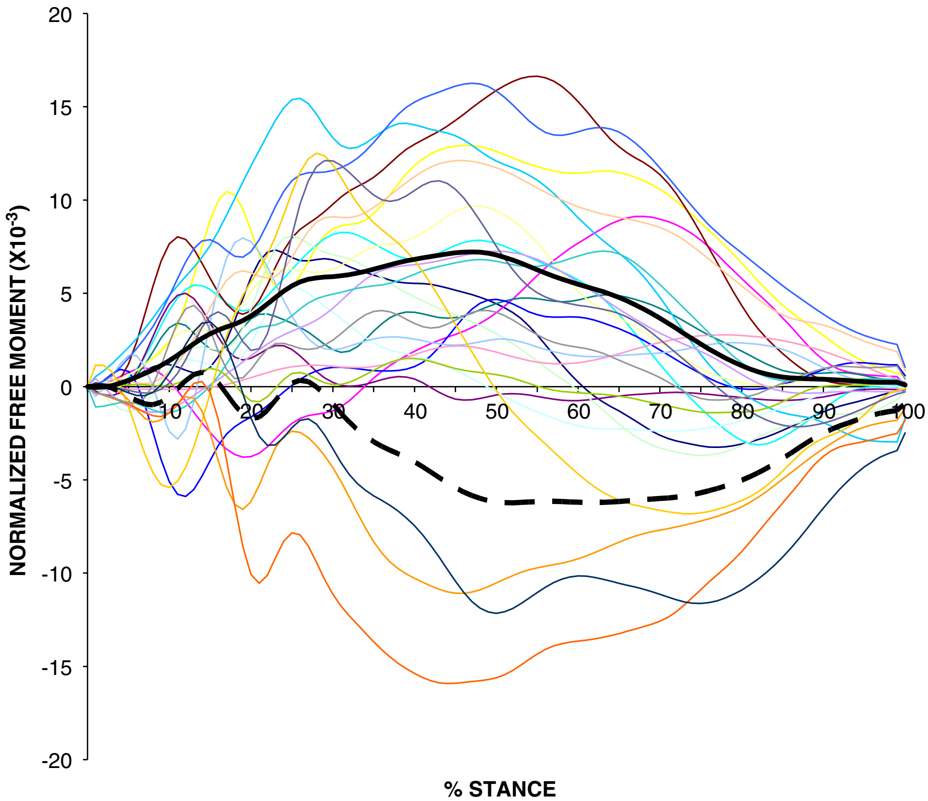

Fig. 3. Average normalized free moment during stance in female runners with a history of TSF. Heavy lines represent average values for subgroups with adduction ($n = 19$; solid) and abduction ($n = 6$; dashed) free moment bias.

