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Original Research

Influence of Combat Boot Types on In-shoe Forces and Perceived Comfort during Unloaded and Loaded Walking

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Declarations

Ethics approval and consent to participate

All methods of this study were performed following the Declaration of Helsinki and were approved by the Nanyang Technological University Institutional Review Board (Protocol Number: 2020-08-013). All participants provided written informed consent before the start of the study.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and analysed during the current study are available at the NIE Data Repository: https://doi.org/10.25340/R4/KS5EE7.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Conceptualization: PWK and EY. Data collection: EY and KC. Data analysis: EY and PWK. Writing—original draft preparation: EY and PWK; writing—review, and editing: EY, KC and PWK. Supervision: PWK. All authors approved the final manuscript and agreed to be accountable for all aspects of this research.

Influence of Combat Boot Types on In-shoe Forces and Perceived Comfort during Unloaded and Loaded Walking

Abstract

Introduction: Combat boots are essential protective gear for military personnel. The purposes of the present study were to examine 1) the influence of combat boot type on ground reaction force (GRF) variables and perceived comfort during unloaded and loaded walking, and 2) the relationship between comfort and biomechanical measurements.

Methods: Four types of combat boot with different physical features (e.g. mass, thickness) and mechanical properties (e.g. cushioning, rigidity) were compared across 61 male participants with experience in military marching while carrying heavy loads. In each boot type, participants completed a 10-m walk under an unloaded and a 20-kg loaded conditions at their preferred speeds. Peak force and loading rate during walking were measured using the loadsol® wireless in-shoe sensor system. Comfort level was assessed using a 7-point Likert scale. Difference between loaded and unloaded walking, and across boot types were statistically compared. Correlation analyses were performed between comfort and GRF variables.

Results: On average across all boot types, participants walked 2.1% slower when carrying 20-kg loads while experiencing 24.3% higher peak force and 20.8% higher loading rate. Boots D was perceived as most comfortable, followed by Boots C, B and A ($\chi^2(2) = 115.4$, $p < 0.001$). Participants walked slightly faster ($p = .022$, $\eta_p^2 = 0.052$) and displayed higher loading rates ($p < .001$, $\eta_p^2 = 0.194$)

in the two more comfortable boots (C and D) than the less comfortable boots (A and B). No significant correlations were found between perceived comfort and any GRF variables.

Conclusions: Combat boot features can influence perceived comfort ratings substantially during walking whereas biomechanical differences among boot types are more subtle regardless of load conditions. The lack of relationship between comfort and force variables suggests that both subjective and objective measurements should be considered for comprehensive evaluation of combat boots.

Keywords: Military, load carriage, combat footwear, gait, ground reaction forces, loading rate

Word count: 297

Key Messages

- This study compared four types of combat boots during walking at self-selected speed while unloaded and carrying 20-kg loads.
- Walking speed, in-shoe ground force and perceived comfort level were measured in 61 males with military experience.
- When carrying 20-kg loads, participants walked slower while experiencing higher peak force and higher loading rate compared with unloaded walking.
- Participants walked slightly faster in the two more comfortable boots, which were also characterized by higher loading rates.
- There were no relationships between comfort and force variables, suggesting that both subjective and objective measurements should be considered to comprehensively evaluate combat footwear.

Introduction

Lower limbs overuse injuries such as plantar fasciitis, patellofemoral pain and Achilles tendinopathy are of concern in the military populations.[1-4] Overuse injuries occur when there is an accumulation of repetitive loading forces acting on the musculoskeletal structures causing microtrauma over time.[5-7] The duties of a soldier are often physically demanding, requiring prolonged periods of dynamic movements and weight-bearing activities which may result in overuse injuries. Indeed, overuse injuries were more prevalent than traumatic injuries such as sudden once-off overload to tissue or joint.[2] Since the recovery and rehabilitation programme of lower limb injures can be extensive,[8] an injured soldier is unlikely to be combat-ready for a long duration resulting in repercussions to effective military operations. Other consequences may include an increased attrition rate and financial costs.[9] Therefore, it is of utmost interest to identify risk factors and develop strategies for injury prevention in the military.

