Journal of Biomechanics 41 (2008) 1160–1165

JOURNAL OF BIOMECHANICS

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Biomechanical predictors of retrospective tibial stress fractures in runners

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Accepted 31 January 2008

Abstract

Both kinematics and kinetics of the lower limb have been shown separately to be related with a history of tibial stress fractures (TSFs) in female runners. However, it is likely that these factors interact together to increase the risk of a TSF. This study was conducted to determine which combination of kinematic and kinetic factors are the best predictors of retrospective TSF in female distance runners. Total 30 female runners who had previously sustained a TSF were recruited, along with an age and mileage matched control group ($n = 30$). Subjects ran overground at 3.7 m/s while kinematic and kinetic data were recorded. Five trials from each subject were used for data analysis and ensemble means were calculated for both groups. The kinematic variables of peak hip adduction (HADD), peak knee internal rotation (KIR) and knee adduction (KADD), peak rearfoot eversion (RFEV) were entered into a binary logistic regression along with the kinetic variables of vertical instantaneous load rate (VILR) and absolute free moment (FM). The variables HADD, FM and RFEV were able to correctly predict a history of TSF in 83% of cases. Increases in HADD, FM and RFEV (odds ratios of 1.29, 1.37 and 1.18) were associated with an elevated risk of having a history of TSF. The addition of VILR, KIR and KADD did not improve the ability to predict previous injury. Based on these results, HADD, FM and RFEV appear to be the most important of the variables of interest in terms of predicting retrospective TSF in female runners.

Keywords: Female; Kinetics; Kinematics; Running; Tibial stress fracture

1. Introduction

Stress fractures are a common problem among runners and may account for between 6% and 14% of running related injuries (James et al., 1978; McBryde, 1985; Taunton et al., 2002). The tibia is the bone most likely to be affected, accounting for between 35% and 56% of all stress fracture injuries (Matheson et al., 1987; Romani et al., 2002). In addition, stress fractures are reported to be more prevalent in females (Arendt et al., 2003; Taunton et al., 2002). It has been postulated that this may be due to females having a lower percentage lean body mass in the lower limb, a history of menstrual disturbance, a low fat diet and lower bone density compared to males (Bennell et al., 1999).

The etiology of stress fractures is believed to be multifactorial in nature arising from issues related to physiology, training, structure and diet (Bennell et al., 1999; Romani et al., 2002). Nevertheless, there are a number of recent studies linking retrospective tibial stress fractures (TSFs) with running mechanics. In a cross-sectional study, Milner et al. (2006b) found that the occurrence of TSF in female runners was related to greater initial loading of the lower extremity. Instantaneous and average vertical ground reaction force load rates along with vertical peak tibial acceleration were found to be significantly greater in the stress fracture group compared to

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0021-9290/$ - see front matter
doi:10.1016/j.jbiomech.2008.02.001

healthy controls. The tibia is also likely to experience torsional loading during running. Indeed, it has been shown that runners with a history of TSF display both an increased adduction and absolute free moment (FM) in comparison to controls (Milner et al., 2006a).

Kinematic variables may also play a role in the development of stress fractures since they may alter the normal alignment of the lower extremity. For example, compared to controls, TSF runners have been shown to demonstrate increased peak hip adduction (HADD) and knee internal rotation (KIR) along with a reduction in peak knee adduction (KADD) (Milner et al., 2005). In addition, rearfoot eversion (RFEV) has been shown to be greater in athletes with running related lower leg pain (Messier and Pittala, 1988; Willems et al., 2006). Abnormal kinematics during running may alter the normal loading pattern placed on the tibia.

In summary, a number of kinetic and kinematic parameters have been related with retrospective TSF in female runners. However, it is unclear which of these factors are most strongly related to the injury. It is likely that a combination of these variables will better distinguish individuals with a history of TSF from healthy controls. Hence the aim of this study was to determine which kinematic and kinetic parameters were the best predictors of retrospective TSF in female distance runners. It was hypothesised that a subset containing both kinetic and kinematic parameters would significantly predict group membership.

2. Methods

2.1. Subjects

All subjects gave written informed consent prior to the commencement of this study. Approval for all procedures was obtained from the Human Subjects Review Board at the University of Delaware before commencing the study. Sixty female runners who were between the ages of 18 and 45 years and rearfoot strikers participated in this project. Thirty subjects with a history of TSF were compared with 30 control subjects (CON) who had no previous lower extremity bony injuries. All subjects were recruited as part of an ongoing prospective study. On entry into the study, the TSF group had reported a previous TSF, which had been confirmed by a medical doctor. Subjects were excluded from the study if they were currently injured (or still recovering from injury), had a history of cardiovascular pathology, had abnormal menses (missed more than three consecutive monthly menstrual cycles in the last 12 months), and were pregnant or suspected they were pregnant. The TSF and CON subjects were matched in terms of age and mileage (Table 1).

