A narrow bimalleolar width is a risk factor for ankle inversion injury in male military recruits: A prospective study

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ABSTRACT

Background: Ankle inversion injuries are one of the most common and burdensome injuries in athletic populations. Research that prospectively identifies characteristics associated with this injury is lacking. This prospective study compared baseline anthropometric and biomechanical gait characteristics of military recruits who sustained an ankle inversion injury during training, with those who remained injury-free.

Methods: Bilateral plantar pressure and three-dimensional lower limb kinematics were recorded in 1065 male, injury-free military recruits, during barefoot running. Injuries that occurred during the 32-week recruit training programme were subsequently recorded. Data were compared between recruits who sustained an ankle inversion injury during training (n=27) and a sample (n=120) of those who completed training injury-free. A logistic regression analysis was used to identify risk factors for this injury.

Findings: A narrower bimalleolar width and an earlier peak pressure under the fifth metatarsal were predictors of ankle inversion injury. Those who sustained an ankle inversion injury also had a lower body mass, body mass index, and a smaller calf girth than those who completed training injury-free.

Interpretation: Anthropometric and dynamic gait characteristics have been identified that may predispose recruits to an ankle inversion injury during Royal Marine recruit training, allowing identification of recruits at higher risk at the start of training.

Keywords: Ankle inversion injury; Bimalleolar width; Prospective; Risk

1. INTRODUCTION

Ankle injuries are one of the most common injuries in athletic and military populations (Cameron et al., 2010; Doherty et al., 2014; Fong et al., 2007), reportedly comprising 15% –18% of all injuries. Ankle inversion injuries are those which result in damage to one or more of the lateral ankle ligaments. The burden of this injury is wide-reaching, as it is associated with a high rate of recurrence (32% - 74%, (Anandacoomarasamy and Barnsley, 2005; Konradsen et al., 2002; Yeung et al., 1994)), as well as future onset of ankle osteoarthritis (Valderrabano et al., 2006). It has been reported that 16% of the annual intake of Royal Marine (United Kingdom) recruits sustain an injury (Munnoch and Bridger, 2007), of which approximately 7% are ankle injuries (Munnoch, 2008). In this population, an ankle injury requires an average of 16 weeks of recovery and rehabilitation time (Munnoch, 2008).

Risk factors for ankle inversion injuries are not well understood (Morrison and Kaminski, 2007) and there is conflicting evidence regarding anthropometric variables associated with this injury (Beynnon et al., 2002). Existing research has associated a larger body mass (Milgrom et al., 1991; Waterman et al., 2010) and a higher BMI (Waterman et al., 2010) with ankle inversion injuries in military recruits. Greater foot width and calf girth have also been associated with increased risk of ankle inversion injury (Milgrom et al., 1991). It was suggested that a wider foot has a greater inversion moment arm (Milgrom et al., 1991), which may result in a greater external invertor moment at initial contact in wider feet than more narrow feet. The greater calf girth was likely influenced by the greater body mass observed, which was also associated with ankle inversion injury risk.

The majority of ankle inversion injuries occur during activities which involve running (Nelson et al., 2007), therefore dynamic biomechanical variables should be considered when assessing ankle inversion injury risk. Dynamic biomechanical variables assessed during barefoot running have been used successfully to identify risk factors for ankle inversion injury occurrence in athletic participants (Willems et al., 2005). A higher peak pressure and impulse under the first metatarsal, a lower impulse under the fifth metatarsal, and a more medially concentrated pressure throughout stance were associated with this injury. Greater rearfoot (subtalar) eversion excursion and later peak eversion were also observed in those who sustained this injury compared with those who remained injury-free, although this was not statistically significant. These findings indicate higher loading under the medial foot relative to the lateral foot in those who went on to sustain an ankle inversion injury. It was suggested that these individuals were loading their feet more medially as a compensatory mechanism to avoid a lateral inversion injury. Dynamic biomechanical variables have not previously been assessed in military populations in association with ankle inversion injury risk.

This study was part of a large, prospective study of Royal Marine recruits, designed to identify anthropometric and gait characteristics associated with lower limb injuries (Nunns et al., 2016). The present study aimed specifically to identify baseline characteristics of Royal Marine recruits who sustained an ankle inversion injury during training. The findings build upon existing findings (Rice et al., 2013), making use of a greater sample size to improve power. It was hypothesised that recruits who sustained an ankle inversion injury would have a greater body mass, BMI and calf girth than those who remained injury-free, based on previous findings within military populations. It was also hypothesised that recruits who sustained this injury would demonstrate more loading under the medial foot relative to the lateral foot, as demonstrated by greater loading under the first metatarsal, less loading under the fifth metatarsal, a more medially concentrated pressure at heel-off, greater rearfoot eversion range of motion and later peak eversion than those who remained injury-free.

