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Article

Comparison of Ground Reaction Forces between Combat Boots and Sports Shoes

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Abstract: It is unclear whether military shoes (combat boots and sports shoes) attenuate loading rate or affect force transfer during walking. Therefore, this study compared ground reaction forces (GRF) related to impact and force transfer between combat boots, military sports shoes, and running shoes. Ten army recruits walked over a walkway with two force plates embedded. GRF were measured when walking barefoot (for data normalisation) and with combat boots, military sports shoes, and running shoes. Loading rate, first and second peak forces, and push-off rate of force were computed along with temporal analysis of waveforms. Reduced loading rate was observed for the running shoe compared to the combat boot ($p = 0.02$; d = 0.98) and to the military sports shoe ($p = 0.04$; d = 0.92). The running shoe elicited a smaller second peak force than the combat boot ($p < 0.01$; d = 0.83). Walking with military shoes and combat boots led to larger force transfer than running shoes, potentially due to harder material used in midsole composition (i.e., styrene-butadiene rubber). Combat boots did not optimise load transmission and may lead, in a long-term perspective, to greater injury risk.

Keywords: gait; loading rate; ethylene-vinyl acetate; styrene-butadiene rubber

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1. Introduction

Physical training is a key part of the job requirements of defence personnel, involving marching, jumping, and walking with large external loads. Several studies have indicated that external loads can contribute to an increased likelihood of injuries during operational tasks [1]. Aerobic and strength training are also prescribed to improve general fitness [1]. During these activities, recruits use various types of shoes, from military boots to regular sports shoes [2]. However, it has been observed that the type of footwear used by military personnel could also increase injury risk, including acute (e.g., foot blisters [3]) and overuse (e.g., stress fractures [4]), particularly when walking with combat boots [5,6].

It has been long established that shoes can affect ground reaction forces (e.g., altering vertical loading rate) during running and walking [7–9] due to the characteristics of the shoe midsole [10] and due to shoe–ground interaction [11]. Among the variables assessed from ground reaction forces, loading rate (i.e., rate of vertical force increments at the initial stance phase) has been a key variable because it relates positively to the velocity at which ground reaction forces are absorbed by the musculoskeletal system [12,13]. Therefore, large loading rates lead to faster transfer of force and less time for the soft tissues to accommodate the load [14], which could lead to overuse injuries. In addition, push-off rate of force (i.e., rate of force decrement late in the stance phase) can indicate how rapidly the forces are applied to propel the body forward during motion [7]. Large rate of force decrement could also lead to overuse injuries given the increased force transferred through the metatarsal heads [15]. Therefore, shoe design could play a role in alleviating force transfer through the foot by improving the cushioning characteristics of shoe midsole.

For army recruits, boots used during marching and other activities have been shown to reduce ankle range of motion [2] without differences in loading rate or push-off rate of force compared to a generic running shoe [7]. Although these findings may show that military boots do not affect force transmission, Paisis et al. [7] tested subjects in their shoes without reporting the shoes' characteristics (e.g., material of the shoe midsole or shoe design), which limit implications from their findings. Military boots have been shown to increase Achilles tendon force [16] and knee load [17] compared to running shoe with EVA (ethylene-vinyl acetate) midsole. However, differences to a shoe with mixed EVA and rubber, as commonly observed in running shoes [15,18], has not been assessed in terms of loading rate or force transfer. This is critical to provide data that could support the improvements in design of military shoes, in order to reduce injury marks in army recruits [1]. Moreover, the temporal analysis of ground reaction forces is critical because it allows for detecting differences in external forces which are not always captured when analysing zero-dimensional data, i.e., peaks and means [19].

Therefore, the aim of this study was to compare ground reaction forces between combat boots, sports shoes designed for military training, and running shoes during walking gait. The option of walking was based on the large proportion of walking activities performed by military personnel, i.e., 60–70% of physical activity [6,20]. The assessment of a sports shoe designed for military training was based on the use of the same type of midsole compared to the combat boot, which should allow for differences in shape between boots and shoes to be further explored. The hypothesis of this study was that the combat boot and the sports shoe would have larger loading rates and push-off rates of force compared to the running shoe.

