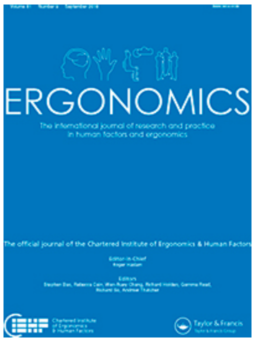

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The influence of boot stiffness on gait kinematics and kinetics during stance phase

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In the study, the influence of different boot prototype stiffness on gait kinematics and kinetics was investigated. The boot stiffness was determined by force-deformation measurement while pressing the foot model inserted into the boot by a custom-made robot. Gait analysis was carried out in nine neurologically intact subjects during walking while wearing two different boots with and without carrying a backpack, and differences were statistically tested using ANOVA.

The results indicated distinctions in the boot shaft and vamp stiffness. The boot with a softer boot shaft enabled a wider range of motion in the ankle joint leading to more power generation in the ankle joint during the push-off, increased step length and gait velocity. The backpack mostly influenced the pelvis and trunk kinematics.

The study has demonstrated the influence of boot shaft stiffness on biomechanical gait parameters and its importance for push-off that manufacturers should take into consideration when optimizing the footwear performance.

Keywords: Footwear stiffness; Gait; Kinematics; Kinetics; Stance phase

1. Introduction

Improving gait and running performance have become an important issue in sport, medicine and military uses. Improved performance relies on efficient transformation of mechanical power output produced by the musculoskeletal system through footwear. Significant efforts have been invested toward optimization and development of the high performance footwear. Roy *et al.* (2006) examined running economy (metabolic energy savings, oxygen consumption) in a group of individuals wearing commercially available running shoes in conditions of modified sole stiffness, which was achieved by inserting a carbon fiber plate throughout the full length of the mid-sole. They concluded that footwear stiffness is an important parameter for achieving energy

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efficient walking and running. Miller *et al*. (2000) investigated the impact of loading and foot mechanics on short-term subjective comfort. The results showed that skeletal alignment, shoe torsional stiffness and cushioning seem to be variables defining the subjective comfort. A reasonable ratio between subjective comfort and footwear stiffness required for foot sole protection and injury prevention should be defined in the process of footwear design. Mechanical properties of the running shoes can be changed by inserting an appropriate shoe insole (Nigg and Liu 1999, Dixon *et al*. 2003), but this may reduce the range of motion in the ankle joint complex. The higher sole stiffness may hinder the movement in the metatarsal joint, consequently reducing the achievable foot clearance (ankle dorsiflexion) in terminal stance and pre-swing phase.

Besides ankle-deep shoes, several types of boots, sport, trekking, hiking, mountaineering and military boots, were also the subject of biomechanical studies. In all over-the-ankle footwear the ankle joint movement is hindered, therefore footwear stiffness may be an even more important feature. Various studies have analysed the influence of outer sole flexibility (heel and bending stiffness) on the power of impact or impact absorption (Arndt *et al*. 2003, Dixon *et al*. 2003) and suggested that the decreased mechanical stiffness of the sole results in an enhanced ability to decrease the power of the heel impact and therefore prevent potential injuries. Indeed, the footwear sole stiffness has to preserve a certain level of hardiness to prevent potential foot or ankle injuries. The boot-shaft stiffness (including sole stiffness) may also have a noticeable impact on the plantar flexion range of movement and ability of the plantarflexor muscle group to generate power during push-off, which is a considerable source of propulsion during level gait in healthy human subjects (Requiao *et al*. 2005). The lack of propulsion power during push-off due to boot-shaft stiffness may lead to compensatory changes at the knee and hip joints. There have been no studies examining the influence of boot-shaft stiffness on ankle, knee and hip kinematics and kinetics during level walking. Additionally, boots are intended for trekking, hiking and military use, where long-continued walking is required, which includes carrying a medium size, reasonably heavy backpack that may further influence gait kinematics and kinetics.