Table 1
Mean (SD) subject characteristics of tibial stress fracture (TSF) and control (CON) groups

Characteristics	TSF ($n = 30$)	CON ($n = 30$)	P
Age (yr)	28 (10)	25 (9)	0.28
Mileage (km week^{-1})	41 (11)	39 (14)	0.81
Height (m)	1.65 (0.06)	1.65 (0.06)	0.21
Mass (kg)	56.6 (5.6)	59.8 (5.8)	0.13

2.2. Protocol

Twenty-five reflective markers were attached to the skin of the pelvis, thigh, lower leg and foot as described by Milner et al. (2006b). A uniaxial accelerometer (PCB Piezoelectronics, Inc, Depew, NY) was attached to the anterior medial aspect of the tibia. Prior to the dynamic trials, a standing calibration trial was recorded. Subjects wore standard, neutral laboratory running shoes and ran overground along a 25 m runway at 3.7 m s^{-1} ($\pm$5%). Running velocity was recorded using two photocells linked to a timer. Marker co-ordinate data were collected at 120 Hz using a six camera Vicon 512 motion capture system (Oxford Metrics, Oxford, UK) arranged around a force platform (Bertec Corporation, Columbus, OH), which was set into the middle of the runway. Force plate and accelerometer data were sampled at 960 Hz. For the TSF subjects, data were captured for the affected limb. In the CON group, a counterbalance of right and left legs was collected (15 right and 15 left).

2.3. Data processing

Five successful trials were selected for further analysis. A successful trial was defined as one where the subject's foot landed fully on the force plate without under or over striding. Raw marker co-ordinate, ground reaction force and accelerometer data were filtered using a fourth order low-pass recursive Butterworth filter. A cut-off frequency of 8 Hz was used for marker data while 50 Hz was implemented for ground reaction force and accelerometer data. Visual 3D software (C-motion Inc, Rockville, MD) was used to create a right-handed anatomical co-ordinate system for the foot, shank, thigh and pelvis. Three-dimensional rearfoot, knee and hip angles were calculated using a joint co-ordinate system where the distal segment was referenced to the proximal segment (Grood and Suntay, 1983). Kinematic variables of interest included peak RFEV, KIR, knee abduction (KABD) and HADD during stance.

All the kinetic variables were calculated using custom Labview (National Instruments Corporation, Austin, TX) software. Peak positive tibial acceleration (PPA) was defined as the highest positive acceleration measured during the stance phase after the mean average value of the signal had been removed to correct for offset (Shorten and Winslow, 1992). Both the instantaneous (vertical instantaneous load rate, VILR) and average (vertical average load rate, VALR) vertical ground reaction force load rates were determined between 20% and 80% of the period between heel strike and impact peak (Milner et al., 2006b). FM was normalised to body weight and height to reduce the effect of these factors between subjects. While most runners exhibit a predominant adduction FM (resistance to toe-out), some demonstrate an abduction FM. Since either will increase the torsional loading of the leg, the peak absolute FM was chosen for analysis. Indeed, the absolute FM was also shown to demonstrate the largest effect size of all the FM variables when comparing TSF and CON subjects (Milner et al., 2006a).

2.4. Data analysis

Descriptive statistics were calculated for each variable including the group mean, standard deviation and effect size. A bivariate correlation was conducted between all combinations of variables prior to entry into the regression. Where variables demonstrated colinearity ($r > 0.65$), only one was put forward into the regression analysis (i.e. the variable that was correlated highest with the others was entered into the regression) (Tabachnick and Fidell, 2001). A forward stepwise binary logistic regression was then conducted using SPSS 14.0 software (SPSS Inc., Chicago, IL) to determine which variables were significant predictors of group membership. We considered alpha levels of 0.05 and 0.1 for entry and removal from the regression model, respectively.

Using the final regression equation, we assessed the combined influence of the significant predictor variables on the risk of having a previous TSF. For the purpose of this analysis we considered the mean values of each of the predictor variables for the CON group to place an individual at low risk since subjects within this group had never sustained a stress fracture.