2. Methods

2.1. Participants

This study design was cross-sectional with randomised crossover trials between types of shoes. Sample size calculation was performed using G*Power 3.1.9.7 [21] for an ANOVA with repeated measurements. Effect size was defined as $f = 0.5$ (large effect), $\alpha = 0.05$, and power = 0.80, with one group performing three trials (one for each shoe). This calculation resulted in nine participants being required. Therefore, 10 army recruits (28 ± 1.8 years of age, 75 ± 3.9 kg of body mass and 177 ± 6.6 cm of height) volunteered to take part in the study. Before taking part in the study, all participants read and signed an informed consent form with details of the study approved by the local committee of ethics in research with humans (approval code: 46243715.4.0000.5235).

2.1.1. Shoe Specifications

Combat boots, military sports shoes, and running shoes (size 43 Europe—see Figure 1), with specifications as described in Table 1, were used in this study. For measurements of shoe mass, a force plate was utilised (resolution of 9 g, FP4060-10, Bertec Corporation, Columbus, OH, USA). Midsole stiffness were collected from testing conducted by manufacturers, following local guidelines for shoe assessments [22].

Figure 1. Military sports shoe (**A**), combat boot (**B**), and running shoe (**C**).

Table 1. Specifications of the combat boot, military sports shoe, and the running shoe.

Shoe Type	Mass (g)	Midsole Height (cm)	Shoe Structure and Midsole Properties	Insole
Combat boot (LV Distribuidora LTDA, Brazil)	550	Forefoot: 270 Height: 380	11 holes cording SBR midsole (≈65 Shore A stiffness)	EVA
Military sports shoe (LV Distribuidora LTDA, Brazil)	350	Forefoot: 280 Height: 380	5 holes cording SBR midsole (≈65 Shore A stiffness)	EVA
Running shoe (Prorunner 17, Mizuno)	260	Forefoot: 210 Height: 350	5 holes cording Carbon sole with 30% EVA (≈45 Shore A for EVA stiffness)	EVA

EVA—ethylene-vinyl acetate, SBR—styrene-butadiene rubber.

2.1.2. Data Collection

Before gait analysis, participants' height and body mass were measured using a weight scale (Prix 2098PP, Toledo, Brazil). After that, all participants were familiarised with the gait analysis procedures, which involved walking barefoot over a wooden walkway with 11 m of length. At the centre of the walkway, a pair of force plates (FP4060-10, Bertec Corporation, Columbus, OH, USA) were embedded to enable measurements of the ground reaction forces. During familiarisation trials, participants were instructed to modulate their gait pattern (via changes in stride length and cadence) in order to walk at 5 ± 0.25 km/h. For assessment and feedback on walking speed, two measurements were taken by two experienced technicians, on the basis of the time taken to cover a distance of 4.3 m (i.e., length of the force plates at the wooden walkway) [23].

After familiarisation, participants performed 10 trials of barefoot walking at the target speed and with a stride length that enabled a full contact of the foot in each force plate (one for each foot). After that, in random order, they performed 10 walking trials using the combat boot, the military sports shoe, and the running shoe. Walking trials were repeated if walking speed varied beyond the prescribed and if participants did not step in full with their feet on the force plates. Ground reaction forces were collected during all trials using the software from the force plates (Digital Acquire 4.0.12.411, Bertec Corporation, Columbus, OH, USA) at a sampling rate of 1kHz (per channel). Time for covering the

4.3 m distance was recorded, using two time-watches (WT058, DLKSports, Barueri, SP, Brazil), in a spreadsheet for later computation of mean walking speed between trials and for provision of feedback on walking speed to participants during each trial.

2.1.3. Data Analyses

Heel strike and toe-off were detected using a 20 N threshold [24] in order to determine stance phases (i.e., contact time) for each foot. After that, first and second peaks were determined from the vertical component of the ground reaction force waveforms for each foot. The slope of 10–90% of first peak force was used to calculate instantaneous loading rate (after heel strike) in order to assess rate of loading (i.e., transfer of force between the ground and the feet). The slope of 90–10% of the second peak force enabled us to calculate push-off rate (i.e., rate of unloading, before toe-off, Figure 2), which allowed us to assess the rate of unloading (i.e., transfer of force between the feet and the ground). Force data were time-normalised to 100 samples using heel strike and toe-off to enable temporal statistical analysis of data. All data processing was conducted using custom made scripts (Matlab, MathWorks Inc, Massachusetts, MA, USA).