2. METHODS

2.1 Data collection

1065 injury-free male Royal Marine recruits who commenced training between September 2010 and June 2012 volunteered to participate in this study. Only males were included as the Royal Marines currently only accept male recruits. Measurements were recorded during week-2 of the demanding 32-week training programme. Recruits were followed up throughout the programme until either their training was interrupted for any reason, or until they completed training at the first attempt. Injuries sustained during training that resulted in removal from the training programme were reported to the Medical Centre, and then recorded by the Physiotherapy Department at the Commando Training Centre Royal Marines. The Physiotherapy Department provided investigators with detailed injury information for relevant cases. Only injuries sustained to the lateral ankle ligaments during training, which were not the result of a traumatic event, were included in the analyses. Traumatic events were defined as those that a recruit could reasonably expect to avoid throughout the entirety of the training programme, such as falling from a rope. The study was approved by the Ministry of Defence Research Ethics Committee and all recruits provided informed consent.

Recruits completed a questionnaire which asked whether they had ‘ever had a significant leg, foot or ankle injury, such as a broken bone, sprain or ligament damage’, and if so they were asked how recently it occurred. Recruit height, body mass, calf girth, calf skinfold (allowing calculation of corrected calf girth) and bimalleolar width were measured by a trained investigator (Olds et al., 2006). Bimalleolar width was the distance between the maximum protrusion of the medial and lateral malleoli of the ankle. This was measured while the participant was standing, using a sliding breadth calliper (Rosscraft, Surrey, BC, Canada). Bimalleolar width was included in this study to provide an indicator of the length of the invertor moment arm. Bimalleolar width was an important variable in the larger study, as it was hypothesised to be lower in recruits who sustained a tibial stress fracture during training (Nunns et al., 2016). Calf girth and skinfold were measured at maximum circumference while the recruit stood with one foot placed on the seat of a chair, with the knee flexed. Calf skinfold was assessed to provide an adjustment of calf girth for adipose tissue (Olds et al., 2006). Bilateral, synchronised kinematic and plantar pressure measurements were recorded during barefoot running at 3.6 $m.s^{-1}$ (±5%), the speed which best represents recruits’ training speed (Creaby and Dixon, 2008). Running trials were conducted barefoot in order to avoid the confounding effects of footwear (McNair and Marshall, 1994). Furthermore, it has been suggested that variables associated with lower limb injury can be identified using both shod and barefoot protocols, but with characteristics more pronounced during barefoot conditions (Willems et al., 2007). Kinematic data were collected at 200 Hz (CodaMotion, Charnwood Dynamics, UK) using two Coda Mpx30 units and 11 active markers per leg, positioned as displayed in Figure 1. Markers were fixed in position using Micropore™ tape (3M, USA). Plantar pressure data were simultaneously recorded at 200 Hz using a pressure plate (RSscan International, Belgium, 4 x 0.5 m x 0.4 m, 4096 sensors) positioned in the middle of a 10 m ethylene-vinyl acetate runway. Kinematic data were filtered with a cutoff frequency of 12 Hz.

