TITLE:

Prospective Study of Biomechanical Risk Factors for Second and Third Metatarsal Stress Fractures in Military Recruits

ABSTRACT

Objectives

This prospective study investigated anatomical and biomechanical risk factors for second and third metatarsal stress fractures in military recruits during training.

Design

Prospective cohort study

Methods

Anatomical and biomechanical measures were taken for 1065 Royal Marines recruits at the start of training when injury-free. Data included passive range of ankle dorsi-flexion, dynamic peak ankle dorsi-flexion and plantar pressures during barefoot running. Separate univariate regression models were developed to identify differences between recruits who developed second (n=7) or third (n=14) metatarsal stress fracture and a cohort of recruits completing training with no injury (n=150) ($p<0.05$). A multinomial logistic regression model was developed to predict the risk of injury for the two sites compared with the injury-free group. Multinomial logistic regression results were back transformed from log scale and presented in Relative Risk Ratios (RRR) with 95% confidence intervals (CI).

Results

Lower dynamic arch index (high arch) (RRR: 0.75, CI: 0.63 to 0.89, $p<0.01$) and lower foot abduction (RRR: 0.87, CI: 0.80 to 0.96, $p<0.01$) were identified as increasing risk for second metatarsal stress fracture, while younger age (RRR: 0.78, CI: 0.61 to 0.99, $p<0.05$) and later peak pressure at the second metatarsal head area (RRR: 1.19, CI: 1.04 to 1.35, $p<0.01$) were identified as risk factors for third metatarsal stress fracture.

Conclusion

For second metatarsal stress fracture, aspects of foot type have been identified as influencing injury risk. For third metatarsal stress fracture, a delayed forefoot loading increases injury risk. Identification of these different injury mechanisms can inform development of interventions for treatment and prevention.

Keywords: foot injuries, biomechanics, soldiers, ankle flexion, plantar pressure

INTRODUCTION

Stress fractures of the lower limb are common in populations undergoing strenuous weight-bearing activity, particularly military personnel and sports participants [1-3]. During their 32-week training programme, which includes running and marching over varied terrain, 4-8% of UK Royal Marines (RM) recruits develop a stress fracture of the lower limb[1,4,5]. Recovery from a stress fracture typically results in significant absence from employment or training[1,5]. If individuals susceptible to stress fracture can be identified at the start of a training period, appropriate interventions may be applied to reduce the likelihood of stress fracture development. Since RM recruits have a prescribed lifestyle, with daily routine, nutritional intake and activity patterns tightly programmed, the training load is well-controlled. This managed population is therefore suitable for the study of risk factors for stress fracture, allowing intrinsic risk factors relevant to similar active populations to be identified.

The region of most frequent stress fracture during RM recruit training has been reported as the metatarsals, with the majority occurring at the 2nd and 3rd metatarsal sites (around 60% of total stress fracture cases) [1]. Despite evidence that stress in the 3rd metatarsal is more sensitive to laterally-directed loading, while stress in the 2nd metatarsal is more sensitive to vertical loading[6], previous studies of metatarsal stress fracture have not tended to differentiate between the metatarsal sites[7,8]. The grouping of all metatarsals together in previous studies may have masked relationships between study variables and injury risk. Thus it appears important to consider the second and third metatarsals separately, in order to investigate risk factors for these injuries.

A restricted passive ankle dorsi-flexion has been associated with a heightened risk of developing metatarsal stress fracture through limiting ankle dorsi-flexion range of motion, thought to cause an early heel lift and an increase in loading experienced by the metatarsal heads[7]. Foot type, characterised by measures such as arch height and foot abduction, has also been suggested to be influential, although evidence is conflicting[8,9]. Measurement of plantar pressures using a pressure plate provides a method for investigating loading at the metatarsal heads, and for quantifying aspects of foot type. This tool can provide dynamic arch index, a functional measure of the arch during locomotion, and can also be used to quantify foot alignment (abduction), where a more pronated foot type is associated with greater foot abduction (toe-out gait).

This prospective study aimed to identify risk factors for the development of second and third metatarsal stress fractures in RM recruits. Specifically, passive ankle dorsi-flexion, dynamic ankle dorsi-flexion and plantar pressure distribution were investigated. Separate groups of second metatarsal and third metatarsal stress fracture cases were identified and compared with a cohort of recruits who completed the training period without injury (injury-free group). The strength of the study variables to predict injury risk was investigated for the following: (i) static (passive) ankle dorsi-flexion; (ii) dynamic ankle dorsi-flexion during running; (iii) foot axis angle (foot abduction) during running; (iv) timing of heel-off; (v) peak pressure magnitude and timing at the metatarsal head areas; (vi) impulse at the metatarsal head areas; (vii) dynamic arch index (percentage ground contact in the midfoot area).

