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Influence of Footwear and Equipment on Stride Length and Range of Motion of Ankle, Knee and Hip Joint

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Purpose: Footwear and equipment worn by military personnel is of importance for them to be able to meet the physical demands specific to their profession daily activities. The aim of the present study was to investigate by means of gait analysis how army-provided footwear and equipment influence the range of motion of hip, knee and ankle joints as well as stride length.

Methods: Thirty-two soldiers were subjected to gait analysis on a treadmill by way of video recordings and goniometric measurements.

Results: The stride length increased when military shoes are worn. We found no influence on stride length in connection to increased loading. The weight of the shoes represents the decisive factor. Neither shoes nor equipment changed the range of motion of the knee joint. Weight of equipment affected range of motion of the hip joint. The range of motion of the upper and lower ankle joints was mainly influenced by the properties of the shoes.

Conclusions: Military footwear and weight of equipment influence stride length and range of motion of joints of the lower extremities in a specific way. Shape of material is the decisive factor.

Key words: *gait analysis, goniometry, overuse syndromes, military equipment*

1. Introduction

In the performance of their duties and daily activities, soldiers are required to engage in strenuous physical activity. Essentially, this will include walking and running carrying various items of equipment often through rough terrain. This is especially tough on untrained recruits and involves potential risks of injury [4]. Therefore, sports and training-related injury patterns frequently occur during basic military training. In the U.S. Army, 80–90% of the injuries occurred during this period are attributable to training-related activities [4]. Some of these injuries are related to items of equipment [5]. Injuries often occur in the knee joints and the spine [3]. For soldiers, the risk of suffering from overuse symptoms and injuries is 2 to 4 times higher than for the civil population [6]. In this context, the equipment provided can contribute considerably to the prevention of injuries. For example, it could be shown that the hardness of their shoes' soles had an influence on the muscle activity of the lower extremities of runners [13], [17]. Gait and movement analyses as well as EMG measurements can help to identify deficiencies representing an increased injury risk both in material and in movement. Hinz et al. [2] were able to prove that changes in the properties of a shoe's sole, such as a softer sole, may lead to a reduction of the stress exerted on the area around the metatarsal bones and thus to a reduction in the number of march fractures. EMG analyses on the influence of footwear on the muscles of the lower extremity have given indications that there is a connection to the development of pain, e.g. in the case of shin splints

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[6]. The influence of footwear on joint motion ranges has also been investigated by different groups. A study by Majumdar et al. [7] showed that in comparison with barefoot measurement, stride length increased when combat boots were worn. Stacoff et al. [15] were able to show that torsion and pronation develop unfavorably if athletic shoes are worn as compared to running barefoot. It has been proven that children who wear footwear have longer strides and increasing motion ranges of their knees and upper ankle joints [18]. However, the range of motion of lower ankle joints is reduced by shoes [19]. Shoes, in particular high-top shoes providing ankle support, are attributed to have a protective effect against injuries of the upper ankle joint [16]. In addition, special kinds of shoes may significantly reduce pain, e.g. in patients with osteoarthritis of the knee joint [9]. Ankle joint mobility varies with age and sex, i.e. range of motion becomes smaller with increasing age and in males [4]. Increasing loads have an influence on body axis and trunk muscles [14].

Not all dimensions of military footwear or equipment influencing the range of motion of lower extremity joints were evaluated so far. Aim of the present study is therefore to analyze joint movements and stride length in relation to the footwear and equipment used by means of gait analysis deriving recommendations on how the results of this study may be incorporated into the design of future military footwear and equipment.

2. Materials and methods

Subjects

32 soldiers participated in this study on a voluntary basis. The study protocol was approved by the Ethics Committee of the University of Rostock (file no.: A 2009 36). After the participants had been informed about the content and progression of the study, all signed a declaration of consent. Before the soldiers underwent gait analysis, a clinical examination was conducted determining joint motion ranges, special characteristics of their physique and general parameters such as body weight, height and age. Participants were between 20 and 53 years of age (mean value: 29.0 years, median: 26.0 years), their body weight varied between 62.5 and 112.0 kg (mean value: 81.6 kg; median: 81.0 kg), their height ranged from 163 to 193 cm (mean value: 177.8 cm; median: 179.0 cm) and their BMI values were between 21 and 34 kg/m^2 (mean value: 25.9 kg/m^2; median: 26.0 kg/m^2).

