Estimates of tibial shock magnitude in men and women at the start and end of a military drill training programme

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Background

Tibial accelerometry using shank-mounted accelerometers has been used to estimate tibial shock during activities such as walking [1], running [2–4] and jumping [5]. As the foot contacts the ground, a positive upwards axial acceleration is observed. During walking, this peak has been reported to be 3 – 4 g [1], compared with 6 – 8 g during running [2–4]. Higher values of 9 – 11 g have been reported when running in more challenging conditions, such as when fatigued [4], when stride length is increased [3] or when running downhill [2]. Military drill involves exaggerated heel strikes and foot stamping, and is undertaken frequently during Basic military training [6], thus exploration of tibial shock during drill training is warranted.

Milner et al. [7] identified that runners with a history of tibial stress fracture have higher peak tibial accelerations during running than those with no history of stress fracture, suggesting that higher values may increase injury risk. The magnitude of axial tibial acceleration has been shown to have a moderate [8] to strong [9] positive relationship with the vertical ground reaction force (GRF) loading rate during running, and higher loading rates during running have also been associated with increased risk of tibial and metatarsal stress fracture [10]. Lower limb musculoskeletal injuries make up over three-quarters of training injuries during Basic military training [11,12] and represent a significant burden resulting in lost training time and medical discharge. It is estimated that the cost of musculoskeletal injuries in Army personnel will be £1.2 billion over the next 15 years [13]. In particular, lower limb stress fractures are common amongst military recruits, with a considerably higher incidence than in elite athletes and the general population [14]. Stress fractures are especially burdensome to military personnel due to the lengthy recovery time required [15] and increased likelihood of being medically discharged from training [16]. To date, the magnitudes of tibial shock during military training activities have not been investigated.

Carden et al. (2015) reported that tibial acceleration magnitude was greater during drill manoeuvres (~13 g) than marching (~3 g), was 80% higher in men than women during drill, and that trained soldiers elicited over 60% higher acceleration magnitudes than novices. The authors postulated that the greater lean muscle mass in trained soldiers compared with novices may have enabled them to ‘impart more force into the ground.’ This may also explain the higher values amongst males than females. However, Carden et al. (2015) estimated tibial accelerations using double differentiation of motion displacement data from a marker positioned on the tibial tuberosity, rather than a shank-mounted accelerometer. Although this approach can provide important insight, accelerometers give far more accurate values [17], as they directly measure the accelerations, whereas small artefacts in marker displacement are magnified during double differentiation. Furthermore, the data were not collected in the field during drill training. Accordingly, the aim of the present study was to quantify tibial accelerations during drill training sessions using shank-mounted accelerometers. Secondary aims were to compare tibial shock between male and female participants, and to determine whether the magnitude of tibial shock changed between the first and final training weeks when participants were considered 'untrained' and 'trained' respectively. It was hypothesised that the magnitudes of tibial shock during drill training would be greater than those previously observed during high impact physical activities such as running. Based on existing findings [6], it was also hypothesised that male participants would display higher values than female participants, and that magnitudes would be greater during drill training in the final week compared with the first week of training.

Methods

Participants

Five female (mean (SD), age 24 (5) years, height 1.68 (0.05) m, mass 66.4 (11.8) kg) and five male (mean (SD), age 20 (1) years, height 1.75 (0.07) m, mass 72.5 (6.9) kg) British Army recruits volunteered to take part in this study. All participants were recruited during week-1 of their British Army Basic training at the Army Training Centre, Pirbright. The men and women were part of two single-sex training troops (groups of approximately 40 recruits), both of which commenced training on the same day. Each participant had the study procedures and risks fully explained in writing and by oral brief before providing written informed consent. All participants passed an initial medical assessment and were therefore declared medically fit to train. The first five female and five male participants who reported no previous history of shin pain or tibial stress fracture were included in the study. This study was approved by the Ministry of Defence Research Ethics Committee (Ref: 753/MODREC/16) and was completed in accordance with the Declaration of Helsinki.