The aim of this study was to investigate the influence of boot-shaft stiffness on kinematics and kinetics during walking of human subjects with and without carrying a 20 kg backpack. Two types of boots with apparently different boot-shaft stiffness were tested. We hypothesized that different boot stiffness will have evidently different influences on kinematics and kinetics in various gait subphases in all three joints of the lower extremity. Additionally, we hypothesized that carrying a backpack will further amplify these changes.

2. Methods

2.1. *Boot stiffness determination*

Two types of military boots (footwear 1 and footwear 2) with apparently different bootshaft stiffness characteristics were examined (figure 1). The stiffness of running shoes, likewise of ankle-deep shoes, can be determined using the force-deformation characteristic. Different techniques should be used for boots that consist of a boot-shaft with a rather strong heel-lift, welting, vamp and sole. The boot-shaft's contribution to overall stiffness cannot be neglected as, besides offering stability and protection of the ankle joint, it also hinders the ankle joint range of movement.

Figure 1. Prototype boots used in the study. A foot model with flexible ankle joint in all three planes was used to assess boot stiffness in selected angles of stance phase.

A foot model (center in figure 1) was inserted into each boot in a way that fits perfectly into the heel-counter, thus having the same size-number as the tested boots. The model has a three degrees-of-freedom (DOF) ankle joint and a single DOF metatarsal joint. The model was fixed in the robot (Jožef Stefan Institute, Slovenia - figure 2) end-effector enabling the movement in Cartesian space (Nemec and Leonardi 1998).

Determining the footwear stiffness characteristics of boots required the assessment of load-deformation (Divert *et al.* 2005) (force-position) in several positions of a simulated gait stance phase. In order to simulate appropriate conditions, the ground surface was inclined as the robot movement was limited to the vertical direction. The slope inclination varied in range from -25° to $+25^{\circ}$ in discrete steps which created conditions similar to ankle kinematics throughout the stance phase of normal gait. The robot was moving the attached foot model inserted into the boot toward the inclined slope. When the boot contacted the slope, the robot switched to hybrid control and started to push the boot downward until the measured force reached the value of 300N, which was the maximum force that the robot could exert (Nemec and Leonardi 1998). The force was applied at low speed (approx. 0.1 km/h) to ensure accurate assessment. A 6DOF force-torque transducer (JR3 Inc. Woodland, CA, USA) was mounted under the slope. Seven discrete slope inclination values were assessed within four testing conditions:

- heel contact at slope angles -15° and -20°; (figure 3a) plantarflexion at ankle joint - stiffness of the boot shaft (upper) and heel base,
- heel and then toe contact at slope angles -2° and -5°; (figure 3c) slight plantarflexion at ankle joint - stiffness of the boot shaft (upper),

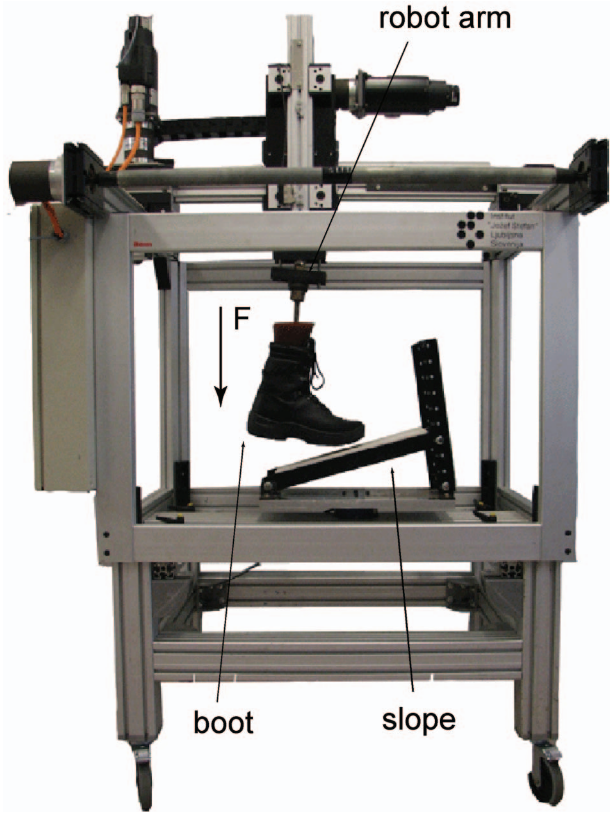

Figure 2. Cartesian type robot manipulator in shoe/boot stiffness assessment task. A slope created artificial conditions similar to various stance subphases.

