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Effects of speed on plantar forces in three-foot regions during treadmill walking: A preliminary study using force sensing insoles

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Abstract

Study aim: The foot has region-specific biomechanical functions for absorbing shock, however, the effects of walking speed on plantar forces in the foot regions are unknown. The purpose of this study was to investigate the measurement repeatability and changes of regional (forefoot, midfoot, and rearfoot) plantar force by a triple-sensor wireless insole by gait speed modifications during treadmill walking.
Material and methods: Twenty young adults walked on treadmill at five speeds (self-selected, two slow and two fast conditions). Regional plantar forces were measured using a wireless in-shoe system (loadsol, Novel INc., St. Paul, MN). Intraclass correlation coefficients (ICC1, *k*) were used to assess repeatability. Repeated measures analyses of variance were used to determine differences in regional forces among speed conditions. Paired sample t-tests compared forces during self-selected speed and slow or fast conditions to determine foot regions influence.
Results: Across foot regions and conditions, ICCs ranged from 0.799 to 0.971 for contact time and from 0.918 to 0.981 for peak force. Repeated measures analyses of variance showed that walking speed significantly affected contact time in all plantar regions and peak force in the forefoot and rearfoot (all values $p < 0.01$), but not in the midfoot ($p = 0.85$). Contact time in all foot regions increased at slower walking speeds and decreased at faster walking speeds. In forefoot, peak forces decreased at slower walking speeds and increased at very fast speeds. In rearfoot, peak forces increased at faster walking speeds. In midfoot, peak forces did not change at any walking speeds.
Conclusions: The ability to measure plantar force data across three foot regions and at different walking speed has potential to broaden the research question investigated and explore clinical applications. The midfoot may be the most functional region to shock absorption from exposure to peak force during walking.

Keywords: Walking speed – Foot region – Plantar force – Treadmill – Wearable sensor

Introduction

The foot plays an essential role in all weight-bearing activities because it is the only point of contact with the ground. During the stance phase in the gait cycle of a rearfoot strike pattern, the plantar region that contacts the ground starts from the heel, passes through the midfoot, and ends at the forefoot. These plantar regions have region-specific biomechanical shock absorption functions and facilitate the forward propulsion of the body. Numerous studies have focused on the shock absorbing function and the factors attributed to plantar compression or pressure, such as plantar soft tissues[6, 11, 17], the medial longitudinal arch [9], and foot posture [4, 32]. Although pressure patterns among plantar regions depends on various factors such as foot function and structure, these studies did not consider how biomechanical factors vary with walking speed in the three plantar regions.

Understanding how these biomechanical factors interact with walking speed is crucial for making accurate assessments and comparisons. The gait patterns of individuals with any foot disorders are often analyzed in comparison with those of healthy individuals. However, since individuals with any foot disorders tend to walk slower and change the contact time in each foot region[20, 29, 30], without knowing which biomechanical variables are likely affected by gait speed, this comparison may not be appropriate. Thus, to improve our knowledge of the effects of gait speed on biomechanical variables is of paramount

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importance for clinicians who commonly rely on the outcomes of gait analysis to optimize patient care [33].

The speed at which a person walks affects biomechanical variables such as contact time and ground reaction forces. Fukuchi et al. [15] showed that walking speed affects ground reaction forces, with decreases at slow speeds and increases at fast speeds compared to the comfortable speed. They also reported that contact time decreased as the speed increased. However, the reviewed articles did not examine the plantar regions separately. With respect to region-specific biomechanical functions of the foot, it seems that three foot regions have specifically different speed-dependent responses to ground reaction force and contact time. It is known that the highest forces are loaded on the rearfoot, small forces on the midfoot, and moderate forces on the forefoot during walking [7, 16].