METHODS

Ethical approval was obtained from the Ministry of Defence Research Ethics Committee. Participants were RM recruits (all male) who provided informed consent in week-1 of military training. Following a power analysis based on previous data collection,[10] a requirement for a minimum of 1000 recruits was determined in order to obtain sufficient injury cases. Data were collected in week-2 of training for a total of 1065 recruits, when all were injury-free (between September 2010 and July 2012). Recruits were then monitored throughout training, and those reporting lower limb pain were examined by medical staff and stress fracture confirmed by positive MRI scan. Of the 1065 recruits, 14 individual recruits developed a unilateral third metatarsal stress fracture and 7 different recruits developed a unilateral second metatarsal stress fracture during the 32-week training period. Data for the second metatarsal stress fracture (MT2) group and third metatarsal stress fracture group (MT3) were compared with data for recruits who completed the training programme without interruption due to injury (injury-free). 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 [11]. To obtain 120 complete sets of data, data from 150 recruits were analysed. Thus, the stress fracture cases were compared with an injury-free group of 150. For the injury-free cases, left or right limb was selected randomly for inclusion.

For all 1065 recruits, age, height and body mass were recorded. Synchronised bilateral three-dimensional kinematic and plantar pressure data were collected for barefoot running at 3.6 $m.s^{-1}$ (± 5%). Recruits were required to run across a 2 m pressure plate (footscan®, RSScan, Belgium) set flush with a 9 m long EVA runway covered with a thin rubber mat. Running velocity was monitored using photocells. After familiarisation, five acceptable running trials were collected for each recruit. A trial was deemed acceptable if the correct running speed was observed and two consecutive foot strikes were recorded without deviating from a natural stride.

Kinematic data were collected at 200 Hz using two bilaterally aligned mpx30 Coda units (Codamotion, Charnwood Dynamics, UK). Active markers were placed on each leg at the following locations: greater trochanter; medial epicondyle of the knee; lateral epicondyle of the knee; midline of the Achilles tendon, just inferior to the muscle belly of the gastrocnemius (posterior lower leg); superior posterior aspect of the calcaneous; inferior posterior aspect of the calcaneous; lateral malleolus; lateral aspect of the fifth metatarso-phalangeal joint; medial aspect of the first metatarso-phalangeal joint. Raw coordinate data were exported from Codamotion software and filtered using a 12 Hz recursive fourth-order low-pass Butterworth filter. Dynamic lower limb angles were calculated using customised Matlab code (v.2008a, The Mathworks, USA). Peak ankle dorsi-flexion angle was calculated for each step analysed.

Plantar pressure data were collected at 200 Hz and analysed using the Footscan Gait software (RSScan, Belgium). For each trial, peak pressure and impulse were recorded across anatomical areas defined within the software, representing the medial and lateral heel, midfoot, five metatarsals, greater toe and lesser toes. Pressure time histories were exported and the peak pressure magnitude and occurrence time

(% stance) were identified. Pressure data also provided measures of dynamic arch index (percentage midfoot contact area relative to total foot contact area) and foot abduction angle (longitudinal foot angle relative to the direction of travel).

The amount of passive dorsi-flexion available to each recruit was assessed using a weight-bearing static lunge test based on that described in Bennell et al.[12]. The mean of five trials was calculated for each dynamic variable for each recruit. The mean of three trials was calculated for the measurement of passive ankle dorsi-flexion. Separate univariate regression models were developed having each key variable as outcome to identify significant ($p<0.05$) between-group differences between each of the stress fracture groups and the injury-free group.

