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“Four biomechanical and anthropometric measures predict tibial stress fracture: A prospective study of 1065 Royal Marines”

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Michael Nunns: Involved in study design, data collection and analysis, main author of manuscript.

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**ABSTRACT** (181 words)

Background: Tibial stress fractures cause a significant burden to Royal Marines recruits. No prospective running gait analyses have previously been performed in military settings.

Aim: We aimed to identify biomechanical gait factors and anthropometric variables associated with increased risk of TSF.

Methods: 1065 Royal Marines recruits were assessed in week-2 of training. Bilateral plantar pressure and 3D lower limb kinematics were obtained for barefoot running at 3.6 m.s-1, providing dynamic arch index, peak heel pressure and lower limb joint angles. Age, bimalleolar breadth, calf girth, passive hip internal/external range of motion and body mass index (BMI) were also recorded. Ten recruits who sustained a TSF during training were compared with 120 recruits who completed training injury-free using a binary logistic regression model to identify injury risk factors.

Results: Four variables significantly (p<0.05) predicted increased risk of TSF (odds ratios and 95% CI): smaller bimalleolar width (0.73, 0.58-0.93), lower BMI (0.56, 0.33-0.95), greater peak heel pressure (1.25, 1.07-1.46) and lower range of tibial rotation (0.78, 0.63-0.96).

Summary: Reduced impact attenuation and ability to withstand load were implicated in tibial stress fracture risk.

*What are the new findings?*

*-- Risk of tibial stress fracture was associated with reduced ability to withstand load (lower BMI and narrower bimalleolar breadth), and reduced impact attenuation (higher peak pressures at the heel, lower range of tibial rotation).*

**INTRODUCTION**

The 32-week continuous training programme for Royal Marines recruits involves running, marching and jumping, over a range of exercise intensities and durations, over differing terrain, and carrying various loads. Between 2004-2008, 5% of Royal Marines recruits experienced a lower limb stress fracture, with tibial stress fractures accounting for around 25% of these[1]. Injured recruits require an average of 21 weeks (range 10-47 weeks) before returning to full training[1]. Stress fracture development is generally influenced by the ability of bone to withstand load, and the characteristics of the applied load. Risk factors include younger age[2] and lower lean muscle mass as indicated by lower BMI in individuals with low body fat[3, 4]. Smaller tibial cross-sectional area, resulting in a lower area moment of inertia[3] and lower calf circumference, linked with reduced ability to resist tibial bending[3] have been associated with tibial stress fracture occurrence. Excessive passive external hip rotation, leading to increased tibial rotation during gait[5]; the reduction in impact force attenuation linked to pes cavus[6] and excessively high[7] or limited[8] rearfoot movement, suggested to increase tibial rotation or reduce impact attenuation respectively, are also risk factors.

Although the magnitude and loading rate of the external load is of interest in tibial stress fracture aetiology, evidence linking these variables with tibial stress fracture is equivocal[9]. The use of ground reaction force data to quantify external load does not account for the ability of individuals to detect and attenuate potentially damaging loads. Such a response is in evidence when barefoot runners adapt their footstrike to reduce potentially painful local plantar pressures[10-12]. While the ability to manage lower limb loading during Royal Marines training is likely to be an important determinant of injury risk, ground reaction force data represent the acceleration of the whole body towards the ground, and do not provide data on heel loading specifically[13]. The examination of peak plantar heel pressures may provide a more valid indication of whether participants are able to attenuate plantar heel forces effectively during running.

We aimed to prospectively identify anthropometric and running gait characteristics that predispose certain Royal Marines recruits to tibial stress fracture, compared with recruits who complete training without sustaining an injury. It was expected that younger age, lower body mass and BMI, narrower tibial width (bimalleolar distance) and lower calf muscle mass (calf circumference), would be associated with increased tibial stress fracture risk. Additionally, it was expected that greater passive external hip rotation and plantar heel pressures, and a lower dynamic arch index (indicating a higher-arched foot) and lower tibial rotation, would be associated with greater tibial stress fracture risk.