Measurement protocol

Successively, the soldiers have worn all the shoes listed in Table 1. The equipment items also worn succesively by the participants were helmet (1.5 kg), load carrying strap (1 kg), backpack (15 kg)

Table 1. Properties of the footwear examined

Shoes	Weight (dependent on size)	Properties
Dress shoe	approx. 530 g	– cow leather – rubber sole – 3 hole lacing
Combat boot	approx. 1,135 g	– adherent rubber sole – leather with smooth leather lining – bolstered boot leg – 8 hole lacing
Outdoor athletic (old design)	approx. 500 g	– leather – nubby rubber sole – padded around the ankle joint – 6 hole lacing
Outdoor athletic (new design)	approx. 720 g	– leather and textile – molded rubber sole – padded boot leg and insole – toe protection – 6 hole lacing
Indoor athletic	approx. 600 g	– cow leather – Texon Baking insole – molded rubber sole (fine) – textile lining – 6 hole lacing

and rifle (3.63 kg). Additionally, an analysis of privately procured athletic shoes was carried out for nine soldiers who valued them for their wearing comfort. These shoes were put into a separate group. All analyses were carried out with test subjects walking on a treadmill (Kettler Tempest, Ense-Parsit, Germany; Motor: 1.8 HP (horse power); Running surface: 140 cm × 40 cm; Slope adjusted at 0%) with a constant speed of 3.2 km/h.

During measurements, a minimum of 5 double steps each were recorded. Each shoe and equipment change was followed by a familiarization phase in which the test subjects walked on the treadmill at full test speed for about 2 minutes. For each piece of equipment there were two trials for the goniometer measurements and one trial for each camera position. Camera positions (right and behind the treadmill) are shown in Fig. 1. There was only one camera available therefore both positions were used successively.

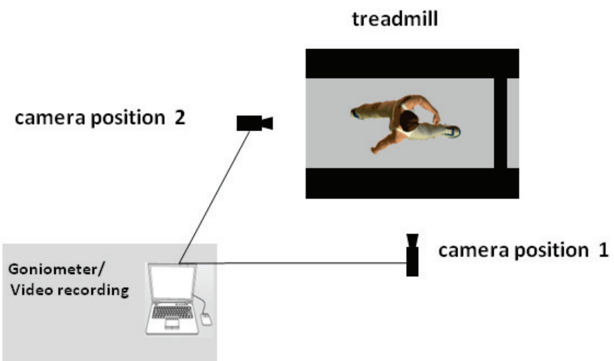

Fig. 1. Camera positions during measurement

Motion analysis

Two dimensional (2D) video-based motion analyses were conducted using a Dartfish measurement setup, which consisted of a digital video camera (GR-D770, JVC, Yokohama, Japan; measurement frequency: 50 Hz; spectral frequency: visible light 400–780 nm; video resolution: 400 Kpix) and the Dartfish^{TM} motion analysis software (version 4.0.6.0, Dartfish, Fribourg, Switzerland). Video recordings were made laterally from the right and subsequently from the dorsal side. For good optical tracking of the measuring points in the software, white adhesive plasters with a black dot (diameter: 0.5 cm) were attached to all reference and measuring points on the participant's body.

Stride lengths and joint movements were tracked and analyzed in the videos using the Dartfish^{TM} software. In doing so, the center of rotation of the joint to be measured was determined and the zero line of the range of motion was marked in the respective video sequence at first. Subsequently, the joint angles of knee, ankle and hip were determined using reference lines along the corresponding proximal and distal extremities, crossing at the joint (Fig. 2). The reference lines to determine the joint angles and later the range of motion (ROM) were as follows (Fig. 2): knee joint: proximal reference line (a): greater trochanter to center of rotation of the knee joint, distal reference line (b): center of rotation to malleolus lateralis; upper ankle joint: proximal reference line: head of the fibula to malleolus lateralis (c), distal reference line (d): malleolus lateralis to caput os metatarsale 5; lower ankle joint (dorsal view): proximal reference line (e): along the Achilles tendon to its insertion at the calcaneus, distal reference line (f): from the insertion of the Achilles tendon at the calcaneus along the centerline of the heel to the ground.

