Available online at www.sciencedirect.com

SCIENCE DIRECT®

Clinical Biomechanics 21 (2006) 412–419

CLINICAL BIOMECHANICS

www.elsevier.com/locate/clinbiomech

Comparison of static and dynamic biomechanical measures in military recruits with and without a history of third metatarsal stress fracture

Sharon J. Dixon [a,*], Mark W. Creaby [a,b], Adrian J. Allsopp [c]

[a] *School of Sport and Health Sciences, University of Exeter, Exeter EX1 2LU, United Kingdom*
[b] *Centre for Health, Exercise and Sports Medicine, School of Physiotherapy, The University of Melbourne, Victoria, Australia*
[c] *Institute of Naval Medicine, Alverstoke, Gosport PO12 2DL, United Kingdom*

Received 21 March 2005; accepted 23 November 2005

Abstract

Background. For Royal Marine recruits in training, the third metatarsal is the most common site for stress fracture. Previous evidence regarding biomechanical factors contributing to metatarsal stress fracture development is conflicting, possibly due to the lack of differentiation between the metatarsals. The present retrospective study compares static anatomical characteristics and dynamic biomechanical variables for Royal Marine recruits with and without a history of third metatarsal stress fracture.

Methods. Ten Royal Marine recruits with a history of third metatarsal stress fracture were compared with control subjects with no previous stress fracture occurrence. Selected static anatomical variables were measured to describe the ankle and subtalar joints. Peak ankle dorsi-flexion and rearfoot eversion were measured during running. In addition, peak vertical and horizontal ground reaction force variables were compared for the two study groups.

Findings. No significant differences in static anatomical variables were identified between study groups. During running, peak rearfoot eversion was found to occur significantly earlier for the stress fracture group than for their matched controls, suggesting an increase in time spent loading the forefoot. The peak applied resultant horizontal force during the braking phase was directed significantly more laterally for the stress fracture group. In addition, the peak magnitude of resultant horizontal force applied during the propulsion phase was significantly lower for the stress fracture subjects.

Interpretation. The findings of this study highlight the importance of including dynamic biomechanical data when exploring variables associated with the development of third metatarsal stress fracture and indicate that successful interventions to reduce the incidence of this injury are likely to focus on forefoot function during braking and propulsion.

Keywords: Running; Injury; Military boots

1. Introduction

It has been well documented that stress fractures are a major problem in military personnel, with the most common injury sites being the tibia and the metatarsals (Meurmann, 1981; Evans, 1982; Riddell, 1989; Pester and Smith, 1992). Ross and Allsopp (2002) have identified that for Royal Marine Recruits in training, stress fractures are the single most important cause of lost training days. These authors describe how, although the number of cases of stress fracture appears low at around 4% of recruits, between 6 and 12 weeks is typically required for adequate recovery and return to full training. Total time to complete training is therefore

* Corresponding author.
E-mail address: s.j.dixon@exeter.ac.uk (S.J. Dixon).

0268-0033/$ - see front matter
doi:10.1016/j.clinbiomech.2005.11.009

increased, together with an increased financial cost through treatment and rehabilitation. Of the stress fracture sites reported in this study of Royal Marines, the third metatarsal was found to be the most common site, accounting for 38% of reported stress fracture injuries (Ross and Allsopp, 2002).

Despite various biomechanical variables previously being associated with the development of lower extremity stress fractures, evidence regarding the cause of stress fractures at specific sites is inconclusive (Beck, 1998). This makes it difficult to identify recruits likely to be predisposed to injury development and thus to confidently apply appropriate interventions to reduce the likelihood of injury. A limitation of previous studies of lower limb characteristics is that they do not typically differentiate between the metatarsals. The specific mechanism for stress fracture of individual metatarsals will likely differ, suggesting that the categorisation of all metatarsal stress fractures together when investigating anatomical characteristics associated with injury may have masked relationships. The present study therefore focuses on biomechanical variables in individuals with and without a history of third metatarsal stress fracture.

