External Frontal Plane Loads May Be Associated with Tibial Stress Fracture

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ABSTRACT

CREABY, M. W., and S. J. DIXON. External Frontal Plane Loads May Be Associated with Tibial Stress Fracture. *Med. Sci. Sports Exerc.*, Vol. 40, No. 9, pp. 1669–1674, 2008. **Purpose:** The role of applied external loads in tibial stress fracture is poorly understood. The purpose of this study was to determine whether the magnitude and angle of frontal and sagittal force vectors and the magnitude of the free moment of ground reaction force (the torsional moment between the foot and the ground) during running gait differ between military recruits with and without a history of tibial stress fracture. **Methods:** Ten male military recruits with tibial stress fracture history and 20 matched controls performed shod running trials over a force plate. The magnitude and the direction of the frontal and sagittal plane ground reaction force, in addition to the free moment, were compared between the groups. **Results:** The frontal plane force vector was directed significantly more medially in the stress fracture group during midstance and late stance ($P < 0.05$). The magnitude of frontal and sagittal plane ground reaction forces and the free moment were not higher in the stress fracture group compared with controls. **Conclusion:** These data highlight differences in the direction with which external forces in the frontal plane are applied in military recruits with a history of tibial stress fracture. These differences may be important in the development of the injury.
Key Words: GROUND REACTION FORCES, OVERUSE INJURY, GAIT, RUNNING, MILITARY

Tibial stress fractures are relatively common in military recruits and runners (5,32). Recovery requires a period of rest from the aggravating activity, typically for 4 to 8 wk (7). With the addition of rehabilitative training, in military recruits, typically 19 wk of full training are lost as a result of a tibial stress fracture (32). Similar losses of training time can be expected in athletes (20,37). The loss of training time associated with stress fracture can lead to a reduction in physical fitness and significant frustration for the individual.

High levels of strain or strain rate are known to be instrumental in the development of bony microdamage (8,34), and when combined with repetitive activity, such as running, may ultimately result in the development of a stress fracture (6,38). The measured bone strain is dependant upon the applied external load and the structural and material properties of the bone (8,9). Thus, in addition to well-established differences in tibial structural (2,18,26,27) and material properties (2,4), differences in loading patterns may be present in individuals with a history of tibial stress fracture compared with uninjured controls.

Measurement of the ground reaction force provides an approximation of the external load acting upon the tibia during gait and has been compared in runners with and without tibial stress fracture history in studies using a cross-sectional retrospective study design (3,13,19,28,29). Although this study design does not allow a causal relationship to be established, it is often used to evaluate features of injured runners, as prospective longitudinal studies require many participants and a long observation period. Furthermore, it is likely that ground reaction force parameters remain stable because similar findings of higher ground reaction force loading rates in runners with stress fracture history were observed in a cross-sectional study (29) and a pilot prospective study (14). Thus, observed differences in ground reaction force parameters may represent risk factors for the development of stress fracture injury. A higher magnitude of the vertical ground reaction force is often implicated in overuse injury development (11,23,39) and has been observed in a small study of female runners with and without tibial stress fracture history (19). More recent works with larger cohorts, however, indicate that no difference exists in vertical and anteroposterior forces (3,13,29). Further insight into the relationship between tibial stress fracture and external loads may be gained by considering additional characteristics of the

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ground reaction force. A recent study by Milner et al. (28) reported that the adduction and absolute free moment of ground reaction force—the rotational moment between the foot and the ground—is greater in female athletes with a history of tibial stress fracture and suggests that this may indicate increased torsional loading on the tibia in those with fracture history.

The magnitude and direction of the ground reaction force vector may also have important implications for tibial stress fracture. In the sagittal plane, the ground reaction force vector contributes toward the sagittal plane bending load acting on the tibia. As described in the mathematical model of Scott and Winter (35), a more posteriorly directed sagittal plane ground reaction force vector will increase this bending load. Similarly, the orientation of the frontal plane ground reaction force vector will contribute toward tibial bending loads in this plane. Given the varus orientation of the tibia during the stance phase of running (24) and the predominantly medially directed ground reaction forces (10), it would be expected that the frontal plane force vector is directed more medially in subjects with tibial stress fracture—indicating higher bending loads.