Stride length was measured based on the distance between the malleoli in the sagittal plane of the left and right ankle joints during the double support phase (heel strike of one foot and toe-off of the other foot).

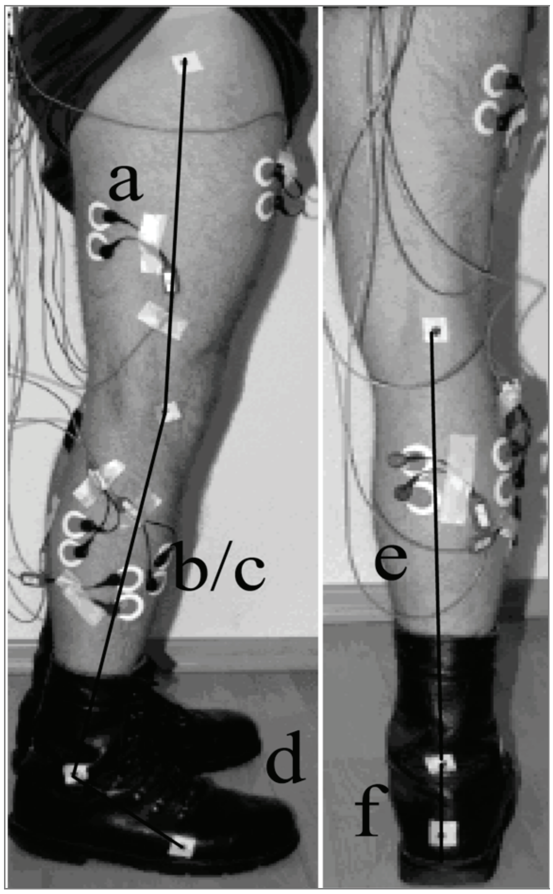

Fig. 2. Representation of the reference lines to determine joint angles: knee joint, proximal (a); knee joint, distal (b); upper ankle joint, proximal (c); upper ankle joint, distal (d); lower ankle joint, proximal (e); lower ankle joint, distal (f).

Goniometric measurement

In addition to the visual approach of measurement a uni-axial joint motion measurement was carried out by means of an electromechanical goniometer (Noraxon, Scotsdale, AZ, USA). It was fixed on the lateral side of the left knee joint. The goniometer was applied with its limbs fastened parallel to the leg axis and attached by Velcro straps above the knee joint, creating optimum conditions for measurements of extension and flexion in the knee joint. The goniometer's center of rotation was positioned at the height of the joint cavity. Via a wireless transmitter, the measurement data were transmitted to a personal computer and recorded there. The resolution of the goniometer is 25 mV/degree and the nominal output range is ±160°.

The MyoResearch software (Noraxon, Scotsdale, AZ, USA) was used to subsequently evaluate the measured goniometric data. During measurements, a minimum of five double steps each were recorded. Each shoe and equipment change was followed by a familiarization phase in which the test subjects walked on the treadmill at the given speed for about two minutes.

Statistical methods

For all measured values, descriptive statistics were determined (mean, standard deviation, minimum and maximum). Data were evaluated for normal distribution using Kolmogorov–Smirnov test. Differences between the groups were tested for significance by the unpaired Student's *t* test and the Mann–Whitney *U* test. The level of significance was established at $p \leq 0.05$. All data were computed using the statistical program SPSS version 15.0 (SPSS Inc. Chicago, IL, USA).

3. Results

Stride length

In principle, stride length increased significantly, i.e., by 2 to 4 cm, as a result of wearing the footwear examined compared to barefoot measurement (Fig. 3). Significant increase occurred especially in the case of the combat boot and the leather dress shoe ($p < 0.001$ and $p = 0.006$, respectively), with a greater increase for the combat boot than for the outdoor shoe ($p = 0.005$). The rise was lowest for athletic shoes, and there were no significant differences between different types of athletic shoes. Furthermore, no relevant differences could be seen when subjects wore personal equipment. Neither weight nor load distribution had influence on stride length.