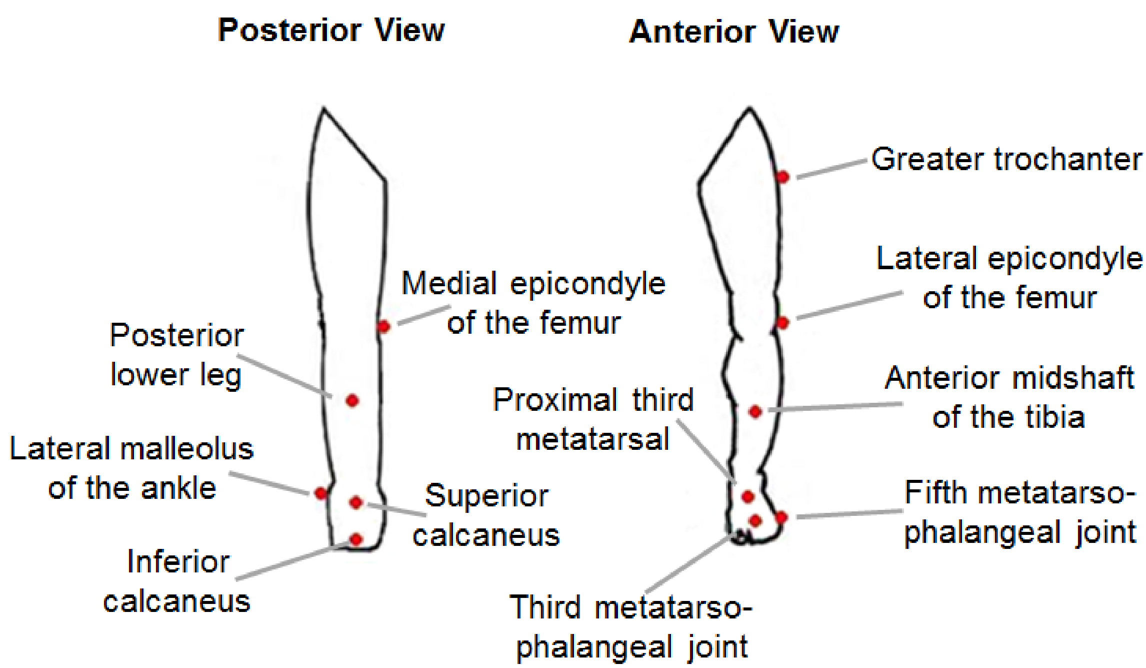

Figure 1: Coda marker positions displayed on the left leg

Recruits were asked to run with a relaxed style, ensuring two consecutive steps contacted the plate. Foot strike modality was self-selected. Recruits completed familiarisation trials until successful trials were repeatedly performed. Successful trials were those in which stride was not adjusted for plate contact, the run appeared relaxed to the investigator, and the required speed was achieved. Five successful trials were recorded per recruit, followed by a standing trial with recruits stood in a relaxed position with legs shoulder-width apart. This standing trial allowed for adjustment of dynamic joint angles relative to a neutral position, giving anatomical meaning to the kinematic data.

Of the 1065 recruits from whom data were collected in this study, 419 (39.3%) completed training at the first attempt injury-free and 27 (2.5%) sustained an ankle inversion injury. 55% of these injuries were to the right ankle, and 54% to the dominant limb, suggesting no bias by side or dominance. 120 of the 419 recruits who remained injury-free were randomly selected to create an injury-free group, and data from a randomly selected limb were analysed. A group size of 120 injury-free recruits was deemed appropriate based on estimates using cumulative means analysis (Bates et al., 1983). The 147 recruits included in the final analysis had mean (SD) age: 21.3 (3.1) years; height: 1.8 (0.1) m; mass: 75.8 (7.0) kg; and BMI: 24.1 (1.9) $kg.m^{-2}$.

2.2 Data analysis

Pressure trials were exported from the Footscan software (RSscan International, Version 7) after adjustment of automatically identified zones. Zones were manually adjusted by two investigators to represent the five metatarsals (M1-M5), and the medial and lateral heel (Figure 2). Inter- and intra-observer reliability for this adjustment, assessed by three repeats of fifty pressure trials, was high (ICC > 0.99 for peak pressure and impulse). Pressure variables included peak pressure, impulse, and time of peak for each zone. Bivariate correlation analyses were conducted between pressure variables (peak pressure and impulse) for each zone and body weight, to determine which variables should be normalised to body weight. All pressure variables demonstrated a weak correlation (Dancey and Reidy, 2007) with body weight (peak pressure variables: r < 0.18; impulse variables: r < 0.27), thus pressure variables were not normalised. Medial-lateral (ML) forefoot pressure distribution ratios were determined at heel-off (first frame with no heel contact) using two different calculations; ML Ratio 1 was the difference in pressure under the first and fifth metatarsals; ML Ratio 2 was the difference in pressure under M1+M2 and M4+M5. These values provided an indication of how medially concentrated the pressure was at heel-off. Both ratios were divided by the total vertical force under the foot. Ground contact time was also determined from pressure data.