Procedures

Data collection took place during a drill training session in week 1 and 12 of British Army Phase One training. These data were collected as part of a larger study which included additional physiological measurements. The men and women completed drill training in separate troops, and sessions were led by different drill instructors. The male and female troops were scheduled to complete the same sessions on the same days throughout training, albeit on occasion, at different times of the day. All drill training sessions followed a standard course syllabus and took place on the drill square at the Army Training Centre, Pirbright, and all participants wore standard Army issue drill uniform and drill shoes, and were not wearing or carrying any additional military equipment..

Accelerometer data were collected at 1000 Hz from the right antero-medial, distal shank of participants during drill training. IMeasureU accelerometers (IMeasureU 9-axis inertial measurement unit, Auckland, NZ) were positioned such that the vertical axis was aligned with the long axis of the tibia [8], and with the bottom of the sensor approximately 10 mm above the superior medial malleolus. These sensors (40 x 28 x 15mm, 12g) were secured as tightly as possible using adhesive straps, without causing discomfort to the individual [3]. The accelerometers were positioned and recording started prior to participants moving across camp (as part of a troop of recruits) to commence the drill training session. The training session followed the recruit training schedule, and was not adapted in any way to accommodate data collection procedures. Accelerometers were removed from participants when each troop returned to the accommodation block at the end of the session.

Data Analysis

Data were analysed in Matlab R2016a (Mathworks, Natick, MA, USA). Axial accelerations (along the long axis of the tibia) and the resultant of accelerations in three directions (axial, anterior-posterior and medial-lateral) were obtained. The average value in each direction was subtracted from all data points, prior to any analyses [7]. Magnitudes of tibial shock were presented in units of g, where 1 g = 9.81 $m.s^{-2}$. The accelerometers read a maximum value of 15g in the positive direction. Where the values exceeded these peaks, data were extrapolated to estimate the true peak based on the slope determined from four frames either side of the clipped peak (Figure 1). Thresholds of 5 g, 10 g, and 15 g were selected to approximately represent *moderate*, *high* and *very high* tibial shock, respectively. These thresholds were guided by typical accelerometry values observed during walking (3 - 4 g, [1]) and running (6 – 11g, [2–4]). The number of peaks that exceeded each threshold was recorded for information. Peak positive acceleration (PPA) was defined as the peak value in the positive direction during the activity. PPA for each participant was reported, as well as the mean value of the highest ten peaks. This latter variable was termed the *average PPA*. PPA and average PPA were obtained for comparison to existing literature, where data were collected during discrete movements over shorter durations, rather than in the field. The rate at which each threshold was exceeded (peaks per minute), and the mean value of peaks above each threshold were also calculated.