- toe and then heel contact at slope angles 5° and 10°; (figure 3d) slight dorsiflexion at ankle joint - stiffness of the boot foreshaft and vamp,
- toe contact at slope angle 15°; (figure 3b) dorsiflexion at ankle joint - stiffness of the boot foreshaft, vamp and outsole.

For each of the discrete slope inclinations the stiffness characteristics of each item of footwear were determined and the overall boot stiffness for each condition and slope angle was calculated:

$$stiffness = \frac{\Delta F[N]}{\Delta z[mm]}, \tag{1}$$

2.2. *Subjects and experimental protocol*

In the study, nine neurologically intact male volunteers ranging in age from 21 to 28 years (24.7 ± 2.1 years, 178.6 ± 5.7 cm and 73.9 ± 4.1 kg) participated. The criteria for participation were: 1) no neurological or musculoskeletal impairments 2) no illness, sickness, ailment or infirmity. The data on the subjects are given in table 1.

The subjects were instructed to walk along a 7-m-long walkway with the self-selected speed that enabled comfortable gait in the kinesiology laboratory equipped with VICON

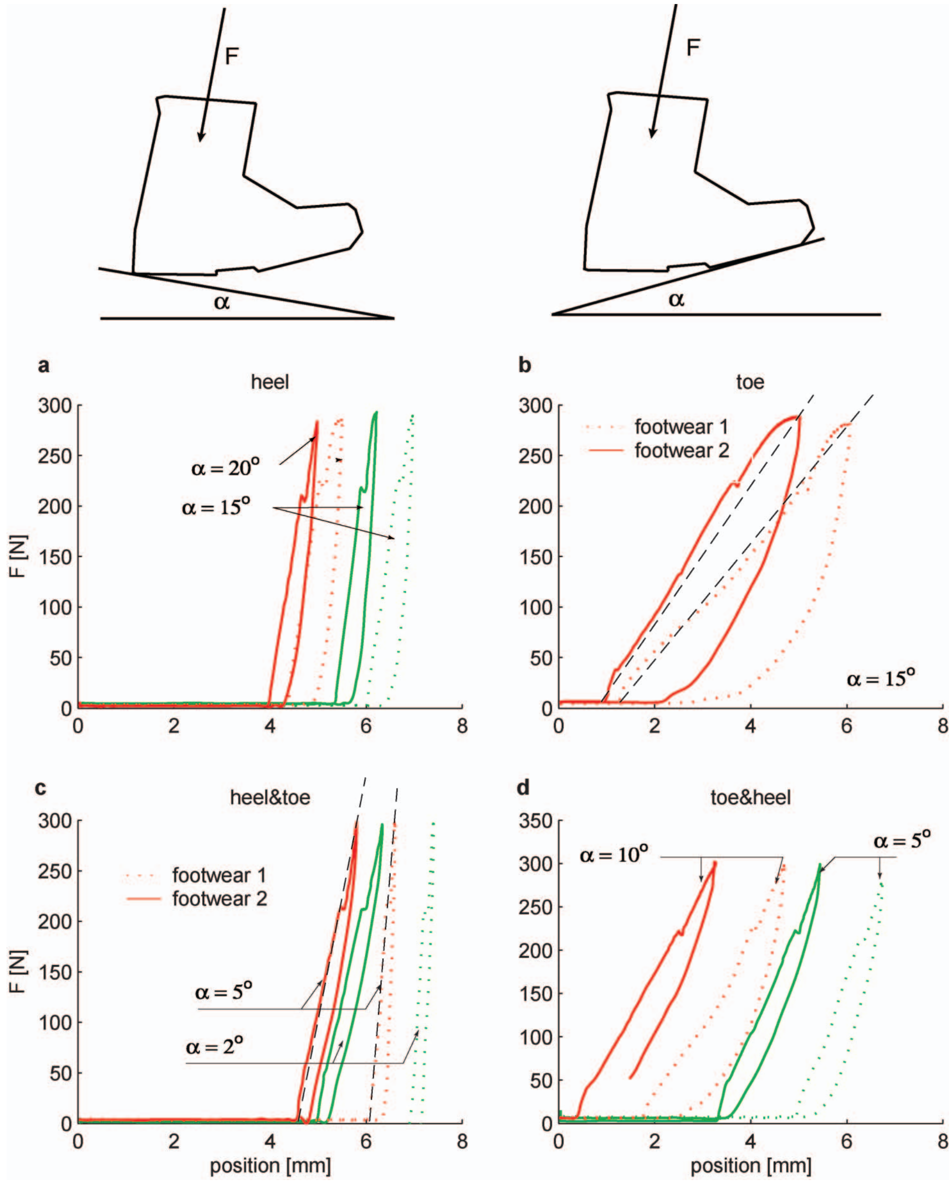

Figure 3. Stiffness characteristics (force - position) at 7 discrete slope inclinations (**a.** heel strike only at -20° and -15°, **b.** toe contact only at 15°, **c.** heel and toe contact at -2° and -5°, **d.** toe first and then heel contact at 5° and 10°) for each boot type (footwear 1 and footwear 2). The new boot type (footwear 2) demonstrated significantly lower stiffness for condition c (55–64%). The upper figures clarify the α angle and the assessment methodology.