Over the last decade, some devices have been developed that allow for the assessment of force measures through in-shoe pressure insoles. The development of the devices has allowed researchers and clinicians to assess loading parameters in walking [8, 18, 26]. Recently, a triple-sensor insole was developed by Novel Electronics (St. Paul, MN, USA), which can collect plantar force data for three regions: rearfoot, midfoot, and forefoot. Thus far, some studies have published data concerning the validity and reliability of the single-sensor loadsol during walking [27], running [5], stop jump [24], and landing [25]. These studies have not assessed data from the triple-sensor loadsol, which may be more sensitive to different plantar regions. The repeatability of force data assessed using the triple-sensor loadsol is unknown.

Therefore, the primary purpose of this study was to investigate the effects of five different walking speeds on plantar forces in three foot regions (rearfoot, midfoot, and forefoot) during treadmill walking. In addition, the secondary purpose was to determine the repeatability of the triple-sensor loadsol measurements during treadmill walking.

Material and methods

Twenty healthy young adults (10 female, 10 male, mean age 20.6 ± 1.2 years; height 1.64 ± 0.08 m, weight 56.1 ± 9.1 kg, body mass index 20.8 ± 2.0 kg/m^2) participated in this study. The inclusion criteria were available to visit the laboratory, to fit one of three different sizes on loadsol insoles, and to walk comfortably on a treadmill. The exclusion criteria were injury or surgery of the lower extremity in the year prior to testing, plantar skin disease, and neurological disorders affecting gait. All study participants provided written, informed consent, using a letter approved by the Institutional Review Board, prior to study enrollment. The study was approved by the Institutional Review Board (#2105-03) and conducted in accordance with the Declaration of Helsinki.

The sample size needed for paired *t*-tests (effect size = 0.80, based on the results of the our preliminary experimental setup; α error = 0.05; power = 0.80) was calculated using G*power 3.1 software (Heinrich Heine University, Duesseldorf, Germany) [13, 14]. The results showed that at least 15 participants were required; therefore, 20 participants were recruited in this study to account for potential withdrawals.

Each participant was fitted with a pair of triple-sensor insoles (loadsol, Novel Electronics, St. Paul, MN, USA) and was provided a pair of neutral walking shoes at the beginning of the session (Figure 1). The loadsol has three capacitive force sensors that are segmented by the manufacturer into thirds based on sensor length, representing the rearfoot, midfoot, and forefoot plantar regions, in this study. The weight of the participant was entered in

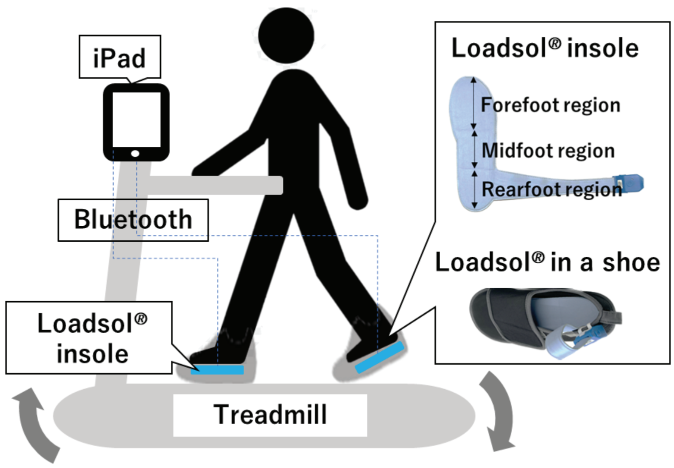


Figure 1. Experimental setting for the assessment showing the loadsol insoles in the shoes, iPad connected to the loadsol sensors via Bluetooth, and the treadmill

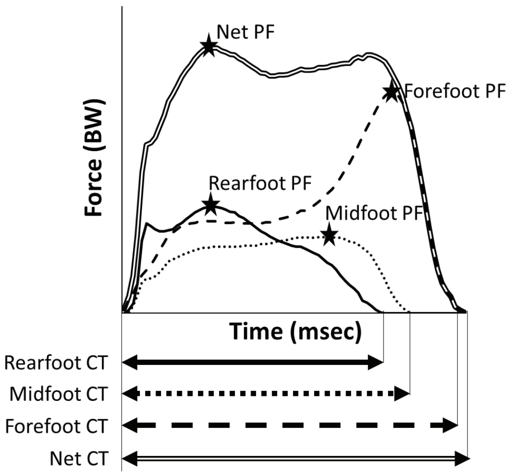


Figure 2. Example force-time data of the net (double line), rearfoot (solid line), midfoot (dotted line), and forefoot (dashed line) for one limb, collected during a stance