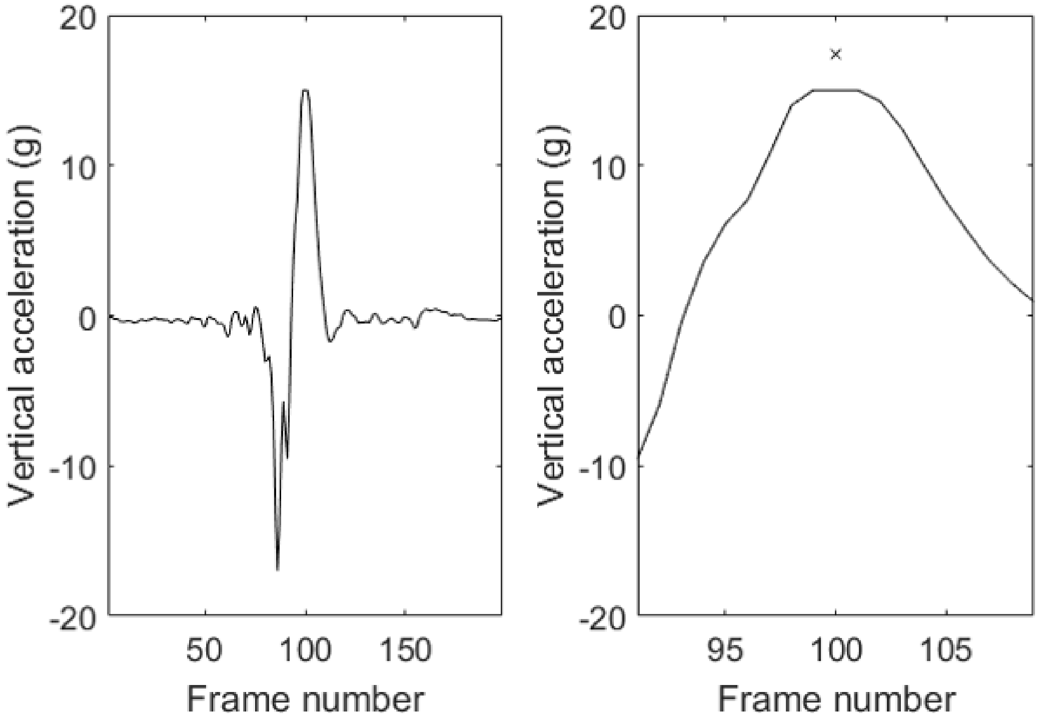

Figure 1: Example of vertical accelerations exceeding the maximum threshold. The same example is presented over 200 frames (A) and 20 frames (B) for clarity. The 'x' indicates the extrapolated peak.

The accelerometers were set to collect data from the time that they had been positioned and secured on the participants. This meant there were some periods of inactivity prior to the commencement of drill training. The start point for the data to be analysed was determined as the point when the cumulative numerical integration of the absolute value of axial accelerations exceeded 35×10^6 $m.s^{-2}$. This value was used to indicate that accelerations were consistently high enough to be indicative of activity. The end of the activity was determined by identifying periods of inactivity. To detect 'inactivity', time points where absolute accelerations > 75 $m.s^{-2}$ were first identified. Secondly, the first time point when the first derivative of this matrix exceeded 11.5×10^5 $m.s^{-2}$ was identified, and this marked the end of the activity. Where such inactivity was not detected, the end of the recording was used. These cut-offs were based on visual analysis of the data and documentation of the drill events recorded by observation during the first session. These time points were used to quantify the duration of sessions for descriptive purposes. There was no concern about losing relevant drill data using this approach, due to the lengthy recording time of each session.

Statistical Analysis

Mixed ANOVAs were conducted to consider the influence of both sex and time (week of training) on dependent accelerometry variables. These included the rate and magnitude of axial accelerations, the rate and magnitude or resultant accelerations, and the PPA. A value of $P < 0.05$ indicated a significant main or interaction effect. Post-hoc pairwise comparisons with consideration of Bonferroni-corrected alpha were used to identify where significant effects occurred. Where interaction effects occurred, t-tests were conducted to identify significant differences, with Bonferroni-corrected alpha values. Effect sizes were reported using Cohen's d [18] and partial eta squared (η_p^2). The duration of each session and the number of times each threshold was exceeded were reported for descriptive purposes only.

Results

The duration of drill sessions ranged from 53 to 176 minutes within the four sessions (Table 1). Men demonstrated a considerable increase in duration between weeks 1 and 12, whereas the females had a similar duration across both sessions. The high standard deviations observed in the duration of training amongst women in week-1 is due to the fact that two female participants were withdrawn from drill training by their instructors approximately 78 minutes into the session to complete unrelated tasks. The average duration of drill training for the remaining three females was 215 minutes. Mean (SD) values for the rate and magnitude of accelerations, as well as main and interaction effects are presented in Table 2.