**METHODS**

**Sample**

Following ethical approval by the Ministry of Defence Research Ethics Committee, data collection occurred between September 2010 and June 2012 at the Commando Training Centre Royal Marines (CTCRM), Lympstone, Devon, UK. Volunteer recruits provided informed consent and attended testing on day-8 or 9 of the 32-week training programme. In total, 1065 recruits of the 1504 that initially enrolled to training during the study period were assessed (71%). Subsequently, recruits reporting lower limb pain during the training period were examined by CTCRM medical staff, and the presence of tibial stress fracture was confirmed by positive MRI scan. Ten tibial stress fracture cases occurred amongst the study cohort (0.9%), 5 affecting the proximal third of the tibia, 3 the middle third and 2 the distal third. The injury-free group was populated from the 419 recruits who completed training without injury. To determine a suitable injury-free group size, a stability analysis was performed, revealing that stable, representative data would be obtained from a group containing 120 individuals[14]. To obtain 120 complete sets of data, 150 recruits were analysed. Thus, the 10 tibial stress fracture cases were compared with an injury-free group of 150.

**Procedure**

Testing took place at an on-site facility at CTCRM. Recruit height and body mass were obtained in shorts and t-shirt using standard techniques, from which BMI was determined. Calf circumference was measured at the site of maximum circumference and corrected for subcutaneous fat mass by subtracting the calf skinfold thickness[15]. Measurements were made to the nearest mm, and the average of three measurements was reported. External hip range of motion was assessed using a fluid goniometer, with the participant in a seated position with the hip flexed at 90 degrees[16]. Values were reported to the nearest degree until three values within 5° had been obtained for each leg. The mean of these three values was reported for each recruit.

Participants were required to run barefoot at 3.6 m.s-1 (± 5%) over a 2 m pressure plate (RSScan International, Belgium, 2 m x 0.4 m x 0.02 m, 16,384 resistive sensors, 200 Hz, 10 sensors/4 cm2) set within an EVA runway (0.02 m thick, hardness rating of 65 Shore A) covered by a thin rubber mat with a total carpeted length of 15 m. Synchronised bilateral 3D kinematic data were obtained at 200 Hz using two aligned Coda mpx30 units (Charnwood Dynamics Ltd., Leicestershire, UK). To encourage recruits’ ‘usual’ running style, habituation trials were completed prior to data collection. The observation that 77% of recruits adopted a heel strike pattern in the study sample[17], a figure similar to the distribution previously observed in shod runners[18,19], indicates successful habituation. Five acceptable running trials and one relaxed standing trial were recorded per recruit. Trials were deemed acceptable if all markers were tracked, consecutive footsteps occurred within the 2 m pressure plate without unnatural stride adjustment, and the target running velocity was achieved.

For the assessment of bilateral 3D kinematics, a joint coordinate system was defined based on the principles established by Grood and Suntay[20] and Soutas-Little et al.[21]. Joint coordinates were obtained using three active markers placed non-collinearly on the thigh (greater trochanter, medial and lateral femoral epicondyles), shank (anterior and posterior aspects of the shank, below the level of the calf muscle belly; lateral malleolus) and foot (superior and inferior posterior calcaneous markers; top of the foot, superior to the proximal end of the third metatarsal). Raw coordinate data were exported from Codamotion software and filtered using a 12 Hz recursive fourth-order low-pass Butterworth filter. Tibial rotation range of motion was calculated as the difference between peak internal and external rotation. Filtering and angle calculations were performed in Matlab (v2008a, The Mathworks, US).

For the analysis of plantar pressure data, the medial and lateral heel and midfoot were identified as the regions of interest using zone analysis as described previously [22]. Dynamic arch function was assessed using the midfoot surface contact area[23], defined as the percentage of the contacting surface occurring within the midfoot zone (arch index). The peak pressure was recorded at the medial heel and lateral heel regions and the mean of these two values was used to represent peak heel loading.

**Statistical analysis**

For each participant included in the analysis, mean values for each variable were included in the group analysis. Data from the 10 injured legs were compared with that from one leg of each of the 150 participants in the injury-free group. Initial two-tailed independent *t*-tests were used to identify differences between the TSF and injury-free groups using an alpha level of 0.05.