motion capture and analysis system (VICON 370, Oxford Metrics Ltd., Oxford, UK) for three-dimensional motion of lower limbs, pelvis and thorax assessment. The Vicon system consists of six couple-charged cameras with strobed infrared light-emitting diodes and reflective markers attached to the subjects' skin over designated landmarks according to

Table 1. Subjects' mass and height.

Subject	Age [years]	Weight [kg]	Height [cm]
1	28	72	178
2	24	75	182.5
3	23	73	171
4	27	78	182
5	21	75	190
6	24	71	178
7	24	82	178
8	27	66.5	170
9	24	73	178

the specifications using standardized protocols provided by the manufacturer of the system. Motion data were sampled at 50 Hz sampling rate. Two AMTI force plates (AMTI OR-6-5-1000, Advanced Mechanical Technology Inc., Watertown, MA) positioned in the center of the walkway were used for recording ground reaction forces (sampled at 500 Hz).

The protocol comprised four consecutive experimental conditions: 1. gait wearing footwear 1; 2. gait wearing footwear 2; 3. gait wearing footwear 1 and carrying a 20 kg backpack; 4. gait wearing footwear 2 and carrying a 20 kg backpack. The weight of the backpack was based on the middle-sized military backpack (Arndt *et al*. 2003, Stevenson *et al*. 2004). Within each of the experimental conditions several walking trials were undertaken. At least three clear steps of each leg on the force platform per subject/condition were assessed to produce the subject's means for subsequent kinematics and kinetics analysis. Before each walking trial, the subjects practiced walking for at least five minutes for each experimental condition to become familiarized with the boots. The subjects rested for ten minutes before continuing with the session under the next experimental condition.

The method was approved by the local ethics committee at the Institute for Rehabilitation, Republic of Slovenia, and the subjects gave informed consent.