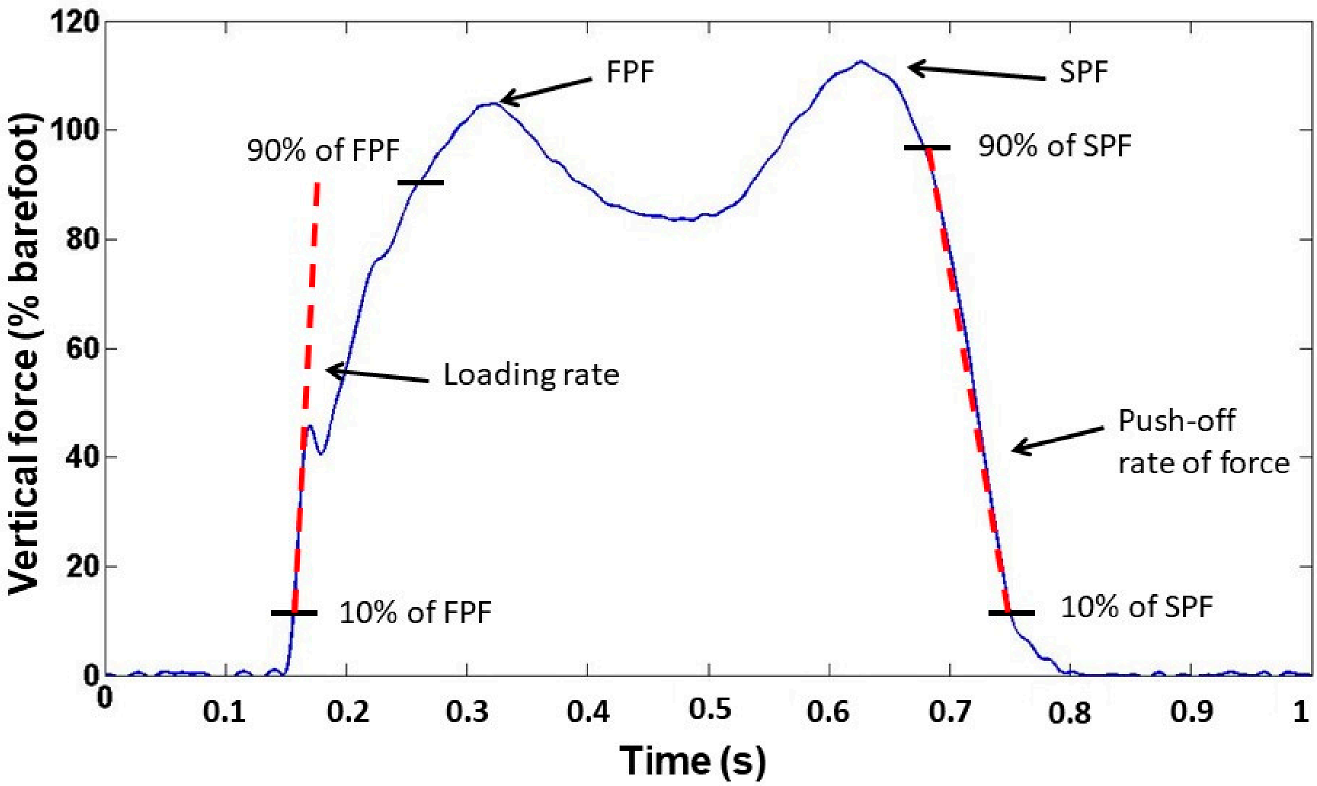

Figure 2. Illustration of the first (FPF) and second (SPF) peak force used to determine a range of 10–90% of each peak force. These ranges were then used to determine loading rate (after heel strike) and push-off rate of force (before toe-off).