Each potential variable was tested in separate binary logistic regression models to assess their eligibility to be included in a fully adjusted model. Individually significant variables were included in the combined binary logistic regression model before being discarded or retained based on significance value. All statistical analyses were performed using Stata version 13.1 (StataCorp. 2013. Stata Statistical Software: Release 13. College Station, TX: StataCorp LP).

**RESULTS**

The mean and standard deviation of each variable, with the result of independent t-tests of between group differences are presented in Table 1. Significant between-group unadjusted mean differences were observed for BMI, calf girth, bimalleolar width and tibial rotation.

Table 1. The group mean (SD) for variables compared between the tibial stress fracture and injury-free groups. The results of two-tailed independent t-tests are presented for each variable.

|  |  |  |  |
| --- | --- | --- | --- |
| Variable | Tibial stress fracture | Injury-free | *P* |
| Age  (years) | 19.70  (2.00) | 21.38  (3.02) | .086 |
| Arch index  (%) | 23.52  (6.60) | 21.97  (4.63) | .327 |
| Bimalleolar width  (mm) | 68.40  (3.50) | 72.24  (4.64) | .011\* |
| BMI  (kg.m2) | 22.77  (1.68) | 24.36  (1.85) | .010\* |
| Corrected calf girth  (mm) | 352.81  (15.34) | 368.11  (18.94) | .014\* |
| EHR  (o) | 26.60  (8.54) | 25.76  (6.77) | .711 |
| Height  (m) | 1.79  (0.08) | 1.78  (0.05) | .373 |
| IHR  (o) | 24.80  (6.70) | 26.58  (7.75) | .480 |
| Mass  (kg) | 74.27  (6.82) | 76.67  (6.62) | .139 |
| Peak heel pressure  (N.cm-2) | 20.81  (6.83) | 17.69  (4.75) | .056 |
| Tibial rotation  (o) | 6.41  (4.30) | 10.32  (5.99) | .045\* |

*P* = statistical significance from independent samples *t*-test; \* = significant difference between groups (p<0.05). EHR = external hip rotation; IHR = internal hip rotation

Results from the binary logistic regression model are presented in Table 2. The model improved from the null model by a log likelihood ratio of [2\*({-34.25} – {-20.40})] = -27.70 with a χ2 probability of p<0.001. In an adjusted model, after discarding the insignificant predictor variables, BMI, bimalleolar width, tibial rotation and heel pressure remained significant. A unit decrease in BMI was associated with 1.79 times the likelihood of having a TSF (p<0.05). The odds ratio for a TSF was 1.37 times higher when bimalleolar width was one millimetre lower (p<0.01). The odds ratio for a TSF was 1.28 times higher when tibial rotation reduced by one degree (p<0.05). The odds ratio for a TSF was 1.25 times higher when peak heel pressure increased by one N.cm-2 (p<0.001).

Since logistic regression models parameterise log of the odds as a linear function of the predictor variables, the estimated effects do not remain linear across the fitted curve when back transformed into a probability scale. Each of the predictor independent variables was examined to determine the threshold value at which a significantly increased risk of TSF would be likely to occur. The threshold levels are presented in Table 2, and Figure 1, showing the predicted probability of TSF against the variables in the model.

Table 2. Results of binary logistic regression analysis of variables which significantly predict tibial stress fracture. Odds ratios and 95% confidence intervals are presented for each variable in the model, with the suggested threshold for avoiding TSF also included.

|  |  |  |
| --- | --- | --- |
| Predictor variable | Odds ratio (95% CI) | Threshold for avoiding TSF |
| Bimalleolar width | 0.73 (0.58 – 0.93)\*\* | >74 mm |
| BMI | 0.56 (0.33 – 0.95)\* | >25 kg.m-2 |
| Peak heel pressure | 1.25 (1.07 – 1.46)\*\* | <13 N.cm-2 |
| Tibial range of motion | 0.78 (0.63 – 0.96)\* | >13 degrees |
| \*denotes p<0.05; \*\*denotes p<0.01; \*\*\*denotes p<0.001 | |  |