One possible factor that may influence lower limb injuries is the choice of combat boots.[10-13] While combat boots are essential protective gear for military personnel, it has been suggested that the poor shock absorption properties, poor fit and inadequate comfort of combat boots can be possible contributing factors to injuries.[1, 11] Appropriate cushioning in footwear has been shown to improve shock absorption during locomotion[14,15] while inadequate cushioning properties were related to large impact forces acting on skeletal structures.[9, 16] Bini et al. reported that walking with military shoes and combat boots led to larger force transfer than running shoes.[10] The authors cautioned against a high injury risk in the long term since combat boots did not optimise the load transmission.

While a shoe may have desirable physical features and mechanical characteristics, it may not be perceived comfortable for all individuals. Hence, subjective rating is another important factor for footwear design and evaluation.[17] The 'comfort filter' concept theorises that if one chooses a comfortable shoe, injury risk may be reduced as one will remain in their 'preferred movement path'.[18] Specific to the military context, Mundermann et al. found that shoe inserts that were perceived as comfortable were able to reduce stress fractures and pain at different locations by 1.5 to 13.4%.[19] Regarding the relationship between plantar pressure and comfort in military boots, Lange et al. reported comfort ratings improved with decreased peak pressure, particularly at the forefoot regions that were associated with high risk for metatarsal fractures.[20] These earlier findings suggested that biomechanical loading and comfort ratings are inter-connected and both factors can influence lower limb injuries.

Most studies on combat boots were performed mainly in the Western demographics such as United Kingdom, Brazil, Australia and Cypriot.[10, 11, 16, 21-22] Their findings may not be directly applicable to Asians due to the foot structural differences such as wider feet and lower instep in Asians than Europeans.[23] Thus, it is important to understand how different features of combat boots could influence the biomechanical loading characteristics and comfort in the Asian population. In regions such as Singapore which is situated near the equator, the humid tropical climate and high temperature may also influence the perceived comfort of combat boots. Another consideration is the high loads of tactical equipment and body armor in combat training and field operations.[21,24] Previous studies tend to focus on either loaded [20] or unloaded [10,11,14,22] walking but biomechanical response and perceived comfort may vary with load carriage. Hence, there is a need to include both loaded and unloaded conditions in the same test protocol for comparison.

Thus, the primary purpose of the present study was to examine the influence of combat boot types on ground reaction force (GRF) variables and perceived comfort during unloaded and loaded walking in Singapore. A secondary purpose was to examine the relationship between comfort and biomechanical measurements. It was hypothesized that (1) walking in combat boots with desirable features would display lower magnitude in GRF variables and higher comfort rating under both unloaded and loaded conditions, and (2) comfort scores would be negatively correlated with the magnitudes of GRF variables. Findings from the present study would clarify the interplay of boot type and load carriage on biomechanical and comfort variables and provide empirical data on Asians under a tropical climate.

Methods

Participants

This study was approved by the [blinded] Institutional Review Board. Written informed consent was obtained from all participants before any experimental procedures. Based on a small-to-medium effect size ($f = 0.15$, 80% power, $\alpha = 0.05$) for four pairs of boots, a sample of size of 62 participants was required. We have initially invited a total of 64 male participants, of which 3 did not meet all inclusion criteria: (a) male, (b) aged between 21 and 45 years old, (c) with boot sizes between US 7.5 to 10.5. Participants were excluded if they (a) had past surgeries for lower limbs, (b) had serious injuries to their back or lower extremities within the past three months which required more than seven days of rest or (c) experiencing discomfort or pain at the time of the study was conducted. The physical characteristics of the 61 eligible participants are shown in Table 1. As national service is mandatory for men in Singapore, all participants had experienced with military marching while carrying heavy loads.