Specific lower limb anatomical characteristics previously associated with metatarsal stress fracture have included forefoot varus, limited range of ankle dorsiflexion and low or high arch height (Hughes, 1985; Simkin et al., 1989). Hughes (1985) identified that army recruits with forefoot varus were 8.3 times more likely to develop a metatarsal stress fracture than those with a neutral or valgus forefoot alignment. Hughes (1985) also identified limited passive ankle dorsi-flexion as placing individuals at a greater risk of metatarsal stress fracture. The mechanisms by which forefoot varus or ankle dorsi-flexion may contribute to the development of third metatarsal stress fracture were not explored. Regarding arch height, whilst an increased overall incidence of lower limb stress fracture has been associated with a high arched foot (Giladi et al., 1985; Brosh and Arcan, 1994), Simkin et al. (1989) found that metatarsal stress fractures were more common in military recruits with a low arched foot than in those with a normal or high arch. Thus, despite evidence relating static anatomical features to metatarsal stress fracture development, the evidence is sometimes conflicting and the mechanism(s) by which stress fractures develop at a specific site is not understood.

Whilst there is some evidence of association between static anatomical measures and metatarsal stress fracture occurrence, in order to understand the mechanism by which these may contribute to injury it is necessary to additionally investigate the resulting movement during running. For example, a common compensation for forefoot varus is rearfoot eversion during stance, suggested to result in altered distribution of load by forefoot structures (Weinfeld et al., 1997). It is therefore desirable to measure the amount of compensatory rearfoot eversion during locomotion, in addition to static forefoot varus, to allow the suggestion of cause–effect relationships. In the same way, knowledge of ankle dorsi-flexion during running gait will reveal whether restricted static range of dorsi-flexion is transferred to locomotion, possibly resulting in an early heel lift and greater loading of forefoot structures compared to an individual with sufficient ankle dorsi-flexion (Hughes, 1985).

In addition to movement patterns, there is some evidence of peak impact force being associated with stress fracture risk (Grimston et al., 1991). However, other studies have found no difference in peak impact force for stress fracture and non-stress fracture populations (Grimston et al., 1994; Bennell et al., 2004). Measurements of pressure beneath the foot during heel–toe running indicate that the metatarsal heads experience peak load during the midstance phase of ground contact (de Cock et al., 2005), highlighting the relevance of loading later than the initial impact phase when investigating metatarsal stress fracture mechanisms. When considering the specific aspects of ground reaction force likely to be associated with stress fracture to the third metatarsal, a study by Arangio et al. (1998) highlighted the importance of horizontal forces. By mathematically modelling the shear and normal stresses through the metatarsals, these authors found that the third metatarsal is less able to withstand horizontal than vertical loads. Thus, the measurement of both vertical and horizontal forces during the stance phase of running may reveal specific loading characteristics associated with stress fracture development at this site.

The aim of the present study was to compare selected static anatomical characteristics and dynamic biomechanical variables for military recruits with and without a history of third metatarsal stress fracture. Based on the literature evidence presented, it was hypothesised that recruits with previous third metatarsal stress fracture would have lower arch height, greater static forefoot varus, lower static range of ankle dorsi-flexion, lower dynamic ankle dorsi-flexion during running, greater rearfoot eversion during running, and greater stance phase ground reaction forces than recruits with no history of this injury.

2. Methods

Twenty Royal Marine recruits participated in the study. All had been forced to break their 30-week training programme due to injury or illness. Ten recruits had been diagnosed with a stress fracture of the third metatarsal and a further 10 participated as controls. Subject numbers were determined following a power analysis focussing on previously measured ranges for rearfoot

Table 1
Mean (SD) age, body mass and week at which training stopped for the stress fracture and control subject groups

	Stress fracture subjects	Controls
Age (years)	20.9 (2.5)	23.0 (4.6)
Body mass (kg)	75.0 (6.1)	77.7 (5.1)
Training week	18.6 (5.7)	22.3 (3.9)

movement and ankle dorsi-flexion during running, with a statistical power requirement of 90%. Control subjects had interrupted their training due to an illness or minor injury of the upper extremity that was believed not to influence their lower extremity function. At the time of data collection, all subjects had been cleared to return to full training. Monitoring of the control subjects when they returned to training revealed that all of these subjects completed the 30-week training without development of a stress fracture. Mean (SD) subject age, body mass and training week reached prior to breaking from training are presented in Table 1.