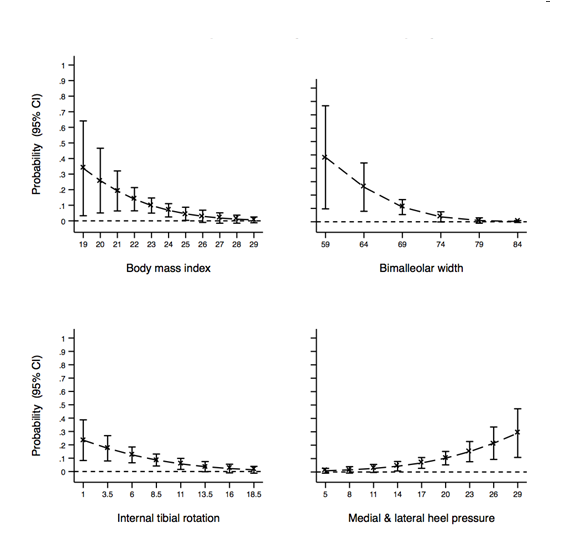
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Figure 1. Predicted probability of suffering a tibial stress fracture for given ranges of each significant predictor variable. For each specified value of the variables presented, the probability of TSF is shown, with 95% confidence intervals represented by error bars.

**DISCUSSION**

In this first study to include running gait assessment as part of a prospective cohort design investigating stress fracture risk factors in a military setting, we identified bimalleolar width, BMI, peak heel pressure and tibial range of motion as predicting tibial stress fracture in Royal Marines recruits. Our data suggest that characteristics associated with the ability of individuals to attenuate impact and resist tibial bending are important determinants of tibial stress fracture susceptibility.

***Anthropometric variables***

Youth has been demonstrated to be a risk factor for tibial stress fracture in military recruits previously[2], possibly due to the presence of growth plates which may reduce the local stiffness of bone[24]. Despite a non-significant result for age in either univariate or multivariate analysis, a mean difference of 19 months between the tibial stress fracture and injury-free groups, and examination of the distribution of cases suggest that age may be linked with tibial stress fracture risk. The minimum age for entry into Royal Marines training is 16, therefore a number of recruits are still years away from accruing peak bone mass, which typically occurs in the late twenties[25], however age was not able to predict risk of tibial stress fracture in the present population.

BMI was lower in tibial stress fracture cases compared to controls, and a significant predictor of injury. Although higher BMI and associated fatness[26,27] has been associated with increased bone mineral density in the general population, Ode, Pivarnik, Reeves & Knous[28] suggest that this measure is not an accurate predictor of fatness in athletes. Royal Marines recruits require a relatively high level of physical fitness upon entry to training, such that greater BMI in this population indicates increased lean muscle mass[29]. Lean muscle mass is the most important determinant of bone mineral density[30]. Lower bone mineral density has been linked directly with more rapid microcrack propagation[31] and has been identified as a risk factor for tibial stress fracture in RM recruits[32].

Lower calf muscle mass correlates with lower values for tibial bone mineral density[4], thus the lower BMI observed in tibial stress fracture cases in the present study and the associated lower calf muscle mass could indicate reduced tibial bone strength in these individuals. The contraction of the calf musculature stimulates bone remodelling, and additionally plays an important role in reducing bending moments acting on the tibia[33]. Lower calf circumference in the tibial stress fracture group (p<0.05) suggests that these recruits may be less able to reduce bending moments compared with the injury-free group. We propose that the data for BMI and calf girth were indicative of lower bone and muscle strength in the lower limb, increasing the risk of tibial stress fracture.

Bimalleolar width has been used to indicate frame size[34], and more specifically as a component of tibial geometry[35]. The lower width for the tibial stress fracture group compared with the injury-free group suggests therefore that recruits sustaining a tibial stress fracture had narrower tibiae than injury-free recruits. A narrower tibia provides a lower area moment of inertia and therefore reduced ability to withstand bending, a factor which has been previously identified as a risk factor for tibial stress fracture[3, 32, 36]. Additional measurements of the lower limb, such as the width of the tibial plateau and the length of the tibia, could give greater detail regarding tibial geometry[35], and could be a useful tool in identifying recruits at higher risk of tibial stress fracture.