The purpose of this initial cross-sectional study, therefore, was to evaluate differences in the ground reaction force vector and free moment of ground reaction force between a group of military recruits with a history of tibial stress fracture and a group of injury-free recruits. We hypothesized that the ground reaction force vector in the sagittal plane would be directed more posteriorly, and in the frontal plane more medially, in the tibial stress fracture group. With regard to the magnitude of ground reaction forces, we hypothesized that the peak sagittal and frontal plane forces and the free moment of ground reaction force would be greater in the tibial stress fracture group compared with the injury-free recruits.

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METHODS

Subjects. Thirty male military recruits participated in this study. Before participation, all subjects provided written informed consent. Ethical approval was obtained from the Ministry of Defence (Navy) Personnel Research Ethics Committee. All subjects in the study had partially completed the initial 32-wk training course for Royal Marine Commando recruits but, as a result of injury or illness, had not completed the full course. The nature and the anatomical location of all injuries and/or illnesses were recorded by the duty medical officer. After removal from the course, all subjects underwent appropriate medical treatment and full rehabilitation; before assessment, subjects were passed fit to return to full training. Ten of the study subjects had sustained a tibial stress fracture during the training course and formed the stress fracture group. Stress fracture was diagnosed by the Principal Medical Officer using an imaging algorithm for stress fracture (1). The control group consisted of 20 subjects with no history of lower limb injury sustained during training and were removed from the course as a result of illness or upper body injury. Subject mass and height were measured with standard scales and a stadiometer.

Running gait assessment. Data collection was performed by an assessor blinded to subject group. Before data collection, all subjects performed several practice trials. Each subject performed 10 successful running trials for each leg while wearing their above ankle combat assault boots (GB Britton, Gloucestershire, UK). Running speed was maintained at 3.6 $m \cdot s^{-1}$ (±5%), monitored using photocells. This running speed is representative of training speeds used during Royal Marine Commando Training. For all running gait trials, ground reaction force data were collected at 960 Hz from a force plate (AMTI, Massachusetts, USA) embedded in the floor of a 20-m runway and orientated in line with the direction of running. A successful trial was defined as one where the foot landed entirely within the borders of the force plate with no obvious adjustments to gait or platform targeting, and the required running speed was maintained. Kinematic data were synchronously obtained using a four-camera optoelectronic system at 120 Hz (Peak Performance Technologies Inc., Englewood, CO). Reflective markers were placed on the foot segment (posterior aspect of the calcaneum and third metatarsal head). This, in addition to the ground reaction force data, enabled the classification of strike index according to the guidelines of Cavanagh and Lafortune (10).

Data analysis. Forces and moments acting about the vertical, anteroposterior, and mediolateral axes of the force plate throughout the stance phase of each successful trial were exported into Matlab (The Mathworks, Inc. Natick, MA) for analysis. The free moment of ground reaction force was computed as described by Holden and Cavanagh (22). The frontal plane magnitude (FP_{mag}) and angle (FP_{ang}) of the ground reaction force vector relative to the vertical were computed using standard trigonometric equations with the magnitude of the vertical (F_z) and the mediolateral (F_x) ground reaction forces as inputs:

$$FP_{mag} = \sqrt{F_x^{\,2} + F_z^{\,2}}$$

$$FP_{ang} = \tan^{-1}\frac{F_x}{F_z}$$

The same procedure was used to calculate the magnitude and angle of the ground reaction force vector acting in the sagittal plane, but with the magnitude of the anteroposterior ground reaction force in place of F_x. In the frontal plane, a positive angle indicates a laterally directed ground reaction force; in the sagittal plane, a positive angle indicates an anteriorly directed ground reaction force.