Combat Boots

Four different types of combat boots with different physical features and mechanical properties were used in this study (Figure 1, Table 2). These four boot types covered the range of typical models used by military personnel and national servicemen in Singapore. There were differences in the shoe mass, dimensions, material used for cushioning (e.g. cork, polyurethane), and moulding technology. In the production process, directly applying the outsole of the boots to the upper lining (Boots A and B) is considered a lasting approach for active use. Alternately, Boots C and D utilized a cold-cementing and additional stitching method to secure the outsole to the upper lining of the boots, increasing its durability. Boots D have two additional distinct features, which were a hiking lace system to provides better ankle stability to improve fit and a honeycomb structure to enhance shock absorption. To minimise the influence and bias associated with boot brands, any indication of the brand were covered by tapes during the study. As the trial boots were brand new, they were broken in by 10 minutes of walking at the start of the study.

Instrumentation

This study used the loadsol® (novel GmbH, Munich, Germany), a wireless in-shoe force sensor, to measure the vertical GRF during walking (Figure 2). Good validity and reliability of the loadsol® system has been demonstrated for walking and running activities.[25] The loadsol® sensor were calibrated using the participant's body weight following the manufacturer's instructions. Data were recorded via the Novel loadsol® application version 1.6.0 on an iPad (6^{th} Generation, Apple, Inc., Cupertino, CA). The resolution of force was set to 5 N in the range of 0 to 2550 N, with the maximum sensor scanning rate of 100 Hz. For the perceived comfort test, a 7-point Likert scale was used.

Procedures

All data were collected in a single session for each participant. The Brannock foot device (The Brannock Device Co., Liverpool, NY, USA) was used to measure the foot size to assign the correct boot size for each participant. The boots were considered fitting if the participants expressed no tightness, pressure points, or extra space in the boots. Participants performed repeated walking trials in four types of boots and two loading conditions, with the test orders randomised.

In each type of combat boots, the participant would first be familiarized with the boots by walking on levelled ground at their own self-selected pace for 5 minutes (Figure 2). Next, they would rate their overall perceived comfort of the boot before the loadsol® sensors were inserted into the boots. The test orders were planned as such to ensure that participant's comfort ratings of the boots were not affected by the loadsol® sensors and the connecting straps. After calibrating the loadsol® sensors, the participant was subjected to two randomly assigned conditions: 1) unloaded walking, and 2) loaded walking with a 20-kg field pack to simulate a realistic training situation such as a road march. The participant walked on a 10-m walkway in their preferred gait style and at their self-selected speeds. After two practice trials, an actual 10-m walk test would proceed with GRF recorded at 100 Hz. The time taken to complete the 10-m walk was noted and used to calculate the mean walking speed.

From the vertical GRF time series data, the loadsol® application displayed a summary of GRF variables that were averaged over all left and right steps over the entire 10-m walk. Two variables were chosen for analysis: 1) peak force, which was the maximum force value of each step taken, and 2) loading rate, calculated as the slope of vertical GRF from 20% to 80% of the time from initial contact to peak impact force. These types of GRF variables are commonly used to evaluate combat footwear during walking.[10]

Statistical Analysis

Statistical analysis was performed using JASP (Version 0.14; JASP Team, 2020) statistical software. Data normality was checked using the Shapiro–Wilk tests. Data are expressed as mean and standard deviations (SD). Statistical significance level was set at $p < 0.05$. For walking speed and GRF variables, a two-way 4 × 2 (Boot × Load) repeated measures analysis of variance (ANOVA) was used to compare across the boots and loading conditions. *Post hoc* analyses using Bonferroni adjustments were used when necessary. Since the comfort data were not normally distributed, non-parametric statistical analyses were applied. First, the Friedman's repeated-measures ANOVA was used to compared across the four boot types, with Conover's *post hoc* tests for pairwise comparison where appropriate. Next, Spearman's rank correlation tests were performed to examine the relationship between comfort ratings and GRF variables during unloaded walking.

Results

Effect of Load

There was a main effect of Load in speed and GRF variables (Table 3). Based on the average body mass of 73.8 kg, the additional 20-kg of loads was approximately 27% of the participants' weight. Averaging across the four types of boots, participants walked 2.1% slower while experiencing 24.3% higher peak force and 20.8% higher loading rate during loaded walking when compared with unloaded walking.