2.3. *Data analysis*

The data acquired for the boot stiffness calculation were filtered off-line with a 7 Hz digital low-pass filter after an FFT control of signal frequency content. The data acquired and sampled ($F_s = 50$ Hz for kinematic and $F_s = 500$ Hz for force plate data) by the Vicon system were used to calculate the kinematic, kinetic and spatio-temporal parameters (Winter 1979, Winter 1991). The parameters such as velocity, cadence, step length, joint angles, joint moments and joint power for the lower extremities were calculated with Vicon Motion software, Polygon 3.0. For each kinematic and kinetic variable the group mean for each experimental condition was calculated from the subjects' means.

Boot stiffness comparisons were made between each type of boot for each of the conditions. A stiffness coefficient was determined as a ratio between footwear 2 (new boot type) and footwear 1 (old boot type) stiffness and expressed as a percentage [%].

Gait cycle (GC) is divided into stance and swing phase, and more precisely into functional subphases (Perry 1992). For this study, the stance phase was considered relevant and was divided into four subphases: initial contact - IC (0–2% of GC); loading response - LR (2–10% of GC); midstance - MS (10–36% of GC); terminal stance - TS (36–56% of GC); and pre-swing - PS (56–60% of GC). In each subphase, the minimum or maximum values representing the peak values of the selected kinematic and kinetic variables were determined, in order to examine the effect on the results under the applied experimental conditions. The variables were visually inspected and those showing the influence of different experimental conditions were statistically tested using 1-way Repeated Measures ANOVA (statistical tool SPSS v13., LEAD Technologies Inc.).

3. Results

3.1. *Boot stiffness*

The mean stiffness characteristics assessed in the boot types applied in the study are presented in figure 3. The left column figures relate to the conditions where the outfit was set up in such a way that the boot contacted the slope by heel only, or first by heel and then by the entire boot sole. The right column presents results for conditions where the equipment enabled initial contact with the forefoot (toe) and by decreased slope inclination also with the entire boot sole. The characteristic's slope defined the boot stiffness for a certain condition, as indicated in figure 3c and b and presented in numerical format in table 2. In this respect there were negligible differences in characteristic slopes between both boot types for conditions a and d, especially at higher contact ground inclination α. At small inclination α for conditions c and d we found up to 64% lower stiffness values for footwear 2. For condition b the footwear 2 was found to be stiffer. The individual stiffness values for each experimental condition are presented in table 2.

3.2. *Kinematics and kinetics*

Group mean kinematic and kinetic variables for each experimental condition are presented in figure 4 (angle joint angle - AAL, ankle moment - AML, ankle power - APL, knee joint angle - KAL, knee moment - KML, knee power - KPL, hip joint angle - HAL, hip moment - HML, hip power - HPL and pelvis tilt - PLT and trunk tilt - THL). A cursory overview of figure 4 provides an insight into the kinematic and kinetic changes across experimental conditions, and distinctions can be noticed (indicated by squares) for ankle power, ankle joint angle, hip joint angle, and pelvis and trunk tilt. As the variation of the hip joint angle in loading response was assumed to be the consequence of pelvis tilt, and as pelvis tilt was correlated to the trunk tilt, only the ankle power, ankle joint angle and trunk tilt were examined in detail (figure 5).

Table 2. Shoe stiffness for various conditions.

Condition	[deg]	footwear 1 [N/mm]	footwear 2 [N/mm]	f2/f1 [%]
heel	15	300.47	336.71	112
	20	250.84	270.79	108
heel-toe	2	594.67	218.76	**36**
	5	529.04	236.79	**45**
toe-heel	5	154.14	129.60	84
	10	99.74	102.63	103
toe	15	57.78	69.60	121