Table 1: Mean (SD) values for descriptive variables

	Men		Women	
Variable	**Week 1**	**Week 12**	**Week 1**	**Week 12**
Duration (minutes)	53.0 (0.22)	176.3 (5.6)	160.2 (82.0)	148.5 (1.3)
Number of times each threshold exceeded in axial direction				
Moderate (>5g)	136 (28)	715 (277)	250 (212)	310 (186)
High (>10g)	47 (18)	248 (97)	68 (61)	77 (19)
Very high (>15g)	26 (21)	115 (108)	36 (35)	6 (13)

Table 2: Mean (SD) values for each variable by sex and time (week of training)

	Men		Women		Main Effects
	Week 1	Week 12	Week 1	Week 12	
	Mean (SD)				
AXIAL ACCELERATIONS					
Rate at which each threshold was exceeded (peaks per minute)					
Moderate (>5g)	2.55 (0.51)	4.06 (1.55)	1.57 (0.90)	2.09 (1.25)	**Sex**
High (>10g)	0.88 (0.33)	1.39 (0.52)	0.41 (0.28)	0.52 (0.13)	**Sex**
Very high (>15g)	0.48 (0.39)	0.64 (0.60)	0.21 (0.15)	0.04 (0.09)	**Sex**
Magnitude above each threshold (g)					
Moderate (>5g)	9.49 (1.47)	9.50 (1.68)	8.57 (1.37)	8.81 (1.31)	-
High (>10g)	14.62 (0.64)	14.70 (0.51)	14.25 (0.61)	14.54 (0.59)	-
RESULTANT ACCELERATIONS					
Rate at which each threshold was exceeded (peaks per minute)					
Moderate (>5g)	19.92 (2.6)	28.66 (10.50)	18.35 (7.23)	34.39 (10.02)	**Time**
High (>10g)	4.62 (2.15)	7.71 (2.59)	6.81 (3.69)	9.35 (3.68)	**Time**
Very high (>15g)	2.28 (0.88)	3.70 (0.90)*	3.48 (2.31)	2.84 (1.20)	**Interaction**
Magnitude above each threshold (g)					
Moderate (>5g)	8.89 (0.89)	9.51 (1.04)	9.72 (1.21)	8.62 (0.66)	**Interaction**
High (>10g)	16.52 (1.91)	16.59 (1.89)	15.02 (1.01)	14.19 (0.78)	**Sex**
Very high (>15g)	20.64 (1.34)	20.79 (0.81)	18.24 (1.18)	18.64 (1.33)	**Sex**
PEAK POSITIVE ACCELERATION (PPA, g)					
PPA	19.32 (2.01)	21.35 (2.73)	20.16 (2.07)	22.41 (1.86)	**Time**
Average PPA	17.19 (1.12)	19.21 (1.88)	17.44 (1.43)	18.43 (1.40)	**Time**

Note: Values are not presented for magnitudes above the *very high* threshold in the axial direction, as only one female participant exceeded this threshold. Where both a main and interaction effect occurred, only the interaction effect was reported.

*** Indicates a significant different from Week 1, P < 0.025.**

Axial Acceleration

There was a main effect for sex on the rate at which each threshold was exceeded (*moderate*: $F_{(1,8)}$ = 11.368, P = 0.010, η_p^2 = 0.587; *high*: $F_{(1,8)}$ = 28.304, P= 0.001, η_p^2 = 0.780; *very high*: $F_{(1,8)}$ = 6.161, P = 0.038, η_p^2 = 0.435). Men exceeded each threshold at 1.8, 2.4 and 4.5 fold the rate of women for *moderate*, *high*, and *very high* thresholds, respectively. There were no main or interaction effects for the magnitudes of tibial shock in the axial direction, at any of the thresholds.