A multinomial logistic regression model was developed to predict the risk of injury for the two sites compared to the injury-free (control) group. Candidate variables for an initial model were identified from the univariate regressions (those with a p' value <0.10) and all were included in the initial model. The variable with highest significance value was discarded from the model and the model was re-estimated to obtain new significance value for each variable and the process continued until the variables that remained were significant at predicting either outcome of the multinomial model. Age, arch index, foot abduction, peak pressure at 3rd metatarsal, peak pressure at 4th metatarsal, impulse at 3rd metatarsal, time of peak pressure at 1st metatarsal, time of peak pressure at 2nd metatarsal and time of peak pressure at 3rd metatarsal qualified for the inclusion in the initial model before being discarded on the basis of their model based significance value. The model was estimated with Huber-White sandwich standard error[13,14] and 95% confidence intervals to account for possible heteroscedasticity in variance parameter due to small numbers. Presented coefficients were transformed back to Relative Risk Ratios (RRR) from log odds. All analyses were carried out with statistical software Stata version 14.1 (StataCorp. 2015. *Stata Statistical Software: Release 14*. College Station, TX: StataCorp LP).

RESULTS

Table 1 presents the descriptive characteristics and significance test of between-group differences from univariate regressions. Height and mass did not differ for the three study groups ($p>0.05$; Table 1).

***Table 1 here ***

For the second metatarsal stress fracture group dynamic arch index was significantly lower for the 2nd metatarsal group compared to the no-injury group (Δ-4.23; CI: -8.32 to -0.15, $p<0.05$).

The third metatarsal stress fracture recruits were found to demonstrate greater foot abduction (toe-out) (Δ+3.82; CI: 0.28 to 7.36, $p<0.05$), greater magnitude of peak pressure at the 4th metatarsal area (Δ+3.82; CI: 0.43 to 7.21, $p<0.05$), later occurrence of peak pressure at the 1st metatarsal (Δ+4.47; CI: 0.99 to 7.95, $p<0.01$), 2nd metatarsal (Δ+3.75; CI: 1.01 to 6.48, $p<0.01$) and 3rd metatarsal areas (Δ+3.06; CI: 0.31 to 5.80, $p<0.05$). The group also demonstrated a borderline significance with younger age (Δ-1.52; CI: -3.17 to 0.13, $p=0.07$) and greater peak pressure at 3rd metatarsal (Δ+3.33; CI: -0.21 to 6.88, $p=0.06$).

Table 2 presents the results (RRR, 95%CI) from the multinomial logistic regression model estimated with robust standard error. All variables satisfying the inclusion criteria were entered in the initial model. The fitted model provided a log-likelihood ratio statistic -49.88 demonstrating an improvement from the null model with a χ^2 statistic 32.43, $p<0.02$. After discarding the variables one at a time that showed no effect on either of the outcomes and demonstrated large insignificant p values, the re-fitted final model provided a log-likelihood ratio statistic of -54.06, χ^2 24.08, $p<0.01$. Further log likelihood ratio testing was carried out to compare the two models (i.e. full model [with all potential predictors] vs. the restrictive model [with significant predictors]) and the test statistic was insignificant at χ^2 8.35, p=0.59, suggesting that the two models were statistically indifferent, and exclusion of the insignificant variables did not affect the model fit. The final model retained arch index, age, foot abduction and time of peak pressure at 2nd metatarsal demonstrating risk of injury on either of the outcomes.

Table 2 here

For 2nd metatarsal stress fracture, one percent decrease in arch index was associated with 25% increased risk (RRR: 0.75, CI: 0.63 to 0.89, p<0.01), while one degree decrease in foot abduction was found to increase risk by 13% (RRR: 0.87, CI: 0.79 to 0.96, p<0.01). For 3rd metatarsal injury, an age of one year younger was found to be associated with 22% increased risk (RRR: 0.78, CI: 0.61 to 0.99, p<0.05), while one unit increase in time of peak pressure at the 2nd metatarsal demonstrated 19% increased risk (RRR: 1.19, CI: 1.04 to 1.35, p<0.01). The observed effects in the model were significant holding the effects of other variables constant, and were an approximation from a logarithmic curve as a linear function of predictors in the model. Since the effect may not be linear in a probabilistic curve, we further predicted the probabilities of injury at different observed values of the predictors to identify the point at which the prediction was significantly different from 'zero' (Figure 1).

Figure 1 here

Each of the point estimates were tested before plotting to see where the confidence intervals were significantly different from 'zero' and thus pose predicted risk for injury. The predicted plot suggested that a value <21% for arch index and <22 degrees for foot abduction posed increased risk of 2nd metatarsal injury, while a value <25 years for age and a value >52% stance for time of peak pressure at 2nd metatarsal posed increased risk for 3rd metatarsal injury.