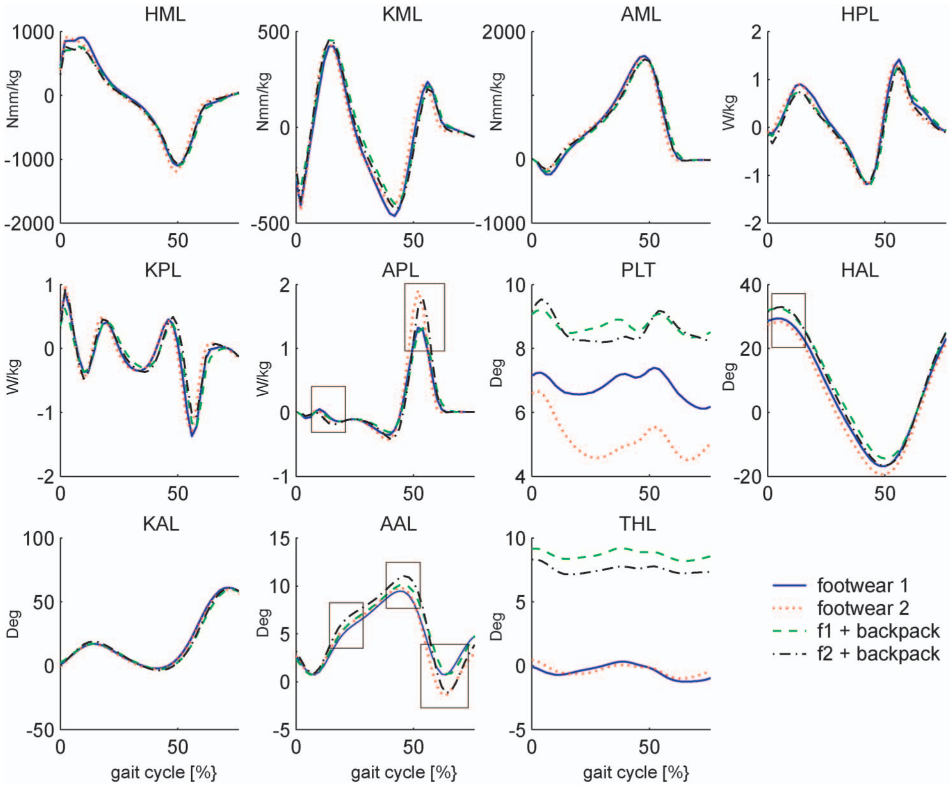

Figure 4. Kinematic and kinetic data (group mean values) of all subjects walking in 4 various conditions (footwear 1, footwear 2 and combinations of footwear with 20 kg backpack). Ankle joint angle (AAL), ankle moment (AML), ankle power (APL), knee joint angle (KAL), knee moment (KML), knee power (KPL) and hip joint angle (HAL), hip moment (HML) and hip power (HPL) were calculated, and pelvis tilt (PLT) and trunk (Th-10 level) tilt (THL) as additional data. Marked trace parts present the significant differences.

In the loading response and terminal stance subphases the ankle power (APL) demonstrated remarkable distinctions under various experimental conditions. Subjects wearing footwear 2 were able to generate 33% more peak power in the ankle joint during the push-off as compared to footwear 1. Additionally, the backpack had no significant impact on the changes of power generation ($<3\%$). The power absorption in the loading response was slightly increased (6%) when carrying a 20 kg backpack irrespective of the footwear. The peak ankle angle (AAL) demonstrated significant increase of plantar flexion in pre-swing when wearing footwear 2 (428% more) irrespective of the carrying backpack condition. The ascendance of footwear 2 was also found in increased dorsiflexion in midstance (4%) and terminal stance (2.6%), more distinctive when carrying the backpack, 6% and 11%, respectively. At the experimental conditions 3, a significant (8.9°) change of trunk tilt (THL - at Th-10 level) was noticed. Slightly less significant was the change at condition 4 (7.9°).

The footwear change had a statistically significant ($\sigma = 0.009$) impact on ankle moment in the loading-response subphase (decrease of dorsiflexion moment from 256.5

(footwear 1) to 170.0 Nmm/kg (footwear 2)), if considered that the significance bound ($P = 0.05/4 = 0.0125$) was decreased due to the multiple comparisons (4 tests on the same data). The difference in ankle power ($\sigma = 0.002 < P$) was found significant in the terminal-stance subphase. The impact on ankle angle in the pre-swing subphase was distinctive ($0.45°$ to $-1.50°$), but not statistically significant ($\sigma = 0.046 > P$). The backpack impact on trunk tilt was distinctive and significant through the entire stance phase ($\sigma = 0.000 < P$). The footwear change also had a statistically significant impact on ankle power in the terminal stance subphase ($\sigma = 0.013 \approx P$) when carrying the backpack.