Newtons (N) in the loadsol application on an iPad (Apple Inc., Cupertino, CA, USA) via Bluetooth. The sampling rate was set at 100 Hz. The loadsol was calibrated using the manufacturer's procedure. Participants were instructed to load the insoles with their full bodyweight in a single-leg stance and then unload the insole three times on each foot following the manufacturer's calibration procedures.

Experimental

Each participant walked on a level treadmill (AR200, Minato, Osaka, Japan) and completed two trials. Their self-paced normal walking speed was determined using a previously established protocol [23]. This protocol allowed participants to acclimate to the treadmill and warm-up. Participants performed one 2-min trial at each of the following percentages of preferred walking speed: 80%, 90%, 100%, 110%, and 120%. Speed conditions were presented randomly and the order varied across trials. Participants rested 5 min between trials.

Data analysis was performed using Windows loadpad analysis software (Novel Electronics). The raw plantar force data from the loadsol sensors (Figure 2) were imported to a Windows computer as forefoot, midfoot, and rearfoot values. For this study only the dominant limb (the preferred limb for kicking a soccer ball) was analyzed. The force-time data in the middle 60 s of each speed condition, during which the participants achieved the treadmill speed, were analyzed. Contact time was counted as the time during which the force signal of the loadsol was equal to or higher than 30 N, based on 5% (2.8kg) of the mean participant bodyweight 56.1 kg estimated into Newton. Peak force was taken as the maximum force value in the stance phase and normalized to body weight (BW) for comparison. Contact time and peak force for rearfoot, midfoot, and forefoot regions independently were averaged over the total amount of steps in the analysis area. Finally, all variables were averaged over two trials.

The repeatability of the loadsol measurements was tested using intraclass correlation coefficients (ICCs), comparing the outcome measures between the first and second collections. All ICCs were run as a two-way mixed model ICC (1,2) for consistency. ICC values greater than 0.9 were defined as excellent, between 0.9 and 0.75 as good, between 0.75 and 0.5 as moderate, and less than 0.5 as poor [19], based on a study reporting on the repeatability of loadsol [25]. To determine differences in the force data across speed conditions, one-way repeated measures analysis of variance (RM ANOVA) was performed for contact time and peak force in each foot region. When a significant main effect was found, the post hoc Bonferroni's test was performed to compare between 100% speed and other speeds to determine if contact time and peak force changed over speed within a foot region. Effect sizes (ESs) were calculated using Cohen's d formula to determine the magnitude of the differences between speed conditions. An ES of 0.2 was classified as small, 0.5 as medium, and 0.8 as large.[10] Significance was set at 0.05, and all statistical analyses were performed using SPSS (Version 24, SPSS INC., Chicago, IL, USA).

Results

Mean values of walking speed and cadence in the different speed conditions are summarized in Table 1. The repeatability of the loadsol data for each speed condition is shown in Table 2. Both contact time and peak force of all foot regions showed good to excellent repeatability across all walking speeds (ICC = 0.799–0.981).