Forces were normalized to bodyweight (Bw.), and moments were normalized to bodyweight multiplied by height (BwHt.). Peak values (angles, forces, and free moment) were calculated from the 960-Hz data. To enable the comparison of data across the stance phase, all trials were

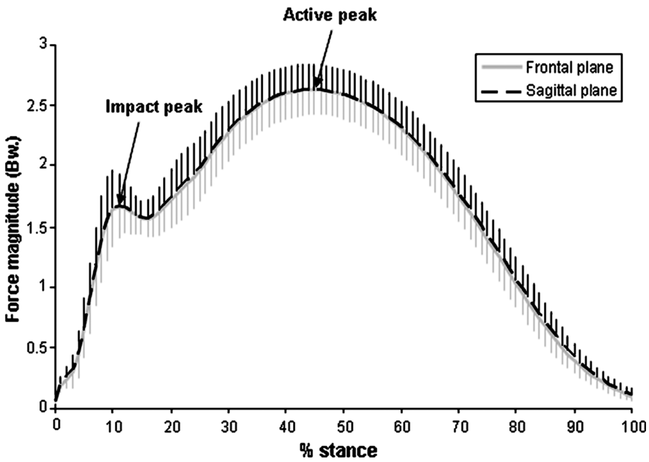

FIGURE 1—Magnitude of the ground reaction forces in the frontal and sagittal planes for the control group, with impact and active peaks identified. A similar pattern was observed in the stress fracture group.

then normalized to 101 data points representing 0% to 100% of stance.

Statistical analysis. One-tailed independent *t*-tests were used to detect differences between groups, based on the directional hypotheses stated previously. The magnitude of the peak adduction and absolute free moment was considered. With respect to the frontal and sagittal plane force magnitudes, their impact and active peaks were considered (Fig. 1). The angle of the frontal and sagittal plane ground reaction force vectors at the occurrence of these peaks was also considered. To gain further insight into possible differences in the direction of ground reaction force vectors, discrete points representing each percentage point of the stance phase, from 0% to 100%, were considered with one-tailed independent *t*-tests.

To aid in the interpretation of the results, the effect size was calculated for all variables as described by Cohen (12). An effect size of less than 0.5 was considered to represent a small difference, 0.5 to 0.8 was considered to represent a moderate difference, and greater than 0.8, was considered a large difference (12).

RESULTS

Descriptive data for the two experimental groups are presented in Table 1. No significant differences in these variables were observed between groups. Control group subjects were removed from the training course as a result of unrelated illness (n = 6); head or neck injury (n = 2); shoulder, arm, or hand injury (n = 7); rib or abdominal injury (n = 2); and low back pain (n = 3). All subjects were classified as rearfoot strikers according to the strike index (10). As illustrated in Figure 1 for the control group, the magnitudes of the ground reaction force acting in the frontal and sagittal planes across stance were similar; an initial "impact" peak was observed at 10% to 15% of stance, and a second "active" peak was observed at approximately 50% of stance. This is consistent with the typical vertical ground reaction force pattern for running (10). Contrary to the study hypothesis, in the frontal and sagittal planes, the magnitude of the impact peaks was not significantly greater in the stress fracture group (P > 0.05; Table 2), and the magnitude of the active peaks was not greater in the stress fracture group (Table 2).

The frontal plane ground reaction force vector was directed significantly more medially in the stress fracture group at the occurrence of the frontal plane active peak (P = 0.05; Table 3). No significant difference was associated with the angle of the ground reaction force vector in the sagittal plane at the time of peak active force (P > 0.05; Table 3). Contrary to the study hypothesis, at the time of the impact peak magnitudes, the frontal and the sagittal force vectors were directed more laterally and anteriorly, respectively, in the stress fracture group (Table 3).

The angle of the ground reaction force vectors in the frontal and sagittal planes for the two experimental groups across stance is illustrated in Figure 2. In the frontal plane, the stress fracture group mean data maintain a medially directed angle until approximately 80% of stance. Although a similar pattern is demonstrated by the control group, the curve is shifted upward. This is evidenced by

TABLE 1. Subject demographics for the stress fracture and control groups (mean ± SD).