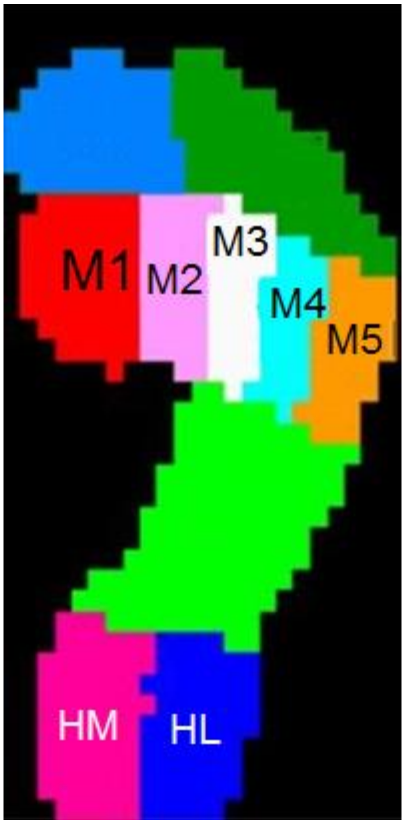

Figure 2: Automatically Identified Zones in RSscan Software

M1-M5: metatarsals 1-5, HM: medial heel, HL: lateral heel

Rearfoot eversion variables (frontal plane subtalar motion) were obtained using a 3D model (Grood and Suntay, 1983). Range of motion (excursion), time of peak (as a percentage of stance) and rate of angular change were considered. The data were exported for each trial and mean values obtained per recruit. Data analyses were performed using customised MATLAB scripts (R2012a, The MathWorks Inc. Natick, MA, USA).

All statistical analyses were undertaken using SPSS for Windows (Version 16.0, SPSS Inc., Chicago, IL, USA). First, normality of each variable was assessed (skewness and kurtosis $|z|$ values < 1.96). Means were then compared using independent t-tests (normally distributed variables) and Mann Whitney U tests (non-normally distributed variables). 2-tailed significance values were reported despite directional hypotheses, due to a lack of consistent existing evidence. Effect sizes (d) were calculated for variables where $P < 0.05$ (Cohen, 1988). Variables that differed between groups were entered into a binary logistic regression analysis. The odds ratio indicated the change in odds based on unit change of the predictor, and Wald values indicated the effect size. Multicollinearity was assessed by the correlation matrix, with a threshold of $r > 0.8$ indicating multicollinearity. Statistical significance was accepted for $\alpha \leq 0.05$.

3. RESULTS

Mean anthropometric characteristics for each group are displayed in Table 1. Those who sustained an ankle inversion injury had a lower body mass and BMI, as well as a smaller calf girth and narrower bimalleolar width than recruits who remained injury-free.

A previous ankle injury was reported by 11.1% of recruits who sustained an ankle inversion injury during training, compared with 18.3% of the 120 injury-free recruits. Mean plantar pressure and kinematic characteristics are displayed in Table 2. Peak pressure under the fifth metatarsal occurred earlier in recruits who sustained an ankle inversion injury compared with those who remained injury-free. There were no differences in kinematic variables between groups.

Table 1: Anthropometric characteristics of injury-free recruits compared with those who sustained ankle inversion injuries

	Injury-free		Ankle Inversion Injury			
Variable	**Mean (SD)**	**95% CI**	**Mean (SD)**	**95% CI**	**P**	**d**
Age (years)	21.3 (3.0)	20.8, 21.8	21.3 (3.3)	19.9, 22.6	0.928	-
Height (cm)	177.6 (5.3)	176.7, 178.6	176.3 (6.1)	173.8, 178.7	0.249	-
Mass (kg)	**76.6 (6.6)**	**75.4, 77.8**	**72.4 (7.7)**	**69.3, 75.4**	**0.004***	**0.60**
BMI (kg.m^{-2})	**24.3 (1.8)**	**23.9, 24.6**	**23.3 (1.8)**	**22.6, 23.9**	**0.009***	**0.55**
Calf girth (cm)	**37.6 (1.9)**	**37.3, 38.0**	**36.4 (2.0)**	**35.7, 37.2**	**0.005***	**0.60**
Corrected calf girth (mm)	**367.8 (18.9)**	**364.4, 371.3**	**357.0 (19.4)**	**349.3, 364.7**	**0.008***	**0.56**
Bimalleolar width (mm)	**71.9 (3.8)**	**71.2, 72.6**	**68.4 (5.5)**	**66.4, 70.5**	**< 0.001***	**0.74**

CI: confidence interval

***** Significant ($P < 0.05$) difference between groups. Note: variables which differed significantly between groups are highlighted in bold.