2.2. Statistical Analyses

Vertical ground reaction force data were normalised to outcomes taken from the barefoot trials in order to reduce non-uniformity distribution of the data, then converted into means from both force plates. Mean and standard deviation of the first and second peak forces, contact time, loading rate, and push-off rate of force were computed. Differences between shoes were assessed using repeated measures ANOVA followed by post-hoc analysis (with Holm's correction) when main effects were observed. Magnitude of differences were rated using Cohen's effect sizes d [25]. Substantial differences between shoes were assumed when $p < 0.05$ and Cohen's d > 0.80. A statistical package (JASP, Version 0.13.1, University of Amsterdam, the Netherlands) was used for statistical analysis.

For analysis of differences between boots and shoes in terms of temporal patterns, one-dimensional force data were analysed by repeated measures ANOVAs using the SPM method (Pataky et al., 2013). Pairwise comparisons were performed using paired samples *t*-tests with Bonferroni correction in order to protect from Type I error. Critical t-thresholds were determined at $\alpha = 0.05$ (Pataky et al., 2016). SPM analyses were implemented in Matlab (MathWorks Inc, Massachusetts, MA, USA) using the spm1d toolbox (http://www.spm1d.org; accessed on the 2 December 2019).

3. Results

The control of timing at the central section of the walkway secured similarities in walking speed between trials ($p = 0.24$; Table 2). There was a reduced loading rate for the running shoe compared to the combat boot ($p = 0.02$ and d = 0.98) and compared to the military sports shoe ($p = 0.04$ and d = 0.92). In addition, the running shoe elicited a smaller second peak force than the combat boot ($p < 0.01$ and d = 0.83). There was also a trend for lower second peak force for the military sports shoe compared to the combat boot ($p < 0.01$ and d = 0.69). These results are shown in Table 2.

Table 2. Mean (SD) gait speed, loading rate, first and second peak forces, and push-off rate of force for walking trials with combat boot, military sports shoe, and running shoes.

	Combat Boot	**Military Sports Shoe**	**Running Shoe**
Gait speed (m/s)	1.41 ± 0.01	1.42 ± 0.02	1.42 ± 0.01
Contact time (s)	0.67 ± 0.02	0.67 ± 0.03	0.67 ± 0.03
Loading rate (% barefoot)	19 ± 3	20 ± 5	16 ±2 *#
First peak force (% barefoot)	106 ± 3	105 ± 3	105 ± 3
Second peak force (% barefoot)	104 ± 1	101 ± 2	101 ± 1 *
Push-off rate of force (% barefoot)	90 ± 12	83 ± 11	86 ± 10

* Indicates difference to combat boot and # indicates difference to military sports shoe when $p < 0.05$ and d > 0.80.

Main effects were detected by the SPM-ANOVA for the vertical ground reaction force between 73 and 78% of the stance, but differences in post hoc test were only observed between the combat boot and the running shoe at 73–74% of the stance (Figure 3).