For contact time, one-way RM ANOVA showed a significant main effect of the speed condition on all plantar regions (forefoot, $F = 90.91$, $p < 0.01$; midfoot, $F = 178.16$, $p < 0.01$; rearfoot, $F = 130.73$, $p < 0.01$). Overall, contact time means of all three foot regions were significantly longer for 80% and 90% speed conditions and shorter for

Table 1. Mean ± SD of speed and cadence for five different speeds (80%, 90%, 100%, 110%, and 120%)

	80%	90%	100%	110%	120%
Speed [km/h]	2.2 ± 0.4	2.4 ± 0.4	2.6 ± 0.4	2.8 ± 0.5	3.1 ± 0.5
Cadence [steps/min]	86.6 ± 1.3	90.7 ± 1.5	94.9 ± 1.5	96.3 ± 1.2	100.0 ± 1.0

Table 2. Repeatability of force data for five different speeds (80%, 90%, 100%, 110%, and 120%)

	Intraclass correlation coefficient (95% CI)				
	80%	90%	100%	110%	120%
Contact time					
Forefoot	0.799*	0.894*	0.914*	0.901*	0.971*
	(0.501–0.920)	(0.738–0.958)	(0.787–0.966)	(0.755–0.961)	(0.927–0.988)
Midfoot	0.963*	0.903*	0.958*	0.881*	0.901*
	(0.909–0.985)	(0.760–0.961)	(0.896–0.983)	(0.705–0.953)	(0.754–0.960)
Rearfoot	0.966*	0.930*	0.943*	0.846*	0.856*
	(0.915–0.984)	(0.826–0.972)	(0.859–0.977)	(0.617–0.938)	(0.642–0.942)
Peak force [%BW]					
Forefoot	0.981*	0.975*	0.973*	0.923*	0.961*
	(0.953–0.993)	(0.937–0.990)	(0.933–0.989)	(0.810–0.969)	(0.903–0.984)
Midfoot	0.961*	0.932*	0.953*	0.965*	0.918*
	(0.904–0.985)	(0.832–0.973)	(0.883–0.981)	(0.912–0.986)	(0.795–0.967)
Rearfoot	0.948*	0.934*	0.967*	0.927*	0.924*
	(0.872–0.979)	(0.836–0.974)	(0.916–0.987)	(0.819–0.971)	(0.812–0.970)

* – $p < 0.01$; CI – confidence interval; BW – body weight.

110% and 120% speed conditions than for the 100% condition (Figure 3). Mean difference of forefoot contact time was 73.2 (ES = 2.76, 54.4–91.2 95% CI, $p < 0.01$ msec) at 80% speed and 36.3 (ES = 1.41, 18.1–54.5 95% CI, $p < 0.01$ msec) at 90% speed, longer compared to the 100% speed condition. Mean difference of forefoot contact time was 24.7 (ES = 0.91, 5.5–43.8 95% CI, $p < 0.01$ msec) at 110% speed and 50.1 (ES = 2.09, 33.1–67.1 95% CI, $p < 0.01$ msec) at 120% speed, shorter compared to the 100% speed condition (Figure 3). These results followed similar trends for the midfoot and rearfoot regions.

For peak force, one-way RM ANOVA showed a significant main effect of the speed condition on the forefoot and rearfoot regions (forefoot, $F = 25.17$, $p < 0.01$; rearfoot, $F = 7.97$, $p < 0.01$), but not for the midfoot region ($F = 0.33$, $p = 0.85$). Mean difference of forefoot peak force was 0.07 BW (ES = 1.41, 0.03–0.11 95% CI, $p < 0.01$) for 80% speed and 0.04 BW (ES = 1.57, 0.02–0.05 95% CI, $p < 0.01$) for 90% speed, significantly lower, and 0.04 BW (ES = 0.74, 0–0.08 95% CI, $p < 0.05$) for 120% speed, significantly higher compared to the 100% speed condition (Figure 4). Mean difference of rearfoot peak force was 0.02 BW (ES = 0.99, 0.01–0.04 95% CI, $p < 0.01$) for 110% speed, significantly higher compared to the 100% speed condition (Figure 4).