Table 2: Plantar pressure and rearfoot kinematic characteristics of injury-free recruits compared with those who sustained ankle inversion injuries

	Injury-free		**Ankle Inversion Injury**			
Variable	**Mean (SD)**	**95% CI**	**Mean (SD)**	**95% CI**	**P**	**d**
M1 peak pressure ($N.cm^{-2}$)	12.16 (4.41)	11.37, 12.96	13.32 (4.00)	11.59, 15.04	0.247	-
M1 impulse (N.s)	23.72 (10.35)	21.85, 25.59	25.04 (9.51)	20.58, 29.49	0.597	-
M5 peak pressure ($N.cm^{-2}$)	11.00 (5.15)	10.06, 11.93	11.67 (4.59)	9.68, 13.65	0.561	-
M5 impulse (N.s)	16.72 (9.43)	15.02, 18.43	17.58 (9.51)	13.46, 21.69	0.691	-
Time M5 peak pressure (%)	**46.49 (6.35)**	**45.34, 47.65**	**43.33 (7.80)**	**39.88, 46.80**	**0.041***	**0.57**
ML Ratio 1	0.05 (0.43)	-0.04, 0.13	0.06 (0.34)	-0.10, 0,23	0.864	-
ML Ratio 2	0.03 (0.72)	-0.11, 017	0.05 (0.71)	-0.29, 0,39	0.896	-
Rearfoot range of motion (degrees)	7.10 (3.06)	6.51, 7.69	6.84 (3.89)	4.91, 8.76	0.753	-
Time of peak eversion (%)	41.88 (8.03)	40.35, 43.40	42.89 (11.69)	36.88, 48.90	0.735	-
Eversion rate ($degrees.sec^{-1}$)	70.79 (29.69)	65.13, 76.45	54.79 (47.54)	29.46, 80.12	0.210	-

CI: confidence interval; M1: first metatarsal; M5: fifth metatarsal

***** Significant (P < 0.05) difference between groups. Note: variables which differed significantly between groups are highlighted in bold.

Based on these results, mass, BMI, calf girth, corrected calf girth, bimalleolar width and time of peak fifth metatarsal pressure were considered for inclusion in the logistic regression analysis. The correlation matrix revealed an association between calf girth and corrected calf girth. Corrected calf girth was deemed the most appropriate for inclusion, as it provides an indication of muscle mass. Therefore, the variables entered into the logistic regression analysis included: mass; BMI; corrected calf girth; bimalleolar width; and time of peak fifth metatarsal pressure. The model correctly classified 84.1% of cases (R^2 = 0.27). Bimalleolar width was a significant predictor of ankle inversion injury, with a one millimetre decrease in bimalleolar width associated with a 14.1% increase in injury risk (Table 3). Time of peak pressure under the fifth metatarsal was also a significant predictor of ankle inversion injury (Table 3). A peak pressure that occurred 1% earlier during stance was associated with a 9.7% increase in injury risk.

Table 3: Odds ratio, 95% confidence intervals and p values for the anthropometric variables

Anthropometric Variable	Odds Ratio	95% CI	P	Wald
Mass (kg)	0.942	0.828, 1.071	0.361	0.833
BMI ($kg.m^{-2}$)	0.873	0.548, 1.390	0.568	0.326
Corrected calf girth (mm)	0.990	0.950, 1.031	0.619	0.248
Bimalleolar breadth (mm)	**0.859**	**0.743, 0.993**	**0.040***	**4.205**
Time M5 peak pressure (%)	**0.903**	**0.824, 0.990**	**0.030***	**4.730**

CI: confidence interval
* Significant (P<0.05) predictor of ankle inversion injury. Note: significant predictors are highlighted in bold.

4. DISCUSSION

This large, prospective study identified anthropometric variables and biomechanical gait characteristics associated with ankle inversion injuries in Royal Marine recruits. This study was part of the largest prospective study to assess gait variables associated with injury occurrence in a military population (Nunns, 2014). The rate of ankle inversion injury was 2.5%, similar to a previously reported rate of 1.5% for recruits undertaking the same programme (Munnoch, 2008). In both studies, only injuries that resulted in removal from mainstream training were included. It is likely that more minor ankle injuries additionally occurred, that did not result in referral to the Physiotherapy Department, and thus would not have been included in the study.