Each subject underwent a podiatry assessment performed by a registered podiatrist. This involved the measurement of peak range of ankle dorsi-flexion, forefoot varus/valgus angle, relaxed standing calcaneal angle, and arch height ratio—calculated as ratio of navicular height to truncated foot length. Ankle dorsiflexion range was assessed in the prone position, using a goniometer to measure the dorsi-flexion angle. The forefoot varus/valgus angle was measured with the foot in its neutral position. One arm of the goniometer was placed along the plantar aspect of the metatarsal heads and the other arm perpendicular to the orientation of the neutral calcaneus. Zero degrees indicated a neutral forefoot, an inverted forefoot indicated a forefoot varus and an everted forefoot a forefoot valgus. For the purposes of this study, a forefoot varus was indicated by a positive sign and valgus by a negative sign. A line was drawn to bisect the calcaneus and the subject was then asked to stand in a relaxed position. The relaxed standing calcaneal angle was measured relative to the floor. For this relaxed standing position, the height of the navicular and truncated foot length were also measured. Arch height ratio was calculated by dividing the navicular height by the truncated foot length. For each of these variables, three to five measurements were taken and the average used to represent the subject's value for each side of the body. A separate investigation of intraoperator reliability by consideration of root mean square deviation (RMSD) about the mean of 10 repeat measurements provided RMSD values of 0.8° for forefoot varus/valgus angle, 0.4° for standing calcaneal angle, 2.1° for peak dorsi-flexion and 1.0 for truncated foot length.

Each subject also performed running trials in the laboratory, for the collection of synchronised ground reaction force and kinematic data. A total of 20 barefoot trials and 20 trials in military boots were performed, where both sides of the body were assessed for 10 trials for each of these conditions. Force plate data were collected at 960 Hz using an AMTI force plate (AMTI, Watertown, MA, USA), whilst three-dimensional kinematic data were collected at 120 Hz using a Peak realtime system (Peak Technologies, Centennial, CO, USA). All kinematic data were smoothed using a quintic spline function (Woltring, 1985). Data were collected for the right and left sides separately, with the investigators blind to the injury side for the stress fracture subjects. For the side being assessed, three reflective markers were placed on each of the foot/boot, lower leg and thigh segments. These markers were used to monitor the three-dimensional orientation of the lower extremity segments and also to define a joint co-ordinate system for the ankle and knee joints. All angles were referenced to a relaxed standing position. A relaxed standing position was selected following evidence that the rearfoot operates about a "neutral" position found to be the resting standing angle, rather than the subtalar neutral position (McPoil and Cornwall, 1994). Running trials were performed at 8 miles h^{-1} (±5%), with average running speed monitored using photocells placed at hip height 1 m either side of the centre of a force plate. Subjects were asked to strike the force plate with the foot of the side under assessment, and were given sufficient practice trials for familiarisation with the test environment before commencement of data collection. Any trials outside of the stated running speed or requiring adjustments in stride to make contact with the plate were discarded and repeated.

For each running trial, ankle dorsi-plantar flexion and subtalar inversion–eversion were monitored. The peak angle during the stance phase was identified for comparison between study groups. Vertical ground reaction force data were characterised using magnitude of peak impact force, peak rate of loading of impact force and peak active force. Horizontal ground reaction force was characterised using the peak resultant horizontal force magnitudes during the braking and propulsion phases (contributed to by the anterior–posterior and medial–lateral force components, Fig. 1) and the angle of application of this force during braking and propulsion. The initial "impact" force observed for some subjects, as illustrated in Fig. 1(ii), was not used in the characterisation of horizontal force since the metatarsals would not typically have made ground contact at this stage of the loading. Application angle was defined as the angle of the resultant horizontal force (resultant of the anterior–posterior and medial–lateral force components) relative to the sagittal plane, with a negative angle indicating a medially applied force by the subject. For each subject, the average of 10 running trials was used to provide representative data for barefoot and shod running for the left and right sides. For subjects of the