DISCUSSION

This study is the first prospective investigation focusing on dynamic biomechanical risk factors for metatarsal stress fractures at specific sites. This approach has highlighted different risk factors for two metatarsal sites frequently reported to develop stress fracture – the second and third metatarsals. The second and third metatarsals have previously been reported to experience the highest forefoot pressures during locomotion[15,16], but do not demonstrate greater ability to withstand these loads through greater cross-sectional geometry than other metatarsals[17]. The high rate of injury at these sites has therefore been attributed to the load applied at the respective metatarsal heads during locomotion[17]. This hypothesis seems reasonable but has not previously been tested in a prospective study. The current study implicates aspects of foot structure and function in the development of second and third metatarsal stress fractures.

The identification of low dynamic arch index and low foot abduction as predictors of second metatarsal stress fracture risk suggests functional foot type influences the load experienced by this structure during running. Lower dynamic arch index indicates less relative ground contact during stance for the midfoot area, suggesting a greater arch height and/or less arch deformation for this injury group. A high arch (or cavus) foot type also typically exhibits adduction of the forefoot relative to the rearfoot[18], consistent with the lower foot abduction observed for this injury group. These results therefore suggest an association between a foot characterised as supinated (high arch and adducted forefoot) and increased risk of second metatarsal stress fracture. This finding is consistent with a previous prospective study of military recruits where a high arch was found to be a risk factor for stress fractures in general[9], but contrasts with evidence provided from the same research group that a high arch is not a risk factor for metatarsal stress fractures specifically[8]. The current prospective study, with well-managed control of extrinsic risk factors, implicates functional foot type, specifically a more supinated/less pronated foot, as increasing risk for second metatarsal stress fracture development during military training.

To understand the mechanism by which lower dynamic arch index increases second metatarsal stress fracture risk, the subsequent influence on metatarsal loading should be considered. Using a finite element model, it has been demonstrated that a high arch results in greater loading of the second and third metatarsals compared with normal and low arched feet[19]. This previous study also detected an increase in magnitude of forefoot external loading with increased arch height. Since factors influencing metatarsal loading include the orientation of the metatarsal (influenced by foot type) and the external loading (magnitude, orientation and point of application of the resultant force vector), investigation of the mechanism by which foot type influences second metatarsal loading using a systematic variation of external load and metatarsal orientation is suggested.

The identification of later timing of second metatarsal peak pressure as the strongest predictor of third metatarsal stress fracture risk suggests metatarsal loading during the propulsive phase of stance is influential. The second metatarsal has been suggested to be a particularly important structure during the propulsive phase of running [20]. A possible mechanism for the later propulsive loading is the greater foot abduction for the third metatarsal stress fracture group which would be expected to result in a less effective lever during propulsion as a result of the shorter sagittal plane lever arm about the ankle joint [21]. A more abducted (toe-out) foot orientation has also been found to increase medially-directed horizontal ground reaction force [22]. Since it has been demonstrated that the third metatarsal is more sensitive to horizontal than vertical loads[6], greater abduction may also be influential on injury risk through a direct influence on loading of the metatarsal, likely effecting both bending and torsional loading. The later forefoot loading may also be associated with arch collapse, consistent with a foot type which exhibits forefoot abduction. Since the finding regarding greater foot abduction as a risk factor for injury is not significant at the desired alpha level, further testing in a larger sample is required to support this suggested mechanism.

The identification of young age as a predictor of third metatarsal stress fracture supports previous evidence[23], where the authors reported 28% increased risk of stress fracture for one year decrease in age, compared with 22% increased risk in the current study. However, without further measures such as bone density and cross-sectional area, it is not possible to suggest the mechanism by which age might influence development of this injury. Since the lower age observed for this group is consistent with previous literature, it is suggested that age should be considered when evaluating suitability for exercise programmes, such as military training and athletic activity.

Our multinomial model produced strong likelihood ratio test statistic in regards to model goodness of fit and comparison between null/full vs. the restrictive model. While the risk ratios are true comparisons and reflections of expected population parameters, further made predictions based on observed values need to be tested in a larger randomly drawn sample with a greater number of injury incidences in order to obtain true population point estimates. The use of barefoot running trials in the current study was selected to reveal intrinsic aspects of foot function placing some recruits at increased risk of these injuries. Since the injuries were sustained during activities predominantly involving wearing of military boots, it is important to also consider footwear effects. We have previously reported data on biomechanical comparisons of military footwear without consideration of foot type.[24] We recommend future study of the interaction of foot type with footwear, including the effect of footwear on metatarsal loading and injury risk.