A narrower bimalleolar width was identified as a predictor of this injury in Royal Marine recruits. A narrower bimalleolar width is indicative of a smaller support base and reduced single-leg stability, which has been associated with increased ankle inversion injury occurrence (Trojian and McKeag, 2006). Royal Marine recruits regularly carry load during training activities (Beck et al., 1996; Blacker et al., 2008), thereby increasing the height of their centre of gravity, and reducing stability. A narrower width may also be evidence of a smaller moment arm for the evertor muscles, reducing their ability to counter inversion. In the previous study where a greater foot width was associated with increased risk of ankle inversion injury (Milgrom et al., 1991), the incidence of this injury was 18% - considerably higher than the 1.2% reported during Royal Marine recruit training (Munnoch, 2008). These Israeli military recruits were from a national service population, therefore the entry requirements likely differed from the Royal Marine entry requirements, which are highly selective. Bimalleolar width is a relatively cost-effective and easy-to-measure variable. Therefore this finding has important implications, as it can be used to identify those at greatest risk of this injury. The upper limit of the confidence interval for recruits who sustained an ankle inversion injury was 70.5 mm, which was outside of the 95% confidence intervals for injury-free recruits (Table 1). Therefore, future recruits with a bimalleolar width ≤ 70.5 mm may be identified at the start of training as being at high risk of this injury. These values may be applicable to other athletic populations, particularly those who carry additional load. Future research is required to determine the most suitable intervention to reduce the risk of ankle inversion injury in these recruits.

An earlier peak fifth metatarsal pressure was the only other significant predictor of an ankle inversion injury, and this finding was not hypothesised. Peak pressure under the most lateral metatarsal occurred during reinversion of the forefoot just prior to midstance, rather than at initial metatarsal contact (as indicated by the time of peak pressure occurring between 40% and 50% of stance). Therefore, earlier peak pressure under the lateral metatarsal may be evidence of earlier supination, and a greater time spent in supination, thereby increasing the risk of excessive inversion. Supination is the action during which the majority of ankle inversion injuries occur (Hertel, 2002).

In contrast to the original hypothesis, recruits who sustained an ankle inversion injury had a lower body mass than those who remained injury-free. These findings contradict existing findings, where a greater body mass was associated with ankle inversion injury in Israeli infantry recruits (Milgrom et al., 1991). As discussed, the difference in selection criteria between populations likely influenced these findings. A low body mass is thought to be associated with increased injury risk in military populations due to the frequent load carriage activities which take place throughout the training programmes (Beck et al., 1996; Blacker et al., 2008).These load carriage activities typically require a pre-determined, absolute load to be carried, rather than a load that is relative to body mass. Recruits with a lower body mass are therefore required to carry proportionally greater loads during training than those with a greater body mass. This increases the physical demand and may increase susceptibility to injury. This finding is likely also applicable in other populations, such as those who carry load for occupational tasks.

The lower BMI observed in those who sustained an ankle inversion injury was also contrary to the hypothesis. BMI in this population is an indicator of muscle mass rather than fat mass, as recruits are highly trained and have a relatively low percentage body fat (Davey et al., 2011). This likely explains why a lower BMI has previously been associated with overall injury occurrence in Royal Marine recruits (Davey et al., 2011). The smaller corrected calf girth values in those who sustained an ankle inversion injury therefore indicate a smaller calf muscle mass. Lower muscle mass may be evidence of weaker evertor muscles, which would be less able to counter forced inversion and have previously been associated with increased ankle inversion injury occurrence (Witchalls et al., 2011). The findings of the present study contradict previous reports of an association between a greater (uncorrected) calf girth and ankle inversion injury (Milgrom et al., 1991). That finding was influenced by the greater body mass in their injury group, where a greater calf girth was unlikely to be indicative of a greater calf muscle mass.

Willems et al. (2005) reported a more medial distribution of loading in those who sustained an ankle inversion injury, which was not supported by the findings from the present study. This may be due to differences between military and non-military populations, and the differing activities during which an ankle inversion injury would occur. Frontal plane rearfoot kinematics were investigated due to the greater rearfoot eversion excursion and later peak eversion observed by Willems et al., despite these differences being non-significant. The findings from the present study, when combined with these existing findings suggest that frontal plane rearfoot kinematic variables during barefoot running are not predictive of ankle inversion injury in athletic populations. The combined actions of ankle plantar-flexion and subtalar inversion and adduction that comprise supination may be of greater importance in the assessment of this injury.

A limitation of working with the Royal Marine recruit population in injury-based research is the possible reluctance of recruits to report injuries. However, completing the demanding 32-week recruit training programme would be extremely difficult if a serious injury occurred, thus it is believed that recruits who were reported to have completed training injury-free were not suffering from a serious injury. A reluctance to report injuries may also influence the reporting of previous injuries, resulting in a possible under-reporting, although there is no indication that this would have differed between groups. Barefoot running does not simulate the conditions in which ankle inversion injuries typically occur during recruit training. It was felt that assessment of baseline characteristics during barefoot running was more suitable than during shod running, due to the confounding effects of footwear. Additional dynamic characteristics that differed between groups may have been identified if these characteristics were also assessed during running in military boots, although it was previously reported that injury characteristics were more pronounced during barefoot than shod conditions (Willems et al., 2007).