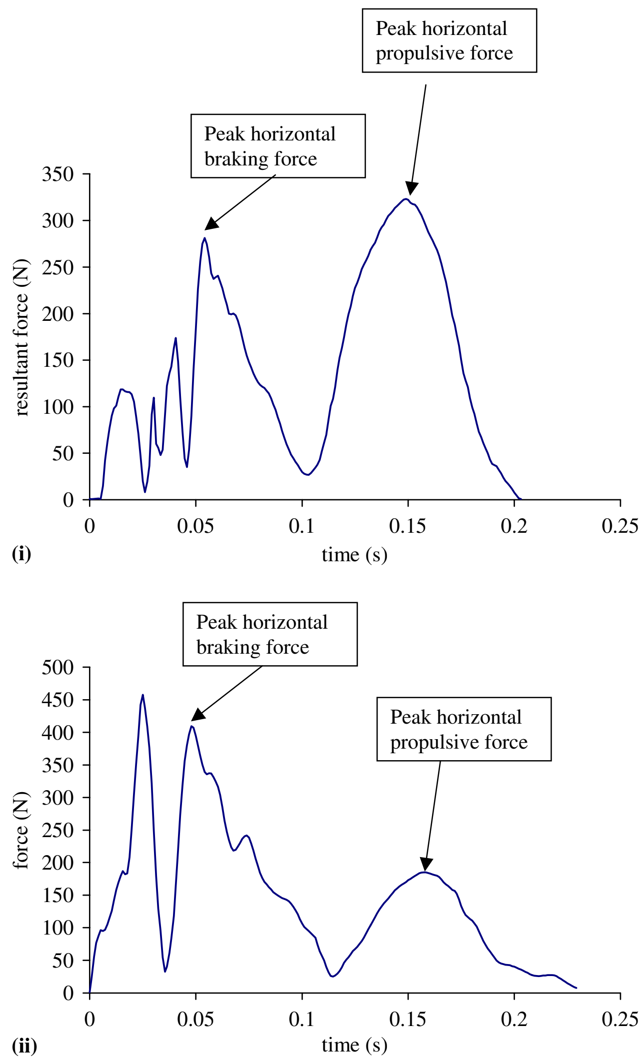

Fig. 1. Sample time-histories for the resultant horizontal ground reaction force, indicating the peak forces during braking and propulsion.

stress fracture group, the previously injured side was selected for analysis. For the control group, each subject was matched with an injury group subject based on body weight and time in training. The same side of the body was analysed for the control as for the matched injury group subject. Mann–Whitney U tests were used to detect significant differences in static variables between the stress facture and control groups ($P < 0.05$). Independent t-tests were used to compare dynamic biomechanical variables ($P < 0.05$).

3. Results

The static data, presented in Table 2, highlight small and non-significant differences between groups regarding navicular height, arch height ratio and relaxed calcaneal standing angle. The greater forefoot varus and

Table 2
Group median (interquartile range) for navicular height, arch height ratio, relaxed standing calcaneal angle, forefoot angle and ankle dorsi-flexion, with P values

Structural measures	Stress fracture subjects	Controls	P
Navicular height (mm)[a]	45.0 (36.0–55.0)	44.3 (34.3–60.0)	0.38
Arch height ratio[a]	0.20 (0.17–0.23)	0.23 (0.17–0.25)	0.22
Relaxed standing calcaneal angle (°)[a]	2.7 (−2.3–6.0)	4.7 (−3.0–5.7)	0.44
Forefoot varus/valgus angle (°)[b]	8.5 (0–10.0)	4.7 (3.0–6.0)	0.07
Peak ankle dorsi-flexion (°)[b]	5.8 (4.0–9.2)	8.8 (6.4–9.8)	0.16

[a] Measured in 50% weight bearing (standing).
[b] Measured in non-weight bearing.

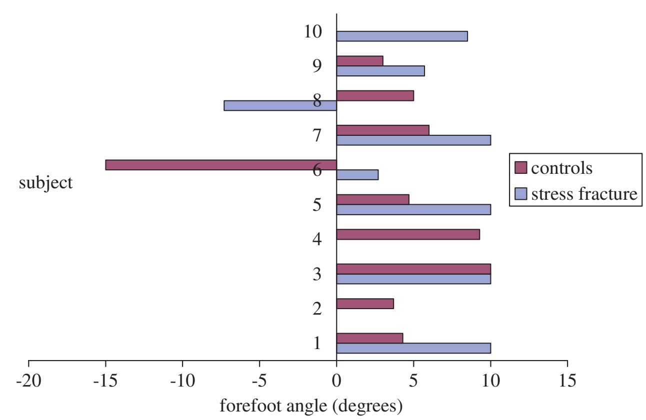

Fig. 2. Forefoot varus/valgus angle for each of the control and stress fracture subjects.

lower range of ankle dorsi-flexion for the injured side compared with matched controls is as anticipated, but these differences were not found to be significantly different ($P > 0.05$). Individual subject data for forefoot varus/valgus angle are illustrated in Fig. 2, showing the large variation between study subjects.