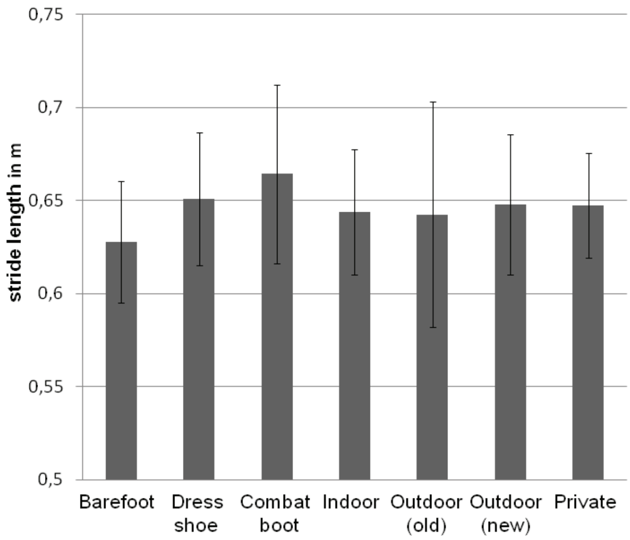

Fig. 3. Comparison of stride length when wearing different types of shoes

Knee joint

Only in the case of the leather dress shoes goniometric knee angle measurement showed a significant reduction in range of motion compared to barefoot measurement ($p = 0.015$) (Table 2), and no further significant differences could be observed between shoe types.

There were no significant differences between the individual shoes regarding the range of motion, neither in the video analysis (data not shown) nor in goniometric measurement but if extension and flexion are regarded separately, goniometric measurements revealed a reduction in the extension of the knee joint caused by wearing shoes ($p < 0.001$; Fig. 4). At the same time, larger flexion values were determined as compared to barefoot measurement ($p = 0.031$, Fig. 5). Also in this case, there were hardly any relevant differences between the individual shoes as such. If these results are summarized, wearing shoes does not lead to a relevant change in the range of motion of flexion-extension, but it results in a shift to enhanced ranges of knee flexion. Personnel equipment had no relevant influence on range of motion of the knee joint, but if flexion and extension were seen separately, there is also a significant shift in the range of motion of the knee joint to an enhanced flexion during wearing higher loads like backpack and rifle ($p < 0.043$).

Table 2. Range of motion in the knee joint determined by goniometer

	Barefoot	Combat boot	Dress shoe	Indoor	Outdoor (old)	Outdoor (new)	Private
ROM	59 ± 11°	57 ± 14°	56 ± 15°	56 ± 15°	58 ± 14°	60 ± 8°	63 ± 4°

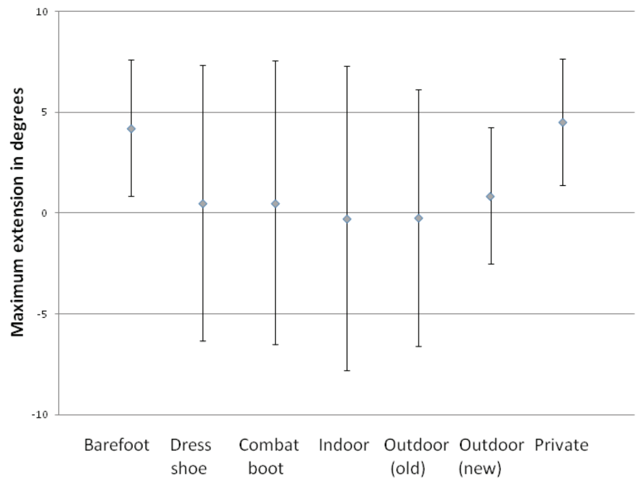

Fig. 4. Extension of the knee joint

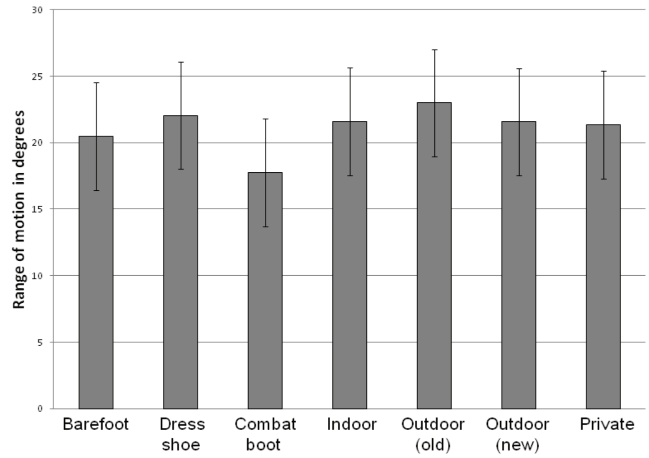

Fig. 6. Comparison of the range of motion in the upper ankle joint when wearing different types of shoes