Variable (Units)	Stress Fracture (n = 10)	Control (n = 20)
Age (yr)	20.3 ± 3.5	22.6 ± 3.8
Mass (kg)	75.7 ± 5.9	77.3 ± 7.4
Height (m)	1.77 ± 0.06	1.76 ± 0.06
Time in full training (wk)	16.6 ± 8.6	20.8 ± 5.6

TABLE 2. Magnitude of the peak sagittal plane forces, frontal plane forces, and free moments in the stress fracture and control groups (mean ± SD).

Variable (Units)	Stress Fracture (n = 10)	Control (n = 20)	Effect Size	P Value
Frontal plane (Bw.)				
Impact	1.90 ± 0.22	1.80 ± 0.26	0.39	0.162
Active	2.49 ± 0.19	2.67 ± 0.20	−0.87	†
Sagittal plane (Bw.)				
Impact	1.91 ± 0.22	1.81 ± 0.26	0.38	0.166
Active	2.49 ± 0.18	2.67 ± 0.21	−0.85	†
Free moment (Bw.Ht.) $\times 10^{-3}$				
Adduction peak	6.2 ± 2.4	5.7 ± 3.1	0.14	0.353
Absolute peak	9.5 ± 2.1	9.3 ± 3.2	0.01	0.402

† In opposite direction to hypothesized difference.

TABLE 3. Angle (°) of frontal and sagittal plane force vectors at peak force magnitudes in the stress fracture and control groups (mean ± SD).

Variable	Stress Fracture (n = 10)	Control (n = 20)	Effect Size	P Value
Frontal plane				
Impact	−1.30 ± 3.83	−1.40 ± 3.40	0.03	†
Active	−2.34 ± 1.57	−1.39 ± 1.36	−0.64	0.050*
Sagittal plane				
Impact	−5.65 ± 3.23	−5.84 ± 4.67	0.05	†
Active	−3.25 ± 1.63	−2.47 ± 1.69	−0.46	0.120

* Significant difference between groups ($P \leq 0.05$).
† In opposite direction to hypothesized difference.

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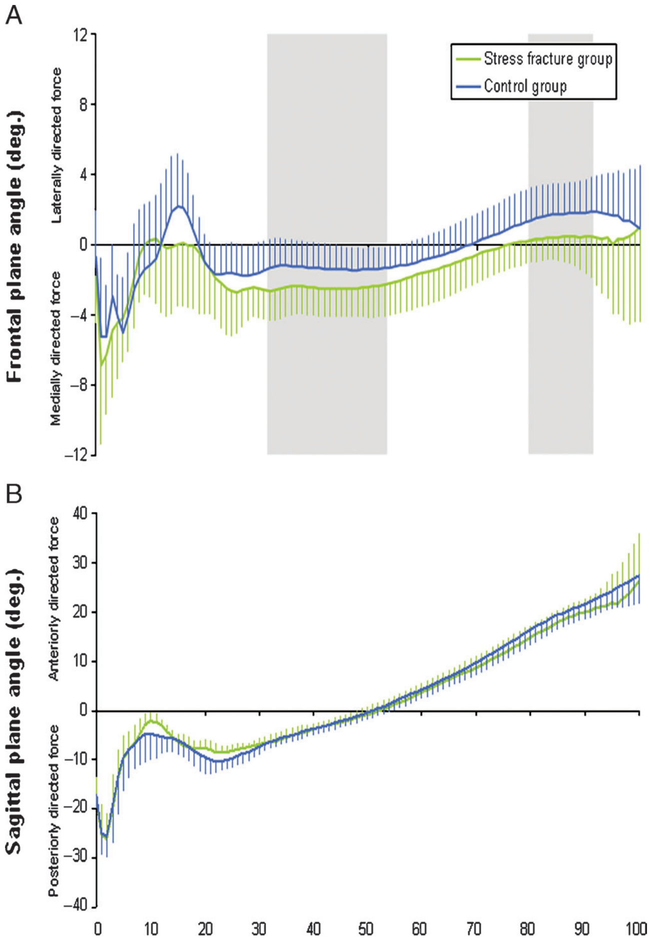