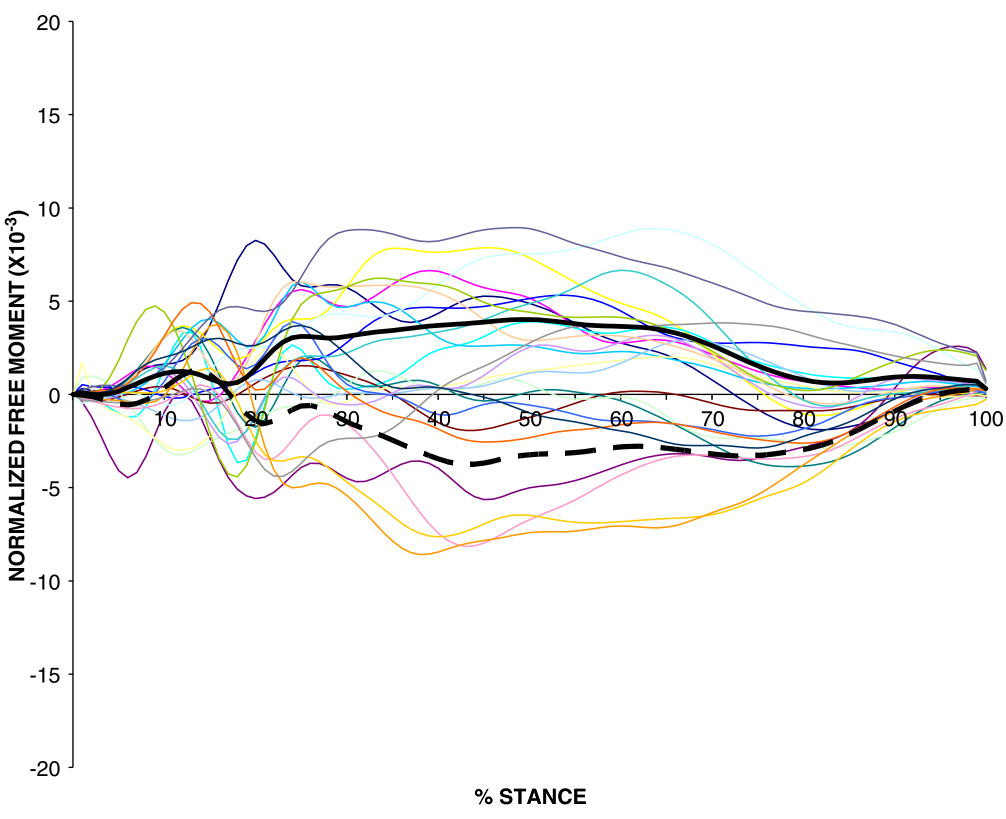

Fig. 4. Average normalized free moment during stance in female runners without a history of TSF. Heavy lines represent average values for subgroups with adduction ($n = 14$; solid) and abduction ($n = 9$; dashed) free moment bias.

had never sustained a lower extremity bony injury. Three of the four FM variables compared between groups were greater in the TSF group. The largest effect size was found with |FM| (although effect sizes of both |FM| and ADDFM were large). Higher values of |FM| compared to ADDFM were found in both groups. Since ABDFM was smaller than ADDFM in both groups, this indicates that in some runners, ABDFM was greater in magnitude than ADDFM. We also observed that some runners have an abduction bias in their FM curve. Therefore, ADDFM does not reflect the highest torque experienced by these subjects. However, |FM| provides an indication of the peak magnitude of the torque acting on the lower extremity in all runners. The higher FM values found in the TSF group suggest that higher than normal torque may be associated with TSF. Since differences in |FM| are larger than differences in ADDFM between groups, the magnitude of the torque may be more important than its direction in relation to stress fracture injury.

The lack of significant difference between groups in IMP, despite a threefold higher value in the TSF group compared to the CTRL group, may be explained by the large spread within the data, particularly in the TSF group. Some runners had a large positive FM, while others had a large negative FM for most of the stance phase, and in others FM was small in magnitude for most of the stance phase. As can be seen in the figures, there was a wide variation in the pattern of free moment during the stance phase of running both within and between groups.

Furthermore, as is typical in ensemble curves, the peaks are attenuated relative to the individual curves due to differences in the timing of peaks between subjects. Group average curves provide an indication of the general pattern of FM during stance, but as can be seen from the large spread indicated by the standard deviation in Table 1, this was quite variable between subjects. Due to the bias of some runners in both groups towards abduction FM, there is a large spread in the groups, particularly the TSF group. While there was no distinct pattern in the relative occurrence of adduction and abduction FM bias between the two groups, inter-individual differences were clear. Consequently, the mean ensemble average curves would be of limited interpretive value in making comparisons with individuals, rather than between groups. In addition, since some subjects have an abduction bias and others an adduction bias, the mean curve lies somewhere in between these and does not represent either well. When the groups were subdivided by FM bias, the resulting mean curves provided a more representative average curve.

The values for FM in the control group were somewhat similar to those reported in the literature (Heise and Martin, 2001; Holden and Cavanagh, 1991). There was some variation between these two studies, with the former reporting ADDFM 4.9×10^{-3} and the latter ADDFM of 9.7×10^{-3}. Reported values for IMP were similar at 5.0×10^{-4} and 4.7×10^{-4}, respectively. ADDFM for the control group in the present study was similar to that reported by Heise and Martin (2001), but IMP in the control group was lower than reported by these two groups. There are several methodological differences between each of these two studies and the present study. Both previous studies used male runners, whereas the present study used female runners. Gender differences in various biomechanical characteristics during running have been reported previously (Ferber et al, 2003). Furthermore, the runners tested by Holden and Cavanagh (1991) ran at a faster speed ($4.5\,\mathrm{m\,s^{-1}}$) than either of the later studies (Heise and Martin, 2001 $3.35\,\mathrm{m\,s^{-1}}$; present study $3.7\,\mathrm{m\,s^{-1}}$). Speed has also been shown previously to affect the mechanics of running (Nilsson et al., 1985) and may, therefore, affect transmission of the torque to the lower extremity and the magnitude of the FM variables. The present study provides information about the characteristics of FM in normal female runners, as well as those with a history of TSF.

Further support for the importance of |FM| in TSF was provided by the binary logistic regression. The results of the binary logistic regression indicate that |FM| is a good predictor of a history of TSF. This suggests that |FM| may be a useful tool in screening for runners at risk of TSF. However, while a predictive relationship with previous TSF has been shown, it is beyond the scope of this cross-sectional retrospective study to determine whether |FM| is also higher in runners before they sustain a TSF. Further prospective studies are needed to determine the utility of |FM| in predicting future TSF in runners.

In conclusion, peak adduction FM, FM at peak braking force, and absolute peak FM were significantly higher in runners with a history of TSF compared to a control group with no previous lower extremity bony injury. This suggests an association between higher FM and history of TSF in female distance runners. The magnitude of absolute peak FM successfully predicted a history of TSF in this group in 66% of cases.

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