The mean walking speed increased by 1% (from 1.57 to 1.58 m/s) comparing the experimental conditions 1 and 2. Carrying the 20 kg backpack resulted in a reduction of the walking speed of 6.4% (from 1.57 to 1.47 m/s). When carrying the backpack the change of footwear slightly increased the walking speed (1.47 to 1.50 m/s). The gait parameters for each experimental condition are presented in table 3.

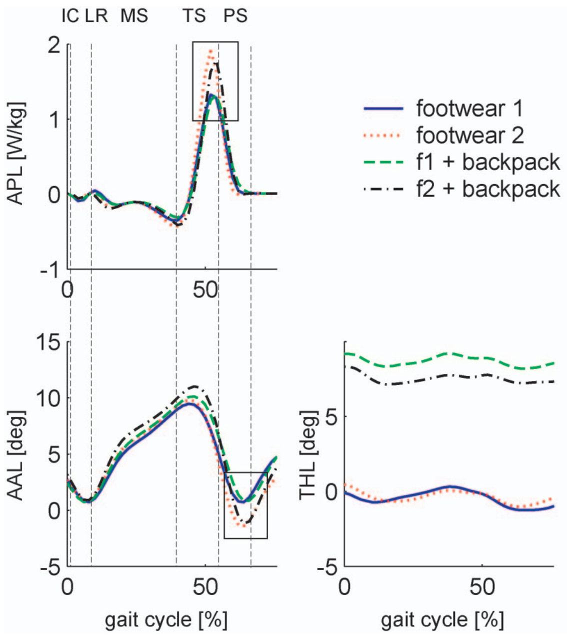

Figure 5. Kinetics and kinematics of walking under 4 various conditions were divided into stance subphases (IC - initial contact, LR - loading response, MS - midstance, TS - terminal stance, PS - pre-swing). The significant deviations between the conditions were the subject of statistical analysis. The use of footwear 2 showed increased ankle joint angle (AAL) range of motion and consequently increased ankle power generation (APL). The influence of backpack weight is noticeable in forward trunk tilt (THL).

Table 3. Gait parameters for various experimental conditions.

	1	2	3	4
velocity [m/s]	1.573 ± 0.245	1.583 ± 0.185	1.472 ± 0.146	1.507 ± 0.182
cadence [steps/min]	114 ± 7	114 ± 6	111 ± 5	111 ± 5
step length [m]	0.817 ± 0.074	0.827 ± 0.059	0.802 ± 0.0538	0.813 ± 0.061

4. Discussion

The results obtained in the boot stiffness analysis demonstrate influential distinctions between two functionally very similar boot prototypes. The main finding of this study is that boot-shaft stiffness considerably influences the kinematics and kinetics of the ankle joint, while contrary to our hypothesis the changes at the knee and hip joints were not significant. These findings were possible only with entire functional boot stiffness analysis and are based on a comparison of two functionally and purposely similar boots. Shoe and boot stiffness or bending is usually tested by inserting strain gauges (Arndt *et al.* 2003) and/or deformation measurement by an optical system. In our study, the boot stiffness analysis was made possible by a custom-made robot (Nemec *et al.* 1998) and a foot model with an ankle joint and a metatarsal joint inserted into the boot. The robot providing accurate position information was programmed to push the foot-model (boot) downward to hit the slope under various conditions simulating conditions during a stance phase of walking, but could also have been programmed for high-speed impact or even heel strike testing. However, the aim of the footwear stiffness test was to identify the basic characteristics of the boot-shaft and the vamp, both important features for the observed kinematic and kinetic changes and performance. The results show that softer footwear enables a larger range of motion and power generation in the ankle joint during push-off, which is in agreement with our hypothesis.