FIGURE 2—Angle of the ground reaction forces in the frontal (A) and sagittal planes (B). The shaded gray regions identify those regions where the frontal plane force is directed significantly more medially in the stress fracture group ($P < 0.05$).

a significantly more medially directed ground reaction force in the stress fracture group from 32% to 53% of stance ($P = 0.02$ to 0.05) and a significantly more laterally directed ground reaction force in the control group from 80% to 91% of stance ($P = 0.02$ to 0.05). A moderate effect size was associated with both of these differences.

With respect to the peak adduction free moment and the absolute peak free moment, these were not significantly greater in the stress fracture group compared with the control group ($P > 0.05$; Table 2).

DISCUSSION

This is the first study to investigate differences in the angle of the ground reaction force vectors between individuals with and without a history of tibial stress fracture. Furthermore, this is the first study to investigate differences in ground reaction force parameters in military recruits, a population at high risk of the injury; all previous studies of ground reaction force have been performed in athletes (3,13,14,19,28,29), and risk factors may differ between these populations. Differences were identified in the angle of the frontal plane ground reaction force vector during midstance and late stance. The magnitude of peak forces in the frontal plane occurs during midstance, where differences in the angle at which this force is directed are observed. The moderate effect size associated with this difference for a single stance phase may have important clinical implications for tibial stress fracture given the high number of steps taken during running and marching.

The observed difference in the direction of the frontal plane force vector during midstance is thought to be of particular importance given the high magnitude of the force during this phase. The importance of the difference observed in late stance is less clear given the low magnitude of the force during this phase. The magnitude and direction of the frontal plane ground reaction forces during midstance are depicted in Figure 3. As the shank typically adopts a varus orientation of around 10° in the frontal plane during running gait (24), the more medially directed frontal plane force vector observed in the stress fracture group indicates that the moment arm to the tibia is increased. Such an increase would contribute toward a greater medial bending moment acting on the tibia. This represents a plausible mechanism to explain how the load acting on the tibia is increased in the stress fracture group and thus may have contributed toward the development of the injury. Prospective study is required to confirm if this more medially directed frontal plane ground reaction force vector plays a causative role in tibial stress fracture development.

It is important to note that frontal plane ground reaction forces are associated with greater between-subject variability than those in the sagittal plane (10,25). Consistent with this, in the current study, there appears to be greater variability associated with the direction of the frontal plane

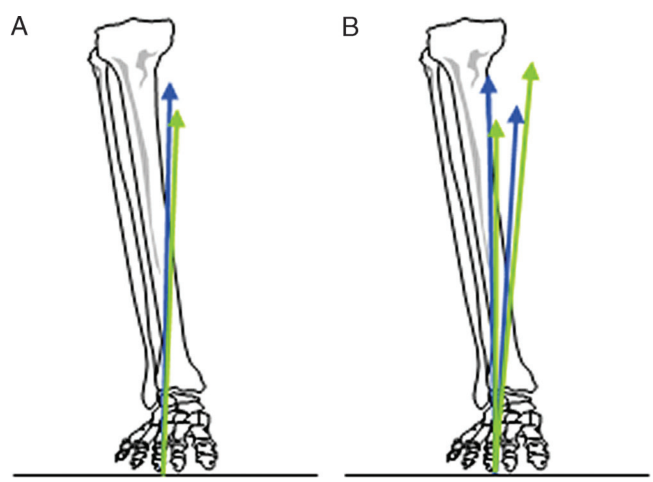

FIGURE 3—Graphical representation of the magnitude and orientation of the mean (A) and range (B) of the frontal plane ground reaction force vectors relative to the lower limb in the stress fracture (*green*) and control group (*blue*) at the occurrence of peak active force. The length of the vectors is proportionate to the magnitude of the force.

force vector compared with the sagittal plane vector. Figure 3b illustrates that, in some control group subjects, the frontal plane force vector at the occurrence of the active peak is directed laterally to the vertical. Given the typical orientation of the shank during the stance phase of running, however (24), this load is unlikely to pass laterally to the tibia. Thus, it is expected that in all subjects, the frontal plane force vector will result in a medial bending load acting upon the tibia.