A predictor variable was considered to place an individual at high risk when it was one standard deviation above or below (direction dependant on whether an injury was associated with an increase or decrease in the variable) the mean of the CON group. The risk of TSF was then calculated in a stepwise manner as one high-risk predictor value was sequentially entered into the prediction equation. For example, the risk of injury was first calculated when low values were entered for each predictor variable. Next, one high predictor variable was added to the equation while the remaining variables were kept low. This process was continued until all the predictor variables in the regression equation were high.

The study design incorporates increased statistical power instead of, for example, using a split-half method of reliability to provide support for validity. This means the study provides the previously unavailable data that can inform this area, and be used for a future study on validity.

3. Results

High colinearity ($r \geqslant 0.65$) was found between VILR and both VALR ($r = 0.936$, $P < 0.001$) and PPA ($r = 0.802$, $P < 0.001$). In addition, VALR was highly correlated to PPA ($r = 0.681$, $P < 0.001$). Therefore, it was decided to use VILR as the input variable for the regression calculations since it provided a good representation of the VALR and PPA. None of the other variables demonstrated colinearity.

The mean peak values of VILR, FM, HADD, KIR and RFEV were all greater in the TSF group compared to the controls (Table 2). A large effect size was found for both FM and HADD between groups. A moderate effect size was also evident for RFEV. The TSF group also demonstrated greater HADD and RFEV throughout the entirety of stance (Fig. 1).

The variables HADD, FM and RFEV were found to be significant predictors of group membership. The first variable entered into the regression was HADD, which was followed by FM and finally RFEV. Together, the three variables resulted in a Nagelkerke R^2 value of 0.496, suggesting that 50% of the variance between the two groups was explained by HADD, FM and RFEV (Table 3).

The logistic regression model containing the variables HADD, FM and RFEV was able to correctly classify 83% ($n = 50$) of the runners into the appropriate TSF or CON groups ($P < 0.001$). The inclusion of VILR, KIR and KADD did not significantly improve the predictive ability of the regression model.

Table 2
Mean (SD) values for the variables entered into the logistic regression for tibial stress fracture (TSF) and control subjects (CON)

Variable	TSF ($n = 30$)	CON ($n = 30$)	Effect size
VILR ($BW\,s^{-1}$)	88.2 (24.7)	83.8 (23.2)	0.2
VALR ($BW\,s^{-1}$)	74.2 (23.5)	66.0 (22.4)	0.4
PPA ($m\,s^{-2}$)	6.5 (3.4)	5.5 (2.5)	0.3
FM ($\times 10^{-3}$)	9.1 (4.2)	6.1 (2.5)	0.9
HADD (°)	11.7 (5.0)	7.7 (3.8)	0.9
KIR (°)	3.7 (5.1)	2.6 (6.8)	0.2
KADD (°)	2.0 (5.0)	2.5 (5.0)	−0.2
RFEV (°)	11.5 (4.3)	8.8 (4.1)	0.6