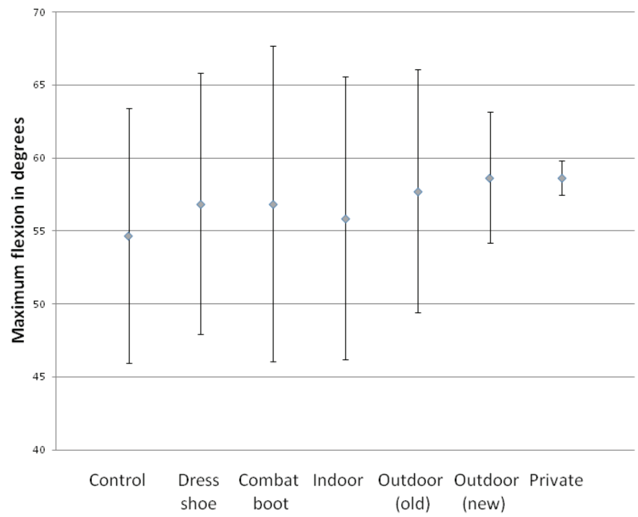

Fig. 5. Flexion of the knee joint

Upper and lower ankle joint

Around the upper ankle joint, we found hardly any relevant changes in the range of motion (Fig. 6). Only the combat boot limited the range of motion significantly ($p = 0.005$). In particular, plantar flexion was limited significantly compared to barefoot measurement ($p < 0.001$) and all other shoe types examined ($p < 0.05$). Relevant limitations of the lower ankle joint's inversion or eversion movement during normal gait could not be detected. Weight of equipment revealed no influence on range of motion of the upper and lower ankle joint.

Hip joint

Wearing different kinds of footwear caused no detectable changes in range of motion of the hip joint. In contrast, increasing loads resulted in relevant reduction of extension and significant increasing flexion ($p = 0.005$; Fig. 7). Furthermore, range of motion was increased from 26 up to 33 degrees during higher load wearing. Maximum increase was detected by wearing the backpack, where an increase of 7 degrees was observed compared to control setup (Fig. 7).