Despite the fact that the recruits were from a highly homogenous population, there may have been confounding variables which were not quantified in the present study. The same training programme was followed by each recruit. However, variables such as training intensity, nutritional intake, quality of recovery time, as well as many sociological and psychological variables may have differed slightly between troops and between recruits. However, the large sample of recruits from within this highly controlled environment provided an excellent opportunity to identify anthropometric and dynamic gait characteristics associated with ankle inversion injury. It is important to consider that the variables identified in the present study as contributors to increased risk of ankle inversion injury, may contribute to either increased or decreased risk of injury of other lower limb structures. Indeed, a smaller bimalleolar width and lower BMI were additionally associated with increased risk of tibial stress fractures in this population (Nunns et al., 2016). It was not possible to assess all lower limb injuries of interest in this study, due to insufficient cases for adequate statistical power.

5. CONCLUSIONS

This prospective study of 1065 Royal Marine recruits identified differences in baseline anthropometric and biomechanical gait characteristics in recruits who sustained an ankle inversion injury during training compared with recruits who completed training injury-free. A narrower bimalleolar width and earlier peak pressure under the fifth metatarsal - indicative of earlier supination - were identified as predictors of ankle inversion injury. Bimalleolar width can be measured easily and may be used to identify individuals at increased risk of ankle inversion injury, particularly in athletic populations who carry additional load. Future investigation should assess interventions designed to reduce the risk of this injury.

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CONFLICT OF INTEREST STATEMENT

We are not aware of any conflict of interest related to the manuscript and its publication.

REFERENCES

Anandacoomarasamy, A., Barnsley, L., 2005. Long term outcomes of inversion ankle injuries. Br. J. Sports Med. 39, e14–e14. doi:10.1136/bjsm.2004.011676

Bates, B.T., Osternig, L.R., Sawhill, J.A., James, S.L., 1983. An assessment of subject variability, subject-shoe interaction, and the evaluation of running shoes using ground reaction force data. J. Biomech. 16, 181–191.

Beck, T.J., Ruff, C.B., Mourtada, F.A., Shaffer, R.A., Maxwell-Williams, K., Kao, G.L., Sartoris, D.J., Brodine, S., 1996. Dual-energy X-ray absorptiometry derived structural geometry for stress fracture prediction in male U.S. Marine Corps recruits. J. Bone Miner. Res. Off. J. Am. Soc. Bone Miner. Res. 11, 645–653. doi:10.1002/jbmr.5650110512

Beynnon, B.D., Murphy, D.F., Alosa, D.M., 2002. Predictive Factors for Lateral Ankle Sprains: A Literature Review. J. Athl. Train. 37, 376–380.

Blacker, S.D., Wilkinson, D.M., Bilzon, J.L.J., Rayson, M.P., 2008. Risk factors for training injuries among British Army recruits. Mil. Med. 173, 278–286.

Cameron, K.L., Owens, B.D., DeBerardino, T.M., 2010. Incidence of ankle sprains among active-duty members of the United States Armed Services from 1998 through 2006. J. Athl. Train. 45, 29–38. doi:10.4085/1062-6050-45.1.29

Cohen, J., 1988. The Analysis of Variance, in: Statistical Power Analysis for the Behavioral Sciences. Lawrence Erlbaum Associates, pp. 148–150.

Creaby, M.W., Dixon, S.J., 2008. External frontal plane loads may be associated with tibial stress fracture. Med. Sci. Sports Exerc. 40, 1669–1674. doi:10.1249/MSS.0b013e31817571ae

Dancey, C., Reidy, J., 2007. Bivariate correlations, in: Statistics Without Maths for Psychology. Pearson Education Limited.

Davey, T., Delves, S., Lanham-New, S., Allsopp, A., Fallowfield, J., 2011. Body composition of Royal Marine recruits during 32 weeks of military training., in: Proceedings of the Nutrition Society. 70, p. E150.

Doherty, C., Delahunt, E., Caulfield, B., Hertel, J., Ryan, J., Bleakley, C., 2014. The incidence and prevalence of ankle sprain injury: a systematic review and meta-analysis of prospective epidemiological studies. Sports Med. Auckl. NZ 44, 123–140. doi:10.1007/s40279-013-0102-5

Fong, D.T.-P., Hong, Y., Chan, L.-K., Yung, P.S.-H., Chan, K.-M., 2007. A systematic review on ankle injury and ankle sprain in sports. Sports Med. Auckl. NZ 37, 73–94.