Effect of Boot

When comparing the four types of boots, there was a significant main effect of Boot in walking speed with a small effect size. Participants walked slightly faster in Boots C and D (1.38 m/s) than boots A and B (1.35 m/s), though no statistically significant *post hoc* differences could be detected (Table 3). For GRF variables, there was a significant main effect of Boot for peak force and loading rate. Significant Boot × Load interaction was also found for loading rate. *Post hoc* analyses revealed that the peak force was lower in Boots C than B, while the loading rates were higher in Boots C and D when compared with Boots A and B.

Comfort Variables

The perceived comfort ratings significantly differed among the four types of boots ($\chi^2(2)$ = 115.4, $p < 0.001$). The highest comfort rating was observed Boots D (6.39 (0.61)), followed by Boots C (6.03 (0.75)), Boots B (4.56 (1.23)) and Boots A (3.95 (1.40)). Conover's *post hoc* analysis revealed no difference between Boots C and D ($p = 0.790$) and these two models were more comfortable than Boots A and B (all $p < .001$) There was no *post hoc* difference between the two less comfortable boots (A vs B, $p = 0.683$). Regarding the relationship between comfort and GRF variables, no statistically significant Spearman's correlation was found (Figure 3).

Discussion

This study examined the influence of combat boot types on forces and comfort during walking and investigated the relationship between comfort and biomechanical measurements. The first hypothesis was that walking in combat boots with desirable features would display lower magnitude in GRF variables and higher comfort rating during walking. Our findings, however, do not fully support this hypothesis.

Perceived Comfort

For comfort ratings, it was clear that participants preferred the two more advanced boot types (C and D) over the basic models (A and B). The two more comfortable boots are generally lighter, more breathable, had lower heel thickness and wider boot width, and offer shoe tongue cushioning and better slip resistance (Table 2). The fitting of the boots can also influence subjective comfort perception. Foot scans for different populations around the world showed Asians have wider feet.[23] The boot models used for this study originated from North American and European manufacturers and therefore may not fit well for Asians. The two more comfortable boots in the present study indeed have a wider boot width (10.6 cm) than the less comfortable boots (9.8 to 10.2 cm). Incorporating foot scan data may provide more detailed information to optimise the fitting of combat boots. The most comfortable model D has two additional features of a hiking lace system for ankle stability and a honeycomb structure for shock absorption. These characteristics should be considered in the design and development of combat boots for optimal comfort.

Ground Reaction Force Variables

In contrast to our first hypothesis, the loading rates were higher in the more comfortable boots (C and D) with advanced features than those the basic models. Silva et al.[26] showed that thicker heels lower maximum deceleration, achieving better attenuation of impact force. The higher loading rates in Boots C and D may be related to the thinner heel thickness (2.2 cm) compared with Boots A and B (3.2 – 3.3 cm). Our findings support previous work that thicker styrene-butadiene rubber material in the military boot midsole was more effective in reducing impact, while the lightest boots with softer polyurethane midsole was the most comfortable.[11]

Another factor that may have affected loading rates is walking speed which was slightly faster in the two more comfortable boots (1.38 m/s) than the two less comfortable boots (1.35 m/s). Faster speeds can contribute to the higher loading rates. If the experiments were conducted on a treadmill with fixed speeds, the influence of boot type on GRF variables would be clearer without being affected by self-selected speeds. Allowing participants to choose their own speeds in a field test, on the other hand, offer better ecological validity to reflect actual operational situations. When sufficient time and resources are available, it will be ideal to include both controlled laboratory trials and field tests to comprehensively evaluate the influence of combat boots design on human performance. It is interesting to note that participants walked faster in more comfortable boots, suggesting that wearing comfortable footwear may offer some advantages in work efficiency. Studies have reported that the weight of military boots can place stress on untrained individuals, with every 100 g added to the foot increases energy expenditure by 1% during locomotion.[27,28] The lighter boots in the present study likely allowed participants to move more economically, feeling more comfortable and walking at faster speeds. Future studies can extend beyond walking to explore how footwear comfort can influence work performance and efficiency in other operational tasks.