Resultant Accelerations

There was a main effect for time on the rate at which resultant accelerations exceeded the *moderate* and *high* thresholds ($F_{(1,8)}$ = 19.946, P = 0.002, η_p^2 = 0.714; $F_{(1,8)}$ = 30.719, P = 0.001, η_p^2 = 0.793 respectively). Rates were greater in week-12 than week-1 by 65% and 49% for the *moderate* and *high* thresholds respectively. There was an interaction effect on the rate at which the *very high* threshold was exceeded ($F_{(1,8)}$ = 8.386, P = 0.020, η_p^2 = 0.512), with men increasing over time (P = 0.023, d = 1.59), and women displaying no change (P = 0.341, d = 0.34). There was a main effect for sex on the magnitude of tibial shock above the *high* ($F_{(1,8)}$ = 5.708, P = 0.044, η_p^2 = 0.416, Figure 2) and *very high* thresholds ($F_{(1,8)}$ = 16.769, P = 0.003, η_p^2 = 0.677, Figure 2). Magnitudes were 13% higher in men than women at the *high* threshold, and 12% higher at the *very high* threshold. There was an interaction effect on the magnitude above the *moderate* threshold ($F_{(1,8)}$ = 8.659, P = 0.019, η_p^2 = 0.520), although post-hoc tests revealed that the value did not significantly change over time for either men or women (P > 0.05).

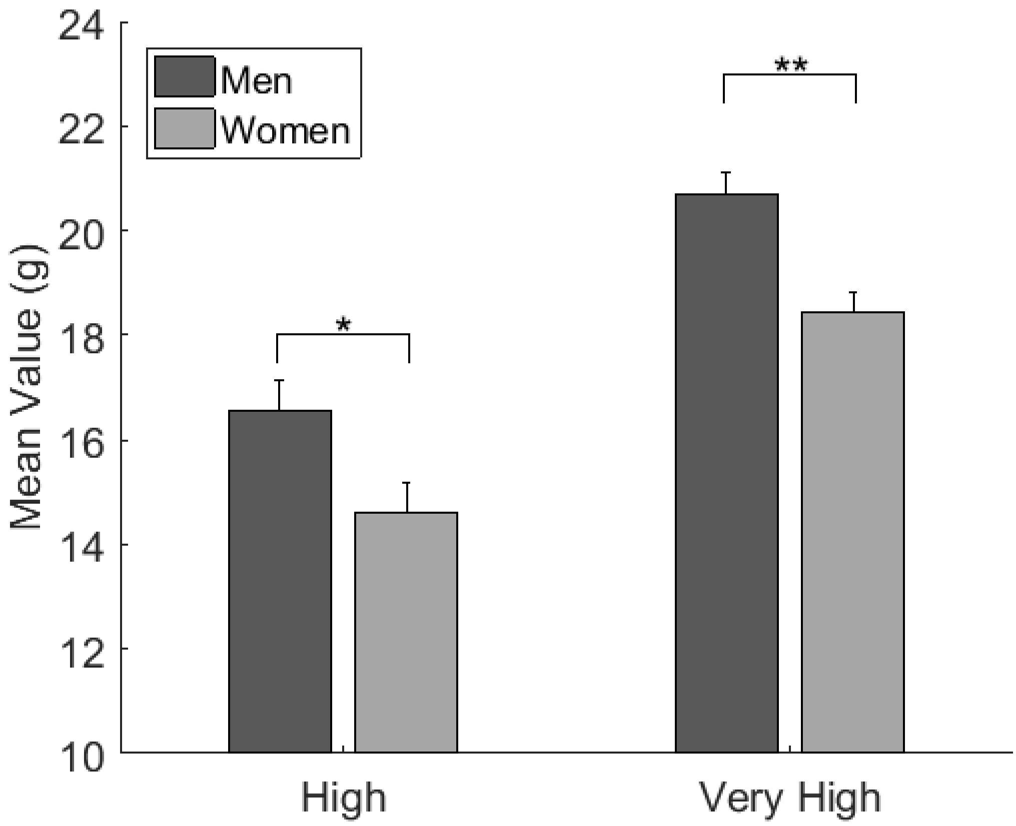

Figure 2: Magnitude of resultant accelerations above the *high* and *very high* threshold.
Error bars represent standard errors, * P < 0.05; ** P < 0.01