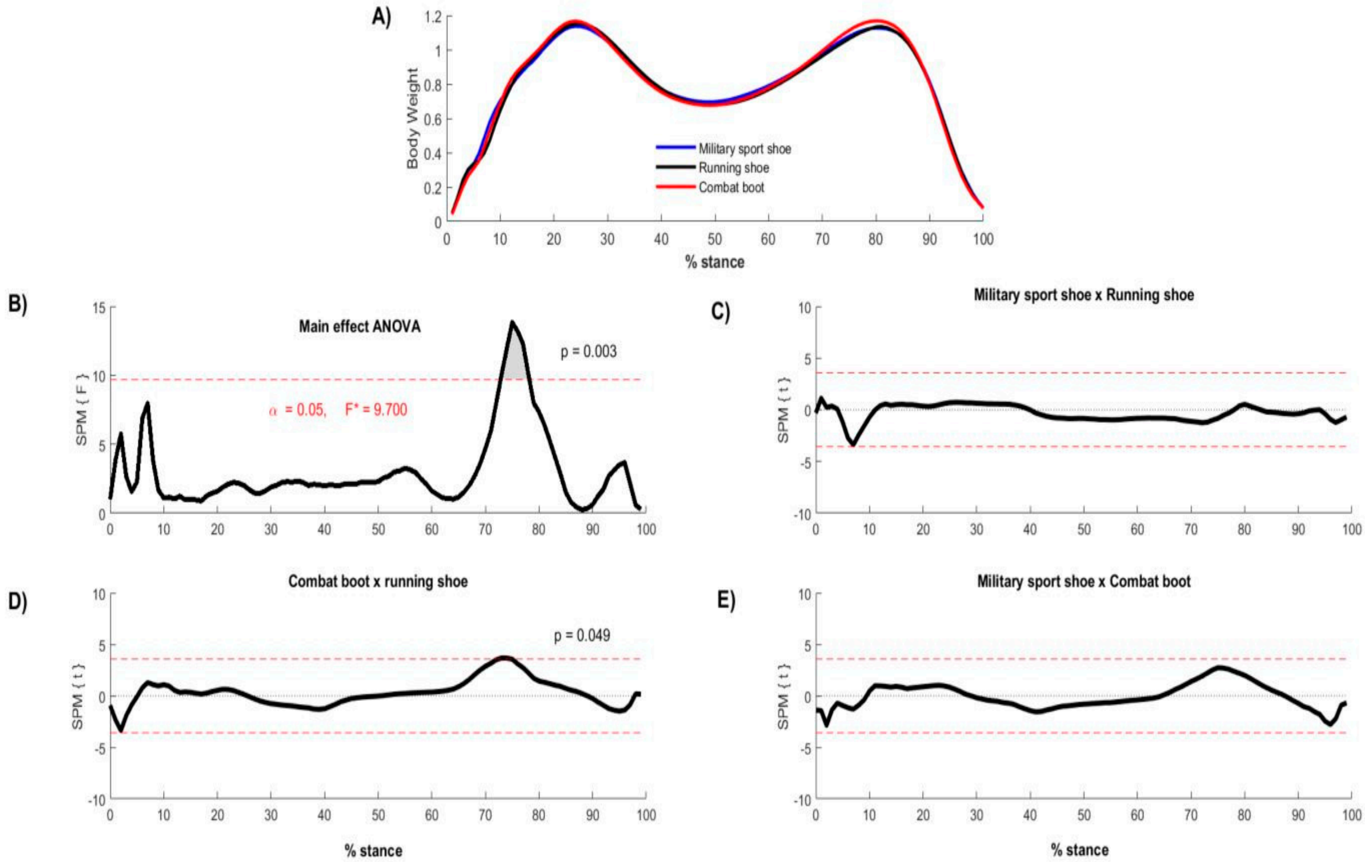

Figure 3. (**A**) Average vertical GRF data. (**B**) ANOVA footwear main effect trajectory. The horizontal dotted lines indicate the critical random field theory threshold of $p < 0.05$. As the SPM F* line crossed the dotted line above, a statistical difference was found. (**C**) *t*-test comparison between military shoe vs. sports shoe. (**D**) *t*-test comparison between combat boot shoe vs. running shoe. (**E**) *t*-test comparison between military shoe vs. combat boot.

4. Discussion

Although research on shoe midsole material has been covered in many studies, the assessment of shoes used by military recruits has received less attention compared to sports shoes [7,16,17,26]. These studies were generally limited to the comparison of combat boots with users' own shoes [7] or custom-made shoes [17,27]. The main finding from the present study was that combat boots and military sports shoes presented reduced cushioning properties compared to a commercially available running shoe. This information is new because it indicates that a shoe with a midsole merging EVA and carbon rubber (i.e., running shoe) provides improved cushioning compared to the SBR midsole used in combat boots and in the military sports shoe. A secondary finding was that a trend was observed towards larger second peak force for the combat boot compared to the military shoe ($p < 0.01$ and d = 0.69). This element suggests that limitations in ankle range of motion described elsewhere [2] from the combat boot could play a role given SBR midsole was common to combat boots and the military sports shoe.