For the running movement data, shown in Table 3, small and non-significant differences are highlighted between groups for peak eversion ($P > 0.05$). The time of peak eversion was found to be earlier for the stress fracture group than for the matched controls, with this difference being significant when running in boots ($P < 0.05$). Whilst the peak ankle dorsi-flexion is consistently lower for the injured side compared with the matched control group and this peak also occurs later for the injury subjects than for the matched controls, none of these differences in ankle dorsi-flexion were found to be statistically significant ($P > 0.05$).

The ground reaction force data, provided in Table 4, indicate a number of significant differences between study groups during the stance phase. For both barefoot

Table 3
Group mean values (SD) for dynamic movement data during running barefoot and in boots for the third metatarsal stress fracture group injured and controls, with P values

Kinematic variable	Barefoot			Boots		
	Stress fracture subjects	Controls	P	Stress fracture subjects	Controls	P
Peak eversion (°)	3.0 (3.0)	3.6 (4.1)	0.34	7.7 (4.1)	7.7 (2.5)	0.44
Peak eversion time (%)	29.6 (6.0)	35.3 (11.2)	0.09	39.7 (6.5)	45.6 (7.1)	0.03*
Peak ankle dorsi-flexion (°)	9.5 (2.9)	11.3 (3.8)	0.20	14.8 (3.2)	16.4 (3.2)	0.13
Peak dorsi-flexion time (%)	54.9 (8.9)	54.1 (4.7)	0.36	59.5 (6.2)	56.8 (2.5)	0.09

* Significant difference from matched controls ($P < 0.05$).

Table 4
Group mean values (SD) for ground reaction force data for running barefoot and in boots, with P values

Ground reaction force variable	Barefoot			Boots		
	Stress fracture subjects	Controls	P	Stress fracture subjects	Controls	P
Impact peak (BW)	2.20 (0.56)	2.30 (0.39)	0.33	1.93 (0.43)	1.88 (0.30)	0.38
Peak loading rate (BW s^{-1})	465 (147)	406 (164)	0.20	156 (54)	178 (49)	0.19
Active peak (BW)	2.46 (0.33)	2.58 (0.16)	0.15	2.69 (0.33)	2.72 (0.22)	0.40
Peak resultant horizontal braking force (BW)	0.34 (0.08)	0.38 (0.05)	0.14	0.38 (0.08)	0.41 (0.05)	0.21
Peak resultant horizontal propulsive force (BW)	0.27 (0.05)	0.32 (0.03)	0.02*	0.28 (0.06)	0.33 (0.07)	0.05
Angle of peak horizontal braking force (°)	7.8 (8.5)	5.6 (4.8)	0.24	13.1 (6.3)	6.4 (6.7)	0.02*
Angle of peak horizontal propulsion force (°)	−3.2 (7.3)	−7.3 (8.4)	0.13	−4.4 (7.0)	−7.4 (8.2)	0.20

* Significant difference from matched controls ($P < 0.05$).

and shod running, no significant differences were detected between groups for magnitude of peak vertical impact force, peak rate of loading of vertical force, and peak active vertical force ($P > 0.05$). One of the control subjects did not demonstrate a clear impact peak in ground reaction force when running barefoot, and so was not included in the analysis of peak impact force variables. For the horizontal ground reaction force data, no significant differences were detected in magnitude or time of occurrence of peak resultant horizontal force during the braking phase ($P > 0.05$). However, the angle of application of peak resultant horizontal force during braking was directed more laterally for the injury subjects compared with matched controls, when running barefoot and when running in boots, with this difference being significant when running in boots ($P < 0.05$). During the propulsive phase, the magnitude of peak resultant horizontal propulsive force for barefoot running was significantly lower for the stress fracture group than for the controls ($P < 0.05$).

4. Discussion

The results of the present study highlight differences between a third metatarsal stress fracture and a control group in a number of dynamic biomechanical variables. Regarding static anatomical variations, no significant differences between study groups have been identified. It is acknowledged that the relatively low subject numbers used in this study limit the drawing of definitive conclusions regarding the role of specific variables in stress fracture risk. This is particularly true where the study findings conflict with those of previous investigations. For example, for arch height, the expected lower arch foot for individuals with third metatarsal stress fracture is not observed in the data of the present study. This is in contrast to a previous study demonstrating that a low arch may predispose an individual to the development of metatarsal stress fractures (Simkin et al., 1989). It is possible that, since the present study specifically considers third metatarsal stress fractures, this discrepancy between studies is a result of the mechanism of third metatarsal stress fracture differing to that of other metatarsals. This is supported by the observation that the second metatarsal, rather than the third, is the most commonly studied (Brukner et al., 1999). However, since the findings of the present study differ from those previously presented and are based on low subject numbers, arch height ratio should not be discounted as a possible indicator of susceptibility to third metatarsal stress fracture development.