Grood, E.S., Suntay, W.J., 1983. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J. Biomech. Eng. 105, 136–144.

Hertel, J., 2002. Functional Anatomy, Pathomechanics, and Pathophysiology of Lateral Ankle Instability. J. Athl. Train. 37, 364–375.

Konradsen, L., Bech, L., Ehrenbjerg, M., Nickelsen, T., 2002. Seven years follow-up after ankle inversion trauma. Scand. J. Med. Sci. Sports 12, 129–135.

McNair, P.J., Marshall, R.N., 1994. Kinematic and kinetic parameters associated with running in different shoes. Br. J. Sports Med. 28, 256–260.

Milgrom, C., Shlamkovitch, N., Finestone, A., Eldad, A., Laor, A., Danon, Y.L., Lavie, O., Wosk, J., Simkin, A., 1991. Risk factors for lateral ankle sprain: a prospective study among military recruits. Foot Ankle 12, 26–30.

Morrison, K.E., Kaminski, T.W., 2007. Foot Characteristics in Association With Inversion Ankle Injury. J. Athl. Train. 42, 135–142.

Munnoch, K., 2008. The Psychological Impact of Physical Injury on Recovery in Royal Marines' Recruit Training. University of Southampton, Southampton.

Munnoch, K., Bridger, R.S., 2007. Smoking and injury in Royal Marines' training. Occup. Med. 57, 214–216. doi:10.1093/occmed/kql170

Nelson, A.J., Collins, C.L., Yard, E.E., Fields, S.K., Comstock, R.D., 2007. Ankle Injuries Among United States High School Sports Athletes, 2005–2006. J. Athl. Train. 42, 381–387.

Nunns, M., 2014. Biomechanical variables associated with tibial and third metatarsal stress fractures in Royal Marines recruits. University of Exeter, Exeter.

Nunns, M., House, C., Rice, H., Mostazir, M., Davey, T., Stiles, V., Fallowfield, J., Allsopp, A., Dixon, S., 2016. Four biomechanical and anthropometric measures predict tibial stress fracture: a prospective study of 1065 Royal Marines. Br. J. Sports Med. bjsports-2015-095394. doi:10.1136/bjsports-2015-095394

Olds, T., Stewart, A., Carter, L., Marfell-Jones, M., 2006. International Standards for Anthropometric Assessment. International Society for the Advancement of Kinanthropometry.

Rice, H., Nunns, M., House, C., Fallowfield, J., Allsopp, A., Dixon, S., 2013. High medial plantar pressures during barefoot running are associated with increased risk of ankle inversion injury in Royal Marine recruits. Gait Posture 38, 614–618. doi:10.1016/j.gaitpost.2013.02.001

Trojian, T.H., McKeag, D.B., 2006. Single leg balance test to identify risk of ankle sprains. Br. J. Sports Med. 40, 610–613. doi:10.1136/bjsm.2005.024356

Valderrabano, V., Hintermann, B., Horisberger, M., Fung, T.S., 2006. Ligamentous Posttraumatic Ankle Osteoarthritis. Am. J. Sports Med. 34, 612–620. doi:10.1177/0363546505281813

Waterman, B.R., Belmont, P.J., Cameron, K.L., Deberardino, T.M., Owens, B.D., 2010. Epidemiology of ankle sprain at the United States Military Academy. Am. J. Sports Med. 38, 797–803. doi:10.1177/0363546509350757

Willems, T., Witvrouw, E., De Cock, A., De Clercq, D., 2007. Gait-related risk factors for exercise-related lower-leg pain during shod running. Med. Sci. Sports Exerc. 39, 330–339. doi:10.1249/01.mss.0000247001.94470.21

Willems, T., Witvrouw, E., Delbaere, K., De Cock, A., De Clercq, D., 2005. Relationship between gait biomechanics and inversion sprains: a prospective study of risk factors. Gait Posture 21, 379–387. doi:10.1016/j.gaitpost.2004.04.002

Witchalls, J., Blanch, P., Waddington, G., Adams, R., 2011. Intrinsic functional deficits associated with increased risk of ankle injuries: a systematic review with meta-analysis. Br. J. Sports Med. bjsports-2011-090137. doi:10.1136/bjsports-2011-090137

Yeung, M.S., Chan, K.M., So, C.H., Yuan, W.Y., 1994. An epidemiological survey on ankle sprain. Br. J. Sports Med. 28, 112–116.