Peak Positive Acceleration

PPA and average PPA from the data collected during all four sessions exceeded the 16 g threshold of the device. When using the extrapolated estimates of PPA, there was a main effect for time on both PPA ($F_{(1,8)} = 6.389$, $P = 0.035$, $\eta_p^2 = 0.444$) and average PPA ($F_{(1,8)} = 6.666$, $P = 0.033$, $\eta_p^2 = 0.455$), with an increase of 11% and 9% in week-12 compared with week-1 respectively. There was no main effect for sex, nor was there an interaction effect.

Discussion

This was the first study to quantify tibial shock during military drill training in the field using a shank-mounted tibial accelerometer. Repetitive impacts at high tibial shock magnitudes were observed. PPA values were higher during drill training than those previously observed during running, which is in support of the hypotheses and previous findings. It is important to note that the PPA magnitudes were estimated using extrapolated values, meaning their accuracy is unknown. However, these values were greater than 16 g, which is more than twice as high as values typically observed during running [2–4], and more than 23% higher than values reported during single-leg drop landings (~13 g [5]). This was expected due to the nature of Army foot drill training, which includes exaggerated stamping of the foot [6]. Higher accelerations are associated with higher loading rates [8,9], and both of these variables have been associated with stress fracture occurrence in runners [7,10]. Single exposures to these high magnitudes are unlikely to result in bone damage, as they would be below the failure threshold of bone[19,20], but repeated exposure to such magnitudes may contribute to the high prevalence of stress fractures in military recruits. Injury was not an outcome measure in this study, and further exploration of any potential associations with injury is required.

Influence of Sex

The *moderate* threshold in the axial direction was used to identify impacts that were similar in magnitude to those regularly exceeded during running. The number of peaks during a session which exceeded this threshold was 353 on average, which is equivalent to the expected impacts during 1.9 km of running, according to estimates from data reported by Mercer et al. [21],. However, different damping mechanisms would be adopted during drill-type activity than during running, which may alter injury risk. Further investigation of this would provide valuable insight. The *very high* threshold was exceeded 46 times per participant, per drill session on average. During the week-12 drill session, male participants exceeded this threshold 115 times on average, compared with just 6 times in female participants. The greater rate of impacts above each threshold in men compared with women was likely due to a difference in the delivery of training, rather than a sex difference *per se.* The men and women completed training separately, and the sessions were led by different drill instructors, which is a limitation in the sex comparison, and makes interpretation of the *rate* of peaks difficult. There was no difference between men and women in the *magnitude* of tibial accelerations in the axial direction, in contrast with the hypothesis. However, the resultant acceleration may be more important than the axial acceleration in understanding the overall demands of this activity, and may provide more information regarding any differences in technique adopted by each sex.

The magnitude of the resultant acceleration is by definition greater than the axial acceleration and is indicative of the *total* acceleration of the shank. Resultant accelerations of 7.5 g and 10.6 g have been reported during running at 3.5 $m.s^{-1}$ and 4.7 $m.s^{-1}$ respectively [1]. Resultant accelerations exceeding the *high* threshold (10 g) can therefore be considered to be similar in magnitude to those experienced during fast running. The magnitude of peaks above both the *high* and *very high* thresholds was greater amongst men than women, which is in support of the hypothesis and previous findings [6]. However, this finding does not explain why women have higher rates of stress fracture than men in military populations [22,23], and suffer from more severe tibial stress fractures than men [24]. That is likely due to the differences in bone geometry and strength between men and women. Males have a greater bone size and strength than females [25–27], therefore the high magnitudes of tibial shock observed in both men and women during drill training are likely better tolerated by men. On the other hand, this finding may suggest that tibial shock during military drill training does not influence stress fracture risk. There were no differences between men and women in the magnitude of *axial* tibial shock, but magnitudes were greater in men than women for *resultant* tibial shock, which suggests that men and women adopt a different technique during drill activities, likely causing differences in the shear loading environment. Cortical bone is weakest under shear loading [28], thus the implications of this may be important in the context of skeletal injury. Differences in the loading environment could be influenced by anatomical and anthropometric differences or a difference in technique, due to a longer stride length for example.