We expected that tibial stress fracture cases would have greater passive external rotation at the hip than the injury-free group, however this was not observed. These results contrast with findings for Israeli military recruits[5, 37], although evidence taken from wider populations reports similar null findings to the present study[4, 16, 38]. One explanation for this may be the better physical conditioning of RM recruits, compared with conscripted Israeli recruits.

***Gait variables***

There was a smaller tibial rotation range of motion in recruits sustaining a tibial stress fracture than the injury-free group (p<0.05). Although the relationship is not linear, rearfoot movement and tibial rotation are closely coupled during running[39]. Previous research has identified both excessively high[7] or limited[8] rearfoot movement in tibial stress fracture cases. Rearfoot motion has been described as an impact attenuation mechanism[40], however the deliberate restriction of rearfoot motion by Kersting et al.[41] did not cause the expected increase in peak impact forces. The authors suggested that altered muscle activation strategies may have been employed to maintain impact forces[41]. In RM training, the utilisation of sagittal plane attenuating mechanisms such as knee flexion[42] and ankle dorsi-plantar-flexion[10, 43] may be restricted by footwear[44] or load carriage[45], placing greater emphasis on the ability of the tibia to rotate to attenuate ground reaction forces. These variables were recorded as part of the protocol, but did not differ between the tibial stress fracture and injury-free groups[14]. Therefore, the lower tibial rotation observed for tibial stress fracture cases may suggest poor impact attenuation, supported by the greater peak heel pressures experienced by this group. The future inclusion of rearfoot motion would provide more information on lower limb function, particularly with regard to impact attenuation.

Research in participants running without shoes has reported reduced touchdown foot angle, suggested to reduce potentially painful loading at the heel[46, 10]. Pressure data were not available to confirm this suggestion in these studies. However, the observation of surface-dependent alterations to footstrike modality in recent work[12, 17 47] supports this suggestion. The presence of higher heel pressures in the tibial stress fracture group indicated that either the heightened loading of the heel was not perceived as potentially injurious, or that the individuals were not as adept at deploying a strategy to reduce this loading.

Dynamic arch index was not associated with tibial stress fracture. Associations between arch height and tibial stress fracture had been proposed based on static assessments of arch height. A high-arched foot may provide poor impact attenuation, and cause greater relative internal rotation of the tibia[48], increasing torsion on the tibia. The data presented indicate that there was no difference in the total midfoot contact area when running.

Binary logistic regression analysis allowed predictors of group membership (either tibial stress fracture group or injury-free group) to be identified. This approach aimed to develop a tool for the future screening of at-risk recruits. Within the population of lean, physically fit males, the analysis identified BMI, bimalleolar width, tibial rotation and heel pressure as predictive of tibial stress fracture cases (p<0.05), where variable-specific thresholds for avoiding tibial stress fracture were also identified. The predictive model requires validation through further prospective screening. However, the results of the present study provide both static and dynamic potential predictors of TSF cases.

If applied, the model presented will highlight potential cases when the risk of injury exceeds 50%. As such, there would be a number of recruits identified who may not go on to suffer a tibial stress fracture, however this would be preferable to missing recruits who may be at risk. Interventions should be aimed at providing increased impact attenuation (e.g. by providing cushioning insoles) and strengthening calf musculature. Future research will first seek to validate the predictive model, followed by investigations into the effectiveness of suggested interventions.

***Limitations***

Despite the scale of the project, only ten TSF cases were identified for analysis. Further cases were identified amongst recruits who commenced training during the data collection period but who did not volunteer for inclusion in the study. Future studies should consider methods for encouraging a greater proportion of recruits to volunteer, thus improving statistical power.

***Summary***

Compared with recruits who completed training without injury, RM recruits with lower muscle mass, reduced tibial width and less effective impact attenuation were at greater risk of sustaining a TSF during training.

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