A restricted ankle dorsi-flexion has previously been identified as a likely contributor to the development of metatarsal stress fractures (Hughes, 1985). Limited ankle dorsi-flexion range of motion has also been suspected of localising pressures on the forefoot (Lin et al., 1996). Whilst the present data have shown no significant differences in static range of ankle dorsi-flexion for third metatarsal stress fracture individuals compared with controls, values are lower for the stress fracture group. The possibility of a restricted ankle dorsi-flexion being transferred to locomotion has been monitored in the present study using dynamic ankle dorsi-plantar flexion data. Although differences were not found to be significant, the peak ankle dorsi-flexion for the stress fracture group was found to be lower than for the matched controls for both barefoot running and running in boots. As these observations of low static range and dynamic ankle dorsi-flexion are consistent with literature suggestions (Hughes, 1985; Lin et al., 1996), the non-significant differences in ankle dorsi-flexion observed in the present study should not be used to discount this variable as a possible contributor to third metatarsal stress fracture development.

The observation of no significant difference in forefoot angle does not support the expectation of a greater forefoot varus for the third metatarsal stress fracture group. The consideration of individual subject data, illustrated in Fig. 2, indicates that the majority of subjects in both groups are classified as having a forefoot varus. A large difference across subjects in the forefoot angle is also highlighted, with values ranging from 10° of forefoot varus to 7.3° forefoot valgus (represented as −7.3°). This large variability between subjects is consistent with previous literature (Cornwall et al., 2004a). Whilst Van Gheluwe et al. (2002) observed high inter-rater ICC's of 0.62 for this variable, it has generally been highlighted that this variable is particularly susceptible to low inter-rater reliability (Cornwall et al., 2004b), hindering the use of this variable to indicate stress fracture risk.

The influence of forefoot deformity on loading of the metatarsals will be influenced by the degree and method of compensation for this anatomical orientation. To accommodate a forefoot varus when standing, a common compensation is to adopt a valgus angle of the calcaneus to allow the medial metatarsals to contact the ground (Weinfeld et al., 1997). For the subjects of the present study, no significant differences were identified for the standing calcaneal angle, suggesting that this compensation for forefoot deformity does not differ for the study groups. Thus, there is no evidence provided in the present study to suggest that those individuals who have experienced a stress fracture of the third metatarsal have different compensation to forefoot deformity when standing. The low confidence in this measure for different practitioners and the observation of no significant difference between populations in this study, suggest that this variable is not a reliable indicator of third metatarsal stress fracture risk.

The running data of the present study have highlighted that those with previous third metatarsal stress fracture have a significantly earlier occurrence of peak rearfoot eversion when running in boots, at 39.7% stance time compared with 45.6% for the controls. Thus, although standing rearfoot angles are similar for the two study groups, there appears to be a functional difference between groups when running. In relation to stress fracture risk, the relatively early occurrence of peak eversion may be related to an earlier attainment of flat foot and a greater period in the propulsion phase. Whilst the heel area experiences relatively high peak pressures in walking, it has been demonstrated that the highest localised plantar pressures during running typically occur at the metatarsal heads, with the highest loading on the area of the second metatarsal head, closely followed by the first and third metatarsal heads (Pink and Jobe, 1997; de Cock et al., 2005). In addition, these forefoot areas have been found to bear the pressure over a longer time period than other areas of the foot (Pink and Jobe, 1997). For the metatarsal stress fracture group of the present study, the earlier attainment of peak eversion may indicate an increase in the time period over which the metatarsal heads are loaded, resulting in an increased load being experienced by the metatarsal shafts. With the increased application of pressure-measuring systems to study human locomotion, it will be possible to test this hypothesis in future study of stress fracture risk factors.