It may seem puzzling that Boots C was characterized by higher loading rate but low peak force than Boots B. This apparent difference in GRF magnitudes is likely due to the way how GRF variables were analyzed. In each walking step, there are two peaks in the vertical GRF time curve which correspond with heel impact and push-off, respectively. The loadsol® software extracts the peak force as the maximum force of a step regardless of the first or second peak. The loading rate, on the other hand, was calculated from the first peak force which is associated with the heel impact. In a laboratory study on army recruits which used the force platform to measure GRF, walking in combat boots resulted in higher loading rates and higher second peak force than running shoes while no difference was found for the first peak force.[10] Thus, it is possible that Boots C had a higher loading rate at heel impact and a lower push-off force than Boots B in the current study.

Relationship between Comfort and Biomechanical Variables

The second hypothesis of this study was that comfort scores would be negatively correlated with the magnitudes of GRF variables. While participants showed clear preferences in the comfort ratings, differences in biomechanical variables were more subtle. There were no significant correlations between comfort and any GRF variables and hence our second hypothesis was not supported. These findings parallel those by Paisis et al.[22] who did not find any association between GRF and comfort ratings of different insoles worn with running shoes and military boots. The authors further reported that military boots were rated poorly even with insoles, suggesting that the shock absorption qualities were not adequate to determine the comfort level of military boots. Other researchers, on the other hand, have reported differences in plantar pressure and tibial acceleration but no difference in footwear comfort ratings among defence boots with different insoles.[14] Our results indicated that perceived comfort and biomechanical measurements assess different dimensions of combat boots. Thus, we cannot simply use comfort to indicate force magnitude, and vice versa. To comprehensively evaluate combat boots, a combination of mechanical, biomechanical and subjective measurements is warranted.

Limitations

First, participants may not be fully accustomed with the combat boots with only 5 minutes of familiarisation time. Future studies can allow participants to wear the boots over a longer period and track the measurement outcomes longitudinally. Second, some participants may have biasedness towards certain boot models. It was impossible to completely blind the boot models because they are commonly available in Singapore. Participant’s prior experience with the boot models could be surveyed and statistically adjusted. Third, this study focused on unloaded and loaded walking on dry, levelled ground. It will be of interest to also examine the influence of combat boots on other military operational tasks on different terrains.

Conclusions

When carrying 20-kg loads, participants walked slower while experiencing higher peak force and higher loading rate across all combat boot types. Combat boot features can influence perceived comfort ratings substantially whereas biomechanical differences among boot types are more subtle regardless of load conditions. Participants walked slightly faster and displayed higher loading rates in the two more comfortable boots than the less comfortable boots. Common features of the more comfortable boots are lighter weight, more breathable, lower heel thickness, wider boot width, presence of shoe tongue cushioning, and better slip resistance. The lighter boots may enable participants to move more economically, feel more comfortable and walk at faster speeds. While the present study focused on walking, it would be interesting to explore further how footwear comfort can influence work performance and efficiency in other military operational tasks. Future studies can also examine the long-term effect of combat boot types on injury risks in military personnel. The lack of relationship between comfort and force variables suggests that we cannot simply use comfort to indicate force magnitude, and vice versa. It is recommended that both subjective and objective measurements should be used for comprehensive evaluation of combat footwear.

Word count: 3169

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Figures

Figure 1. Four types of combat boots commonly used in Singapore.