Shoe midsole has been shown critical to reduce plantar pressure [15], Achilles tendon loading rate [16], and knee loads [17,28] during walking and running. Therefore, the choice for a proper shoe seems to help reducing musculoskeletal loading. Indeed, the running shoe presented better cushioning profile (reduced loading rate) compared to the combat boot and to the military sports shoe potentially because it has 30% of EVA associated with carbon rubber at the midsole. Differently, the military shoe and the combat boot had a SBR midsole (≈65 Shore A stiffness) which is harder compared to the EVA (≈45 Shore A stiffness). Contrary to this, a recent comparison of combat boots indicated that boots with harder midsole were associated with less loading rate [19,29]. In a different line, Paisis et al. [7] observed similar loading rates for combat boots compared to users' running shoe, which could be linked to differences in experimental design. In the present study, a brand-new shoe was used rather than the users' shoes, which should present altered midsole properties from long term use [30]. A second difference involves the assessment of ground reaction forces using overground walking (present study) rather than treadmill walking, which would influence walking gait style. A third difference was that loading rate was normalised, for each shoe in the present study, by the individual's loading rate during barefoot trials in order to reduce the variance from individual's gait profile [31]. However, further studies may be required to fully examine other gait changes related to the use of shoes and boots with different design (e.g., kinematics of boots and shoes with the same midsole structure).

The second part of stance phase is related to the propulsion of the body towards the swing phase [32]. Therefore, the trend for the larger second peak force when walking with the combat boot at the same speed could be associated with an attempt to mitigate the limited ankle plantar flexion [2] (i.e., reduced angular velocity). In order to sustain equivalent ankle power, we should expect that ankle torque would increase for the combat boot. This would then possibly lead to larger force applied between midstance and toe-off. This element was partially highlighted by Sinclair et al. [16], who observed increased loading rate at the Achilles tendon when recruits ran with combat boots rather than with running shoes. In addition, larger second peak forces may lead to increased pressure at the metatarsal heads [15], increasing the risk of injuries in the forefoot. However, more data are needed to ascertain if larger forces could be associated with larger pressure at the forefoot when using combat boots.

Although differences in loading rate and second peak force were observed between combat boots compared to running shoes, contact time during stance was unaffected by footwear. This result suggests that stride length was potentially similar between shoes due to walking speed control. For overground walking, the control of speed is critical because, different from treadmill walking, larger degrees of freedom are available during overground walking, which could affect ground reaction forces. Therefore, previously observed increases in activation of peroneous longus, tibialis anterior, and rectus femoris when walking with combat boots could be related to participants attempting to optimise force transfer through the ankle joint and control joint kinematics given the restriction in ankle motion [26]. We also did not observe substantial differences between shoes in terms of temporal patterns (i.e., force waveforms), which could be associated with the prescribed walking speed. This is somehow surprising because SPM analysis have been shown sensitive to determine differences between boots with SBR vs. polyurethane midsole [19]. It may be that combat boots and military shoes with the same type of midsole may have subtle differences that are not detectable by the SPM analysis. The fact that the SPM analysis was conducted using data normalised by body weight rather than the barefoot trials could also add differences to the outcomes. Future studies could explore new ways to normalise ground reaction force data in order to use these waveforms for temporal comparisons.

The present study was limited to some extent. The absence of measurements of muscle activation and joint kinematics limited the combined analysis of joint control and ground reaction forces, as conducted in other studies [2,26]. The use a different insole for the running shoe, compared with the combat boot and the military shoe, may have impacted our results, although all insoles were built from EVA. In addition, data from Paisis et al. [7] showed that EVA and polyurethane insoles did not affect loading rate or push-off rate of force. Therefore, it is unclear if the type of insole largely influenced our results. It is also important to acknowledge that the mass of shoes was not controlled, which could have implications in ground reactions forces during walking [19]. As example, energy expenditure while walking can increase by 0.7 to 1% for every 100 g increase in footwear mass [33]. The mass increment of the combat boot and military sport shoe could increase muscle activity and muscular fatigue [34], leading to an increased impact during gait.

5. Conclusions

In conclusion, combat boots and military sports shoes presented larger loading rate than running shoes during walking, which was thought to be potentially due to harder material used in the midsole (i.e., SBR). Combat boots also elicited increased second peak force, which was possibly associated with limited ankle range of motion. Combat boots used by army recruits do not optimise load transmission and may lead, in a long-term perspective, to greater injury risk.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data will be made available upon reasonable request to the corresponding author.

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Conflicts of Interest: The authors declare no existing conflict of interest for the content of the article.

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