The vertical ground reaction force data of the present study have failed to highlight any notable differences between the stress fracture group and their matched controls, during impact and propulsion. However, significant differences have been detected in the horizontal loading during braking and propulsion. Whilst horizontal ground reaction force data, particularly the anterior–posterior braking/propulsion force, have been reported in previous studies of stress fracture risk (Bennell et al., 2004), resultant horizontal force and the angle of application of this force have not previously been focussed on. The greater angle of braking horizontal force detected in the present study, indicating a more laterally applied horizontal force by the subject at this time, suggests that the braking phase of ground contact is important in the development of this injury. Arangio et al. (1998) reported that the third metatarsal is less able to withstand horizontal than vertical loads, leading to the focus on this aspect in the present study. It is suggested that the more laterally applied braking force will subject the metatarsal to transverse bending loads that this structure is not well able to withstand. Since ground reaction force data do not measure direct loads on the bone, a modelling approach incorporating metatarsal anatomical data is suggested for more detailed future investigation.

Although the peak impact force has most commonly been focussed on in injury studies, the peak loads experienced by muscles and joints of the body typically occur later in the stance phase when the forefoot is in contact with the ground (Scott and Winter, 1990), suggesting peak load on bone occurs beyond the initial impact phase. A recent paper by de Cock et al. (2005) has described in detail the loading pattern of the foot during running using plantar pressure data. These authors reported that first contact with the ground for the forefoot occurs at around 8% total stance time and that the entire forefoot is flat on the ground before 20% of stance. This indicates that the metatarsal heads are loaded when peak resultant horizontal braking force occurs (at around 20% stance time, Fig. 1). The different angle of application of this braking force for the injury group compared with their matched controls may therefore indicate a difference in the braking function of the forefoot as it initially contacts the ground, thus potentially influencing the direction of loading on the third metatarsal. This suggestion that the braking phase is relevant when considering the mechanism of third metatarsal stress fracture further highlights the importance of considering forefoot structure and function when investigating the development of this injury. It is therefore suggested that, although significant differences in forefoot varus have not been identified in the present study, that differences in forefoot function should be investigated further using plantar pressure data collected during running.

The cause of the lower magnitude for peak resultant horizontal force during the propulsion phase of barefoot running observed for the stress fracture group is not clear. It is possible that the propulsion function is restricted in subjects at higher risk of third metatarsal stress fracture. However, there is also the possibility that the previous injury has influenced the forefoot function, reducing the effectiveness of the forefoot during this phase of stance. This highlights the inherent limitations of the retrospective design of the present investigation. Owing to the retrospective study design, it is not possible to say whether any biomechanical differences have contributed to the occurrence of stress fractures or are an adaptation following the previous stress fracture. Despite this limitation, this retrospective cross-sectional study has allowed the identification of variables differing between third metatarsal stress fracture and previously uninjured subjects, thus informing the choice of study variables for a future prospective study. In addition to the static variables of arch height ratio and ankle dorsi-flexion, which have previously been linked with metatarsal stress fracture risk, the future study will include the dynamic variables of ground reaction force, plantar pressure, peak ankle dorsi-flexion and timing of rearfoot eversion. Methods for modelling of the forefoot to allow estimation of third metatarsal loading will also be investigated, to further the understanding of the mechanism of this injury development.

5. Conclusion

The observation in the present study of significant differences in dynamic biomechanical variables between those with a history of third metatarsal stress fracture and a control group, even in this relatively small data set, supports the inclusion of dynamic variables in the future study of possible indicators of stress fracture risk. In particular, magnitude and angle of horizontal force warrant more consideration than previously given. Ultimately, the results of a planned prospective study measuring variables selected based on the present study findings, will be used to inform the screening of Royal Marine recruits for stress fracture risk. With the support of prospective study results, it will be possible to investigate suitable interventions to influence loading. Based on the earlier occurrence of peak rearfoot eversion for the stress fracture group, suggested to result in an earlier loading of forefoot structures, and the observation of significant differences in horizontal loading during stance, it is anticipated that differences will be observed in forefoot loading. Thus, interventions are likely to focus on this period of stance. The results of the present study regarding the braking and propulsion phases of stance support the inclusion of plantar pressure measurement in the planned prospective study, which should also inform the selection of appropriate interventions.

Acknowledgement

The authors acknowledge Kate McNally BSc(pod), SRCh, MChS and Jonathon Palmer BSc(pod), SRCh, MChS for contributions to data collection.

References

Arangio, G.A., Beam, H., Kowalczyk, G., Salathe, E.P., 1998. Analysis of stress in the metatarsals. Foot and Ankle Surgery 4, 123–128.