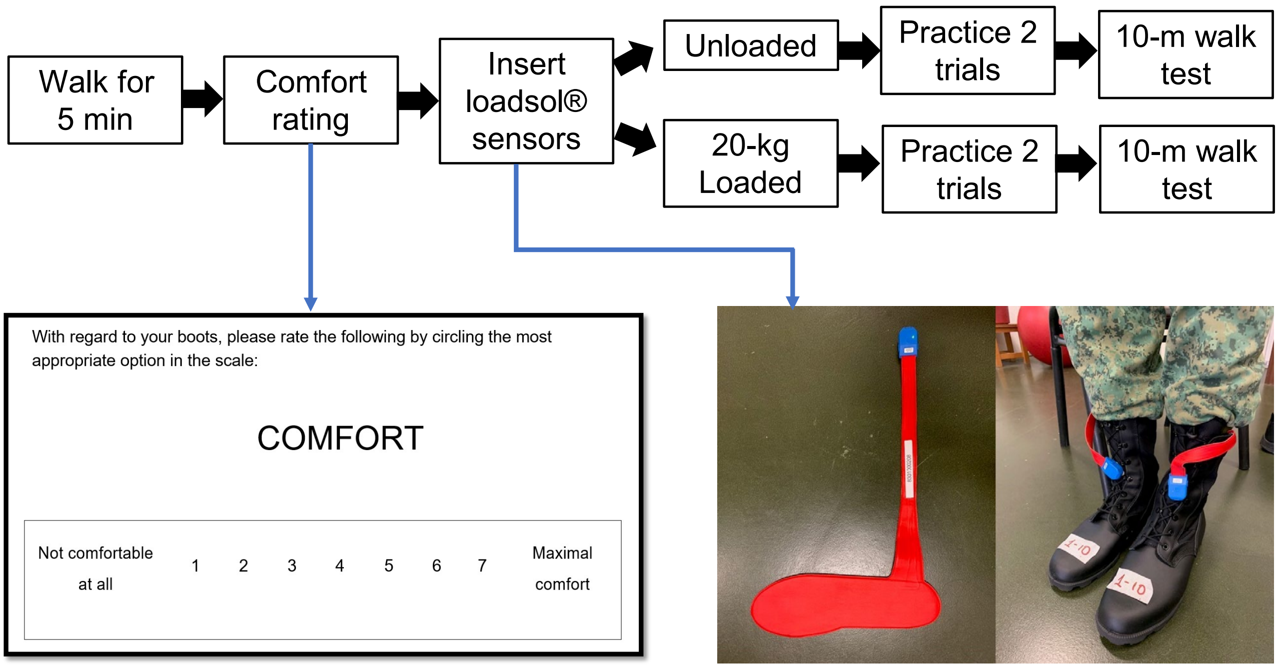

Figure 2 Flow chart of the test procedures and instrumentation: a 7-point Likert scale for comfort rating assessment, and the wireless loadsol® (novel GmbH, Munich, Germany) sensor for measuring the vertical ground reaction force during walking.

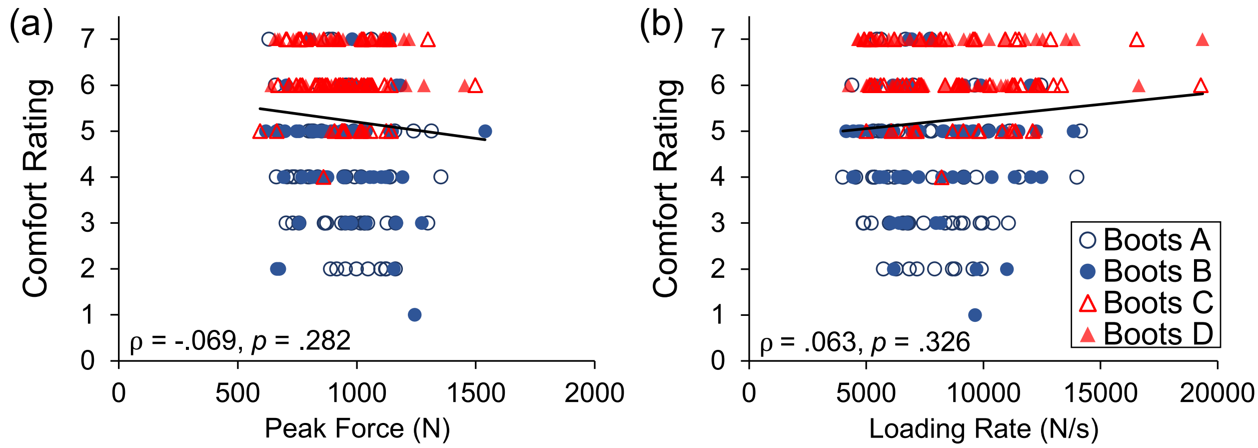

Figure 3. No significant correlations were found between comfort rating and (a) peak force or (b) loading rate during unloaded walking.