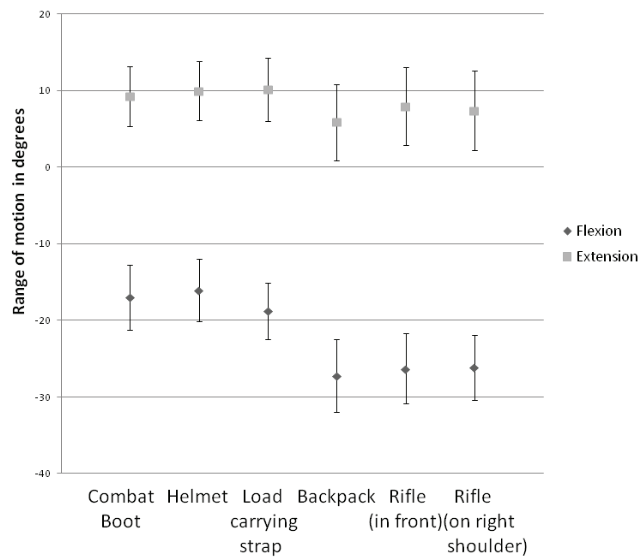

Fig. 7. Range of motion of the hip joint by wearing certain kinds of equipment

4. Discussion

The aim of the present study was to determine how soldiers' footwear and equipment influences the range of motion of the hip, knee and ankle joints. Furthermore, its influence on stride length was investigated. It has been shown that stride length increased significantly if military-issue shoes were worn. Heavy footwear, such as combat boots, led to a more pronounced increase in stride length compared with athletic shoes. Indications of this were already provided by Majumdar et al. [7] in their comparison of Indian military boots and bathroom slippers. Our investigations demonstrate that increase of stride length is not associated with an increase of the range of motion in the ankle or knee joints, thus contradicting Wegener et al. [18] who postulated a general increase in the ROM at the knee and the upper ankle joint if footwear is worn. It has already been proven that, in particular, wearing heavy shoes such as combat boots causes higher muscle activity of the M. rectus femoris to increase compared to barefoot gait and other footwear [13]. This suggests that the larger stride length might be caused by increased hip flexion, for which the M. rectus femoris is of importance [16]. The latter is also responsible for knee joint extension [16]. An increase in knee extension could not be observed in our present study, however, we observed a limitation of extension and an increase in flexion when wearing shoes. This indicates that the increase in stride length can be generated from the hip joint's range of motion in combination with rotational movements of the pelvis. Although the hip joint showed no significant change in ROM through wearing different shoes, the results revealed that stride length is influenced by shoe weight. The weight of the equipment had influence on ROM of the hip joint. This fact was also reported by Madjumdar et al. [8]. In contrast to our study they found increasing ROM of the ankle joint. But there was no information about the used footwear. Increased hip flexion caused by heavy loads led to stronger flexion in the knee joint. The result of these two effects was that stride length did not change at all because of wearing heavy loads. In order to record the range of motion of the hip joints, and particularly that of pelvic rotation, a stationary three-dimensional measurement system for movement analysis is required. However, this was not available for our field trials. A further possible explanation for the increased stride length due to rigid shoes is an increase in push-off power [10]. However, no measurement of the ground reaction force was conducted in our present study.

For both methods, the goniometric measurements and two dimensional video analysis some limitations are given. 2D video analysis is depending on the observer's position from where the motion is tracked. Therefore, only motion in a plane perpendicular to the camera can be measured with sufficient accuracy. Furthermore, different observers may find different angles due to imprecision during tracking markers. Furthermore, the lack of three dimensional measurement methods can lead to specific errors, i.e. changes in the non-measurable plane may influence the result in different ways. For example, a rotation in knee joint movement influences the position of the electromechanical sensors of the goniometer but does not have an influence on the optical range of motion in the lateral view.

Although the values of individual measurements differ, relevant conclusions can be drawn with respect to the range of motion depending on footwear: The influence of footwear on the range of motion of the knee joint is not significant and the influence of footwear on the upper ankle joint is small. Only the combat boot limits flexion in the ankle during normal gait. Whereas an increase in activity of the posterior lower leg muscles could not be observed [13], an increase in activity of the M. tibialis anterior, which is responsible for dorsal extension in the upper ankle joint could be seen. Rigid footwear reaching above the upper ankle joint seems to cause stress on the ventral muscles, which promotes the development of a tibialis anterior syndrome. As flexibility is reduced in general, plantar flexion is restricted more than other movement directions.

In this case, a compromise must be found between wearing comfort and functionality under field conditions. Shock-absorbing insoles can prevent soldiers from developing medial tibial stress syndromes [19]. This might be an option to reduce the negative effects of rigid material used in footwear. However, other options of prevention have not proven effective in this case [19]. The fact that the athletic shoes examined hardly differ with respect to their effects on stride length and ROM matches the results of other working groups that have dealt with the development of running injuries. The latter found that adapted running shoes offer no advantage compared to commercial running shoes as far as the development of running injuries is concerned [20].

There are limitations in this study that have to be discussed. Three-dimensional infrared measuring systems represent the gold standard today and are frequently employed. All our measurements were carried out on military premises where no gait analysis laboratory with three-dimensional movement analysis system was available. In selecting measuring instruments, we thus had to fall back on mobile, robust and at location available measuring systems. However, various requirements with respect to light and environment must be met regarding these systems' operating location, which could not be implemented within military premises. Therefore, the methods of 2D video analysis and electronic goniometry were used in the present study. Moreover, the study population is heterogeneous with respect to BMI and age. It is not possible to form groups due to the small number of cases. However, identical footwear is worn by soldiers of all ages.

5. Conclusions

Our results show that footwear and equipment have relevant influence on gait analysis parameters and thus on the functionality of the lower extremity, especially due to its properties. Weight of equipment affected range of motion of the hip joint. Stride length in particular increases significantly if army-provided shoes are worn. Limitations of the ankle joint movement are influenced by the material and shape of the shoes. Rigid material may be the decisive factor, promoting the development of overloading syndromes such as shin splints. Future developments in shoe design should especially aim for flexibility in the material used, however, functionality, especially under field conditions, has to be ensured.

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