Beck, B.R., 1998. Tibial stress injuries. An Aetiological review for the purposes of guiding management. Sports Medicine 26, 265–279.

Bennell, K., Crossley, K., Jayarajan, J., et al., 2004. Ground reaction forces and bone parameters in females with tibial stress fracture. Medicine and Science in Sports and Exercise 36, 397–404.

Brosh, T., Arcan, M., 1994. Toward early detection of the tendency to stress fractures. Clinical Biomechanics 9, 111–116.

Brukner, P., Bennell, K., Matheson, G., 1999. Stress fractures of the foot and ankle. In: Stress Fractures. Blackwell Science, Asia, pp. 163–186, Chapter 10.

Cornwall, M.W., McPoil, T.G., Frishco, W.D., Hunt, L., Lane, C., O'Donnell, D., 2004a. The relationship between forefoot alignment and rearfoot motion during walking. Australasian Journal of Podiatric Medicine 38, 35–40.

Cornwall, M.W., McPoil, T.G., Fishco, W.D., Hunt, L., Lane, C., O'Donnell, D., 2004b. Reliability of visual measurement of forefoot alignment. Foot and Ankle International 25, 745–748.

de Cock, A., de Clercq, D., Willems, T., Witvrouw, E., 2005. Temporal characteristics of foot roll-over during barefoot jogging: reference data for young adults. Gait and Posture 21, 432–439.

Evans, G.W.L., 1982. Stress fractures at Commando Training Centre Royal Marines, Lympstone—a retrospective survey. Journal of the Royal Navy Medical Service 68, 77–81.

Giladi, M., Milgrom, C., Stein, M., et al., 1985. The low arch, a protective factor in stress fractures: a prospective study of 295 military recruits. Orthopaedic Review 14, 709–712.

Grimston, S.K., Engsberg, J.R., Kloiber, R., Hanley, D.A., 1991. Bone mass, external loads and stress fractures in female runners. International Journal of Sports Biomechanics 7, 293–302.

Grimston, S.K., Nigg, B.M., Fisher, V., Ajemian, S.V., 1994. External loads throughout a 45-minute run in stress fracture and non-stress fracture runners. Journal of Biomechanics 27, 668.

Hughes, L.Y., 1985. Biomechanical analysis of foot and ankle predisposition to developing stress fractures. Journal of Orthopaedic and Sports Physical Therapy 7, 96–101.

Lin, S.S., Lee, T.H., Wapner, K.L., 1996. Plantar forefoot ulceration with equinus deformity of the ankle in diabetic patients: the effect of tendo-Achilles lengthening and total contact casting. Orthopedics 19, 465–475.

McPoil, T.G., Cornwall, M.W., 1994. Relationship between neutral subtalar position and pattern of rearfoot motion during walking. Foot and Ankle International 15, 141–145.

Meurmann, K.O.A., 1981. Less common stress fractures in the foot. British Journal of Radiology 54, 1–6.

Pester, S., Smith, P.C., 1992. Stress fractures in the lower extremities of soldiers in basic training. Orthopaedic Review 21, 297–303.

Pink, M., Jobe, F.W., 1997. The foot/shoe interface. In: Guten, G.N. (Ed.), Running Injuries. W.B. Saunders Company, Philadelphia, pp. 20–29, Chapter 3.

Riddell, D.I., 1989. Rehabilitation of injured Royal Marine recruits. Journal of the Royal Navy Medical Service 75, 171–176.

Ross, R., Allsopp, A.J., 2002. Stress fractures in Royal Marine recruits. Military Medicine 167, 560–567.

Scott, S.H., Winter, D.A., 1990. Internal forces at chronic running injury sites. Medicine and Science in Sports and Exercise 22, 357–369.

Simkin, A., Leichter, I., Giladi, M., et al., 1989. Combined effect of foot arch structure and an orthotic device on stress fractures. Foot and Ankle 10, 25–29.

Van Gheluwe, B., Kirby, K.A., Roosen, P., Phillips, R.D., 2002. Reliability and accuracy of biomechanical measurements of the lower extremities. Journal of the American Pediatric Medical Association 92, 317–326.

Weinfeld, S.B., Haddad, S.L., Myerson, M.S., 1997. Metatarsal stress fractures. Clinics in Sports Medicine 16, 319–338.

Woltring, H.J., 1985. On optimal smoothing and derivative estimation from noisy displacement data in biomechanics. Human Movement Science 4 (3), 229–245.