The boot stiffness determined under different conditions indicates that the boots used in the study had similar stiffness characteristics in certain subphases of stance. Negligibly higher overall stiffness of footwear 2 was found with heel and toe contact, indicating that the metatarsal joint was rather more fixed in footwear 2. The latter may be important for efficient prevention of metatarsal bone injuries (Arndt *et al.* 2003). In the study, the measurements performed with pressure sensors, strain gauges and electromyographic assessment of muscle activity demonstrated decreased loading under the main area of the foot and increased underneath the metatarsal joint. Bone deformation indicated that boots with a less stiff outer sole increased tension. On the other hand, our study shows significantly lower stiffness values of footwear 2 in mid-stance and terminal-stance (table 2), especially at the lowest contact angle, indicating that the lower part of the boot shaft and the boot vamp was softer, therefore enabling more foot compliance. These ascertainable distinctions in footwear stiffness are related to changes of kinematic and kinetic parameters. The softer (and eventually more elastic) back and front boot shaft enabled ankle joint movement to a greater extent in the sagittal plane and generation of significantly higher ankle power. The ankle power generation was found to be an important contributor in limb advancement in gait (Requiao *et al.* 2005), which is necessary for higher gait velocity (longer step length at constant cadence) and may result in a more energy efficient gait when walking speed remains constant. The findings of Arndt *et al.* (2003) suggest that the partial stiffness characteristics of boots related to injury prevention need to be tested. Based on the results of our study, we additionally suggest that complementary information related to ankle kinematics and kinetics may be helpful in finding the optimal ratio between performance and injury prevention.

Backpacks are very common in trekking, hiking, mountaineering or military exercises. Carrying a backpack may have an influence on gait parameters (LaFiandra *et al.* 2002, LaFiandra *et al.* 2003, Smith *et al.* 2006). Quesada *et al.* (2000), similarly to our results, showed minor peak changes in ankle ($\leq 1.5°$) and knee ($\leq 3°$) kinematics and kinetics that are also evident from figure 4 during initial contact and mid-stance when wearing a backpack. Another study determined that minor changes in sagittal kinematics while carrying a backpack were mostly not considered significant (Tilbury-Davis and Hooper 1999). Kinoshita (1985), on the other hand, reported increased knee flexion occurring during walking with load carriage, which is in contrast to our results and the results of Quesada (2000) and Tilbury-Davis and Hooper (1999). Attwells *et al.* (2006) reported on significant trunk anterior tilt during walking, which was a compensation for heavy load carriage. Fiolkowski *et al.* (2006) reported on significant changes in hip flexion during backpack load carriage, less with front pack. Our findings indicate that carrying a middle-sized backpack also had a significant impact on trunk and hip kinematics regardless of the boot-shaft stiffness, while minor impacts on knee and hip kinetics were not significant.

5. Conclusion

Boots, and footwear in general, are designed for various functions, therefore it is reasonable to consider how to bring together the extensive stiffness/elasticity tests with objective dynamical functional testing (gait kinematics and kinetics). In addition to footwear appearance, durable materials, foot protection, etc. the performance has become a very important feature in footwear design. Therefore, to ensure the required characteristics for safety, compliance, strength, solidity and at the same time achieve the desired performance, the footwear stiffness assessment together with its impact on kinematics and kinetics can be considered essential. The results of our study suggest that the major influence of boot stiffness on the kinematics and kinetics appears to be limited to the ankle joint. Therefore, when considering the functional performance of various boot prototypes under development, only the assessment of kinematics and kinetics in the ankle joint may be considered, instead of whole body analysis.

The outcomes of our study demonstrated that assessment of stiffness in various stance gait subphases can play an important role in determination of footwear functional characteristics. Therefore, footwear manufacturers should pay attention to boot stiffness to achieve optimal footwear performance.

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