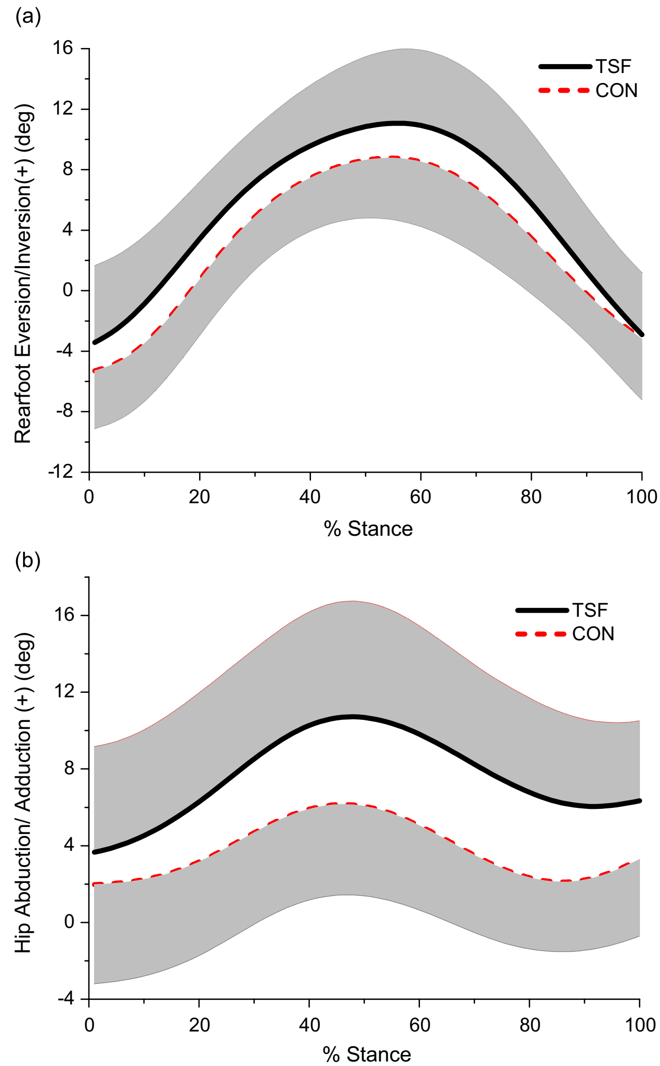

Fig 1. Mean (sd is shaded) ensemble angular displacement curves of rearfoot eversion/inversion (a) and hip adduction/abduction (b) for tibial stress fracture (TSF) and control (CON) groups.

Table 3
Output from binary logistic regression reporting the odds ratio attached to each predictor variable

Variable	Odds ratio	S.E.
HADD	0.255	0.087
FM	0.316	0.110
RFEV	0.161	0.085
Constant	−6.416	1.668

The standard errors of the coefficient are also shown.
Note: Nagelkerke $R^2 = 0.496$, model $\chi^2 = 27.945$ ($P < 0.001$).

The odds ratios of HADD, FM and RFEV were all positive and greater than one. This suggests that increases in these variables were related to an increased likelihood of being in the TSF group (Table 3). The odds ratios revealed that for every 1° increase in HADD, the risk of having a history of TSF increased by 1.29. Similarly, for unit increases in either FM (1×10^{-3}) or RFEV (1°) the likelihood of having a TSF increased by 1.37 and 1.18, respectively. The combined effect of a unit increase in all three variables would raise the risk of a previous fracture to 2.08.

The three predictive variables in the logistic regression were also tested to determine how having high values for several variables influenced the risk of having a previous TSF. When low risk (CON mean) values for all three variables ($\text{HADD}=7.7^\circ$, $\text{FM}=6.1$, $\text{RFEV}=8.8^\circ$) were entered the regression yielded an odds ratio of 0.3. When one predictor variable was high ($\text{HADD}=11.5^\circ$) while the other two remained low, the odds ratio was 0.9. When two risk factors were high ($\text{HADD}=11.5^\circ$, $\text{FM}=8.6$) the odds ratio rose to 1.9. Finally, having high values for all three risk factors ($\text{HADD}=11.5^\circ$, $\text{FM}=8.6$, $\text{RFEV}=12.9^\circ$) increased the subject's risk of a previous TSF by a factor of 3.7.

4. Discussion

The aim of this investigation was to determine which kinematic and kinetic factors were the best predictors of a previous TSF in female runners. We found that increases in peak HADD, peak RFEV and absolute FM increased the likelihood that a subject had sustained a previous stress fracture.

Peak RFEV was found to be 2.7° greater in the TSF group compared to the controls. This value corresponds well with the differences of 2.6° and 1.9° reported between controls and runners with exercise related lower leg pain (Messier and Pittala, 1988; Willems et al., 2006). It may be postulated that excessive eversion leads to early muscular fatigue, which can subject the tibia to abnormal loading. For instance, the posterior tibialis with its medial attachment may serve to reduce the tensile loads on the medial side of the tibia. However, since this primary function of tibialis posterior is to control foot eversion, increased demand may be placed on this muscle in runners with excessive RFEV. This could result in earlier fatigue of the muscle and its protective function in controlling tensile forces on the medial tibia would be diminished. Indeed, Milgrom et al. (2007) concluded that training in a fatigued state increases medial tensile bone strains well above those recorded in rested individuals. Animal studies have also documented that muscular activity can influence the strength and strain properties of bone (Nordsletten and Ekeland, 1993; Yoshikawa et al., 1994). Recreational and competitive runners are prone to stress fractures on the medial posterior surface of the tibia (Boden et al., 2001; Daffner and Pavlov, 1992). As bone is weaker in tension than compression, it is likely that a stress fracture would develop on the side of tension. A number of studies have provided evidence that the medial or posterior aspect of the tibia may undergo periods of tension during the gait cycle (Gefen, 2003; Milgrom et al., 2004; Scott and Winter, 1990). Therefore, running mechanics that tend to increase the tensile stresses normally placed on the medial posterior tibia are likely to be related to stress fractures.