Influence of Time (Week of Training)

Higher PPA values were observed during drill in the final week of training compared with the first, independent of the influence of sex. This was in support of the hypotheses and previous findings [6] and suggests that as participants became more practised at this activity, they may have adopted a technique which resulted in greater tibial shock. The reason for this is unclear, as it could be expected that a more experienced recruit may be better able to reduce tibial shock. The finding may instead reflect a more demanding drill session in the final week of the programme compared with the first. Alternatively, the higher tibial shock at the later phase of training may be the result of the cumulative fatiguing effects of the training programme, supporting previous observations of increased tibial shock when running in a fatigued state compared with unfatigued [4]. Nevertheless, higher tibial shock is likely undesirable in terms of injury risk [7,10], and a more thorough investigation of factors contributing to high tibial shock during drill training is recommended.

The resultant accelerations above both the *high* and the *moderate* thresholds were exceeded more frequently during drill training in week-12 than week-1, and this was independent of the influence of sex. This indicates that the drill training becomes more demanding throughout the programme for both men and women, as may be expected. Future development of military training programmes should consider the demanding nature of military drill training.

Unaccustomed Activity

The participants in the present study were unaccustomed to drill activity at the start of training, meaning the training would have likely led to bone remodelling [29]. It is possible that the high tibial shock reported in the present study may contribute to these early structural adaptations reported in the tibia in response to short periods of military training (Izard et al. 2016). However, in order for beneficial remodelling to occur, sufficient time to adapt to this high loading is required. The bone remodelling process takes approximately 13 weeks in total [30], with bone most weakened and susceptible to further damage two to four weeks after stimulation [31], due to increased microdamage. Therefore, repeated exposure to these high tibial shocks, with insufficient recovery, may increase the risk of stress fracture and further research is required to better understand this relationship.

Limitations

This study provides a useful quantification of tibial shock during military drill training, with a shank-mounted accelerometer the most suitable tool to estimate tibial shock non-invasively in this demanding environment. However, it is important to consider that this does not provide a direct measure of tibia loading or bone strain. Additionally, the peaks which exceeded 15 g were identified by extrapolation, and therefore should only be considered approximate magnitudes of peak tibial shock. These devices were nonetheless able to provide useful indicators of differences between males and females, and differences across the training programme, but the absolute magnitude of PPA values should not be assumed to be accurate. Follow-up studies which assess the magnitude of tibial shock using accelerometers with a greater upper limit are required to support these initial findings. This study also compared tibial shock in men and women. Men and women train in single-sex platoons during British Army Basic training and therefore any differences in tibial shock may be the result of the separate instruction they received, rather than sex differences. However, this would most likely influence the *rate* of peaks above each threshold, rather than the *magnitude*. The difference in duration of training between males and females in week-1 (Table 1) is an example of the differences in implementation of the training programme which can occur. The lengthier drill training session experienced by women than men in week-1 may have resulted in higher levels of fatigue, and this in turn may have influenced the magnitude of tibial shock. A lengthier session is not necessarily indicative of a more intense or demanding session. Further research should identify whether differences in magnitude between sexes are also observed when men and women undertake drill training simultaneously, using a larger sample of participants.

Conclusions

British Army drill training elicits extremely high tibial shock values, greater than those observed during high impact physical activities, such as running and jumping. This may contribute to the high rate of lower limb injuries in military recruits, and particularly the high stress fracture incidence. Men experienced greater magnitudes of tibial shock than women during drill training, and maximal shock increased from the first week to the final week of initial British Army training.

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