The difference in the angle of the frontal plane ground reaction force vector supports the concept that the load acting upon the tibia during midstance may be instrumental in the development of the injury. This is corroborated by data from modeling studies, indicating that peak tibial loads occur during this phase (33,35) in addition to other predictors of tibial stress fracture history (28). Thus, we suggest that intervention to reduce tibial loads, and therefore presumably stress fracture risk, focuses upon mediating loads during this phase. As orthotics have demonstrated limited success in mediating tibial strain (16) and external loads during the active phase of stance (31), mediating tibial loads through techniques such as gait retraining may be beneficial and warrants further investigation. It is important that we proceed with caution, however, as differences in knee mechanics (30) and ground reaction force loading rates (14,29) during early stance have also been implicated in tibial stress fracture. Furthermore, in the current study, the large negative effect size associated with the magnitude of the active ground reaction force peak indicates that load may have been lower in the stress fracture group. Further investigation of the role of frontal plane bending loads is therefore warranted to determine the net effect of differences in the magnitude and direction of applied forces upon tibial bending moments. This may be achieved with mathematical modeling techniques similar to those used to quantify sagittal plane loads (33,35).

In the sagittal plane, contrary to our hypothesis, the magnitude and direction of the ground reaction force vector did not differ between the groups. Importantly, contraction of the plantarflexor muscles plays a significant role in determining the net load acting upon the tibia in this plane (35) and has been implicated in tibial stress fracture risk (4). Thus, although the current study indicates that reaction bending loads acting on the tibia in the sagittal plane are unlikely to differ with respect to stress fracture history, investigation of differences in plantarflexor contribution toward net load is warranted in individuals with and without tibial stress fracture history.

Although measurement of frontal and sagittal plane forces may provide an indication of the bending loads acting upon the tibia, measurement of the free moment of ground reaction force may provide an indication of the torsional loads acting upon the tibia. Contrary to findings in female runners (28), no differences were observed in characteristics of the free moment between the groups in the current study. Interestingly, the magnitude of the free moment for both groups in the current study was markedly higher than reported previously in male (21) and female (28) injury-free runners. Thus, although the magnitude of the free moment does not appear to be a risk factor for tibial stress fracture *within* the study population of military recruits, the higher magnitude of the free moment *between* this population and distance runners may contribute toward a higher incidence of tibial stress fracture in military recruits compared with runners. Furthermore, if torsional loads, as indicated by the higher free moment, are indeed greater in military recruits than runners, it follows that in this population, the strength of tibia to resist these loads may be an important determinant of risk. Supporting this, a prospective study has found a smaller area polar moment of inertia of the tibia in the transverse plane (an index of torsional strength) in recruits that go on to develop tibial stress fracture during training compared with those that do not (26).

By the nature of the retrospective cross-sectional design of the study, it is unclear if the observed differences between the groups were a causative factor in the development of the injury or an adaptation after injury. As all recruits were tested after full recovery and rehabilitation and no pain or other symptoms were present at the time of testing, it was assumed that their gait during testing was representative of that before injury. Supporting this, in an animal model, ground reaction force characteristics returned to prefracture levels after fracture healing (36). In addition, these ground reaction forces are associated with low within-day and between-day variability (15,17). Prospective cohort study would be required to confirm any relationship with the risk of tibial stress fracture development. Although large subject numbers would be required, we consider this to be feasible given the simplicity of ground reaction force measurement over full kinematic gait analysis.

In summary, the frontal plane ground reaction force is directed significantly more medially in military recruits with tibial stress fracture history during midstance and late stance. The magnitude of ground reaction forces was not higher in recruits with tibial stress fracture history. The findings indicate that frontal plane loads may be an important determinant of tibial stress fracture history. Prospective work is required to confirm if these findings present as a risk factor for the development of the injury.

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