Peak HADD was also found to be greater in the TSF group. Increased HADD may be associated with a lateral shift of the axial load placed at the knee. Indeed, an increased HADD angle has been associated with patients suffering from lateral knee osteoarthritis (Weidow et al., 2006). The resulting compression on the lateral tibia condyle may serve to create an increased tensile stress on the medial aspect of the bone.

The absolute FM was found to be greater in the TSF group. The tibia may be loaded in torsion as a result of the FM. The FM is a measure of the torque acting between the foot and the ground during running. Given that the tibia is immediately proximal to the foot, it is likely that this torque is transmitted as a torsional load on the tibia. Hence, the greater FM found in TSF runners may imply greater torsional loads are being applied to the tibia, placing them at an elevated risk for stress fracture.

The three predictive variables in the logistic regression provide an indication of risk when multiple risk factors are present. When low risk values for all the variables were entered into the regression, the risk for having sustained a stress fracture was only 0.33. When one risk factor was present, the odds ratio was still less than 1.0 indicating that subjects were still less likely to be assigned to the TSF group. However, when two or three risk factors were present the subjects were 1.9 and 3.7 times more likely to be in the TSF group, respectively. Hence, having a number of risk factors greatly increases the odds of a subject falling into the TSF group, thus highlighting the multifactorial nature of the injury.

Common treatment for stress fracture involves refraining from high impact activities, such as running, for approximately 6–8 weeks. However, if the underlying mechanisms are not addressed, the injury is likely to recur. Interestingly, the recurrence rate of stress fractures has been reported to be as high as 36% (Hauret et al., 2001). Therefore, interventions should be aimed at reducing these risk factors prior to the subject resuming their running program.

Dynamic alignment angles during running were selected for analysis in this study as opposed to the use of static measurements such as *Q*-angle and foot structural characteristics. This was due to static alignment measures not always being representative of joint kinematics during gait. For instance, no difference in static *Q*-angle was found between a group of females with patellofemoral pain compared to asymptomatic controls (Willson and Davis, 2008). However, an increased peak adduction angle during running was found in the patellofemoral pain group. Similarly, measures of static foot posture are not necessarily predictive of dynamic foot behaviour (Cashmere et al., 1999; Hamill et al., 1989). Since the subjects in the present investigation had experienced stress fractures during running, a comparison of dynamic alignment angles during running was deemed to be of more interest.

The injury mechanisms discussed regarding RFEV and HADD concern abnormal stresses being placed on the medial posterior aspect of the tibia, the most commonly injured site. However, it should be noted that stress fractures might occur in differing locations. A limitation of the current study was that the exact fracture location was not known for all subjects. It is possible that different fracture locations are caused by different loading mechanisms. Future studies attempting to identify potentially harmful loading situations should group stress fractures according to a more precise anatomical location.

External rearfoot markers were placed on the shoe rather than the calcaneus in this study. Rheinschmidt et al. (1997) showed that although external markers attached to the shoe tend to overestimate actual calcaneal motion, they are good indicators of the motion pattern of the underlying bone. Therefore, it is possible that the rearfoot angles reported in this paper overestimate the true bony movement. However, it has also been shown that differences between shoe and skin markers are dependant on the type of shoe and heel counter construction (van Gheluwe et al., 1995). Given that subjects in the present investigation wore the same model of shoe it is suggested that although the true tibiocalcaneal motion may have been overestimated, it would have been consistent across all our subjects.

There are also some limitations associated with the retrospective nature of this study. For example, both training factors and abnormal menses patterns are often implicated with overuse injuries (Bennell et al., 1999). Although the subjects were matched for mileage and required to have normal menses at the time of entry into the study, the status of these variables was unknown at the time of injury. Future prospective data from this ongoing study will be able to account for these confounding factors. Prospective studies are also required to clarify whether the biomechanical risk factors identified in this cross-sectional study are present prior to the initial stress fracture.

In conclusion, greater values of peak HADD, peak RFEV and peak absolute FM were found to be associated with a greater risk of a history of TSF. Together, the three variables were able to successfully predict a history of TSF in 83% of cases.

Conflict of interest

All the authors confirm that there are no financial or personal relationships with other people or organisations that could inappropriately bias the content of this paper.

Acknowledgement

This study was supported by Department of Defense Grant DAMD17-00-1-0515. This support was financial in nature and no conflicts of interest were encountered.

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