Table 1 Physical characteristics of 61 male participants

Characteristics	Mean (SD)
Age (yrs)	28.0 (5.3)
Height (cm)	172.7 (6.1) cm
Body Mass (kg)	73.8 (9.4)
Foot size - left	US 8.6 (1.1)
Foot size - right	US 8.6 (1.1)

Table 2 Physical Features and Mechanical Properties of the Combat Boots following the International Organization of Standardization (ISO) Guidelines

	Boots A	Boots B	Boots C	Boots D
Brand and Model	Wellco Peruana	Altama	Magnum Black	Magnum Green
Mass (kg)	1.52 (0.12)	1.57 (0.13)	1.33 (0.07)	1.45 (0.07)
Production process	Direct moulding	Direct moulding	Cold cementing & stitching	Cold cementing & stitching
Outsole traction	Jungle terrain	Jungle terrain	Jungle & urban terrain	Jungle & urban terrain
Material for heel cushioning	Cork	Polyurethane	Polyurethane	Honeycomb structure
Shoe tongue cushioning	No	No	Yes	Yes
Heel thickness (cm)	3.3	3.2	2.2	2.2
Boot width (cm)	10.2	9.8	10.6	10.6
Slip Resistance				
Heel Part (coefficient of friction)	0.07	0.07	0.14	0.13
Flat Contact (coefficient of friction)	0.22	0.16	0.16	0.18
Rigidity (N)	11.2	18.3	16.4	19
Breathability [mg/(cm^{2}h)]	0.5	1.2	1.8	7.5

Mass values are mean (SD) of 5 pairs of boots (US 7.5, 8.5, 9.5, 10, 10.5). ISO tests: Slip Resistance (ISO 13287:2019); Rigidity (Benewart Flexing Resistance, ISO 17707:2005), referring to the force reached the angle 45°; Breathability (ISO 17699:2003).

Table 3 Comparison of walking speed and ground reaction force variables across boot types and walking conditions

Variables	Combat Boots				Boot		Load		Interaction		*Post hoc*
	A	B	C	D	p	η_p^2	p	η_p^2	p	η_p^2	
Speed (m/s)											
Unloaded	1.37 (0.20)	1.36 (0.18)	1.40 (0.19)	1.40 (0.20)	**0.022**	0.052	**<0.001**	0.241	0.488	0.013	/
Loaded	1.34 (0.19)	1.34 (0.19)	1.36 (0.19)	1.37 (0.19)							
Peak Force (N)											
Unloaded	943.8 (169.2)	959.5 (179.0)	937.3 (162.8)	949.3 (160.9)	**0.009**	0.062	**<0.001**	0.974	.825	.005	C < B
Loaded	1172.9 (183.0)	1194.7 (193.1)	1167.2 (190.0)	1175.7 (177.1)							
Loading rate (N/s)											
Unloaded	7707.9 (2302.7)	7944.1 (2363.6)	8891.3 (2982.6)	8745.7 (3068.6)	**<0.001**	0.194	**<0.001**	0.809	**0.017**	0.055	A < C, D
Loaded	9451.6 (3010.1)	10010.2 (2910.7)	10501.4 (3385.7)	10249.4 (3062.4)							B < C, D

Significant difference ($p < 0.05$) is shown in bold text. Effect size for ANOVA (η_p^2) was interpreted as small ($0.01 \leq \eta_p^2 < 0.06$), medium ($0.06 \leq \eta_p^2 < 0.14$), or large ($\eta_p^2 \geq 0.14$).