Conclusions

The identification of functional foot type, specifically a more supinated/less pronated foot, as increasing risk for second metatarsal stress fracture supports the quantification of measures of foot type when evaluating risk of this injury. This finding has strong implications for the wider athletic population owing to the high incidence of 2nd metatarsal stress fracture. The examination of foot type should inform the development of interventions for treatment and/or prevention, for example footwear interventions and strengthening exercises. For third metatarsal stress fracture, the propulsion phase characterised by a delayed forefoot loading is likely influenced by greater foot abduction, influencing load application at the forefoot. Metatarsal models are required to investigate the influence of footwear or running style interventions on this forefoot function.

Practical Implications

- Quantification of foot type, particularly arch height and foot abduction, is suggested for the identification of individuals at heightened risk of developing 2nd metatarsal stress fracture and to inform potential footwear or exercise interventions.
- Interventions that influence forefoot function during propulsion are likely to be of most relevance for 3rd metatarsal stress fracture risk.
- Young age (<25) should be considered when evaluating suitability for exercise programmes, such as military training and athletic activity.

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Table 1. Descriptive characteristics (Mean/SD) of study recruits for injury-free, MT2 and MT3 study groups

Variables	No-injury(SD) n=150	MT2 (SD) n=7	P^1	MT3(SD) n=14	P^2
Height (m)	1.77(0.05)	1.78(0.09)	0.830	1.78(0.05)	0.713
Mass (kg)	76.64(6.56)	74.77(9.17)	0.472	74.19(6.85)	0.193
Age (years)	21.38(3.02)	20.86(2.12)	0.650	19.86(2.60)	0.068
Arch index (%)	21.97(4.63)	17.74(9.76)	0.037*	21.84(3.40)	0.922
Passive ankle dorsi-flexion (degrees)	31.27(5.46)	33.14(5.34)	0.382	28.53(6.43)	0.102
Dynamic ankle dorsi-flexion (degrees)	-10.97(5.60)	-9.22(4.42)	0.415	-8.93(4.89)	0.239
Time of heel off (% stance)	49.52(5.54)	52.52(4.72)	0.220	49.98(8.34)	0.779
Foot abduction (degrees)	9.27(6.20)	4.91(9.18)	0.109	13.09(7.50)	0.038*
2nd metatarsal peak pressure ($N.cm^{-2}$)	19.38(6.00)	20.17(7.09)	0.766	20.73(8.32)	0.452
2nd metatarsal impulse (N.s)	36.90(12.59)	34.64(12.08)	0.695	37.19(22.02)	0.945
3rd metatarsal peak pressure ($N.cm^{-2}$)	21.06(6.12)	19.27(4.19)	0.497	24.39(8.13)	0.062
4th metatarsal peak pressure ($N.cm^{-2}$)	18.57(5.92)	16.06(5.06)	0.322	22.39(7.26)	0.027*
3rd metatarsal impulse (N.s)	34.54(10.27)	27.00(6.65)	0.093	36.19(14.56)	0.585
1st metatarsal time of peak pressure (% stance)	53.90(5.94)	56.35(4.49)	0.343	58.36(8.44)	0.012**
2nd metatarsal time of peak pressure (% stance)	56.65(4.79)	58.23(3.88)	0.439	60.40(5.75)	0.007**
3rd metatarsal time of peak pressure (% stance)	54.70(5.01)	54.72(4.08)	0.993	57.75(3.88)	0.028*

-$P^{1,2}$ indicates between-group mean difference significance from univariate regression comparing No-injury vs. Metatarsal-2 and No-injury vs. Metatarsal-3 (*$p<0.05$, **$p<0.01$)

Table 2: Multinomial logistic regression model: No-injury vs. 2nd / 3rd metatarsal stress fracture. Relative Risk Ratio (RRR) presented for MT2, MT3 compared to on-injury group

*p<0.05; **p<0.01

Variables	**Outcome: MT2 RRR (95% CI)**	**Outcome: MT3 RRR (95% CI)**
Arch index	0.75 (0.63-0.89)**	1.03 (0.95-1.11)
Age	1.06 (0.85-1.32)	0.78 (0.61-0.99)*
Foot abduction	0.87 (0.80-0.96)**	1.09 (0.99-1.20)
Time of peak pressure at 2nd metatarsal	1.0 (0.86-1.17)	1.19 (1.04-1.35)**

LIST OF FIGURES