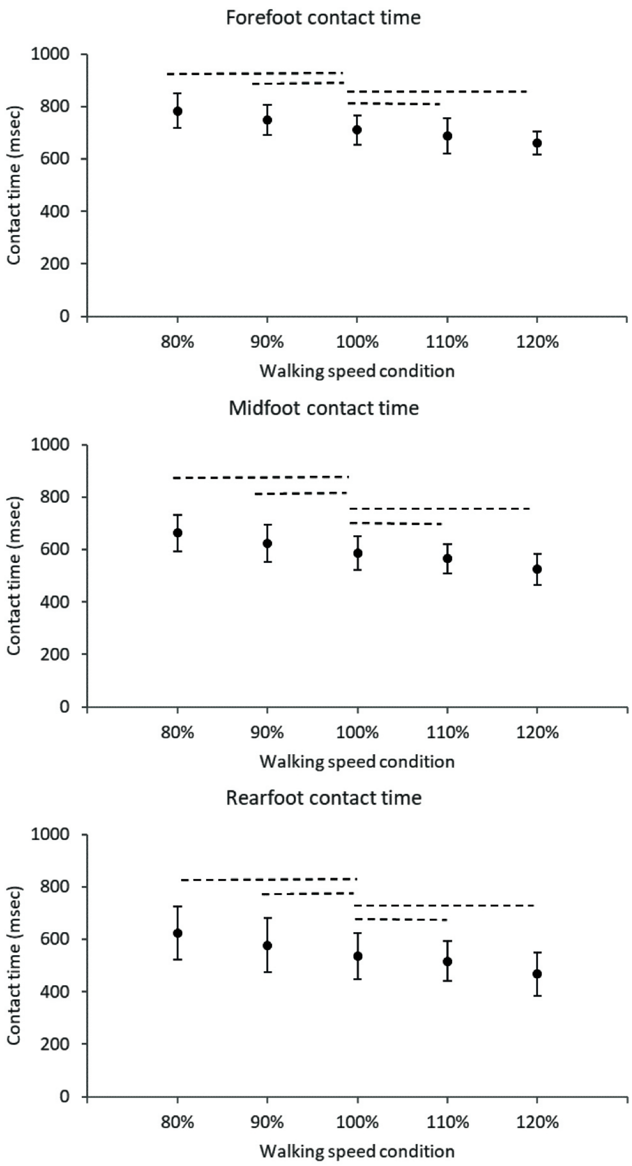
Discussion

The purpose of this study was to investigate the effects of five different walking speeds on plantar forces in three foot regions, and the repeatability of the triple-sensor loadsol measurements. Force data during treadmill walking were compared at either two slow or two fast speeds with treadmill walking at a self-paced normal speed. As in previous studies, force data on the forefoot and rearfoot regions were affected by walking speed. However, the effects of speed on peak force on the midfoot region were not similar to previous studies. These are the first data, to our knowledge, on how walking speed affects foot region-specific patterns of plantar force using a triple-sensor loadsol insoles. We believe that these data can assist clinicians in identifying and treating gait patterns of individuals with any foot disorders.

The ICC (1,2) of force data was 0.799–0.981, which is considered excellent or good repeatability, for all regions and speed conditions. The ICC value of force data in this study was also similar to that in previous loadsol studies [5, 21, 27]. Therefore, the measurement repeatability in the present study can be considered valid.

The contact time was affected by walking speed in all three foot regions. The results found in this study are in agreement with previous studies that reported a decrease in the stance duration with increased walking speed [3].

The peak force was affected by the walking speed, but only on the forefoot and rearfoot regions. Comparing these two regions, changes were more pronounced in the forefoot region, where the plantar peak forces decreased at slower speeds and increased at faster speeds. This pattern at faster speeds is in agreement with a previous study [12]. In the rearfoot region, the peak force changed only at fast speeds with increases, as per the findings of previous studies [22]. However, in the midfoot region, walking speeds were not related to changes in peak forces. Thus,



Figore 3. Contact time – Scatter plots for each speed and foot region. Solid vertical error bars represent standard deviations. Broken horizontal lines indicate significant differences between 100% and any other speed ($p < 0.05$). Contact time for all regions were longer at slower conditions and shorter at faster conditions compared to 100% speed

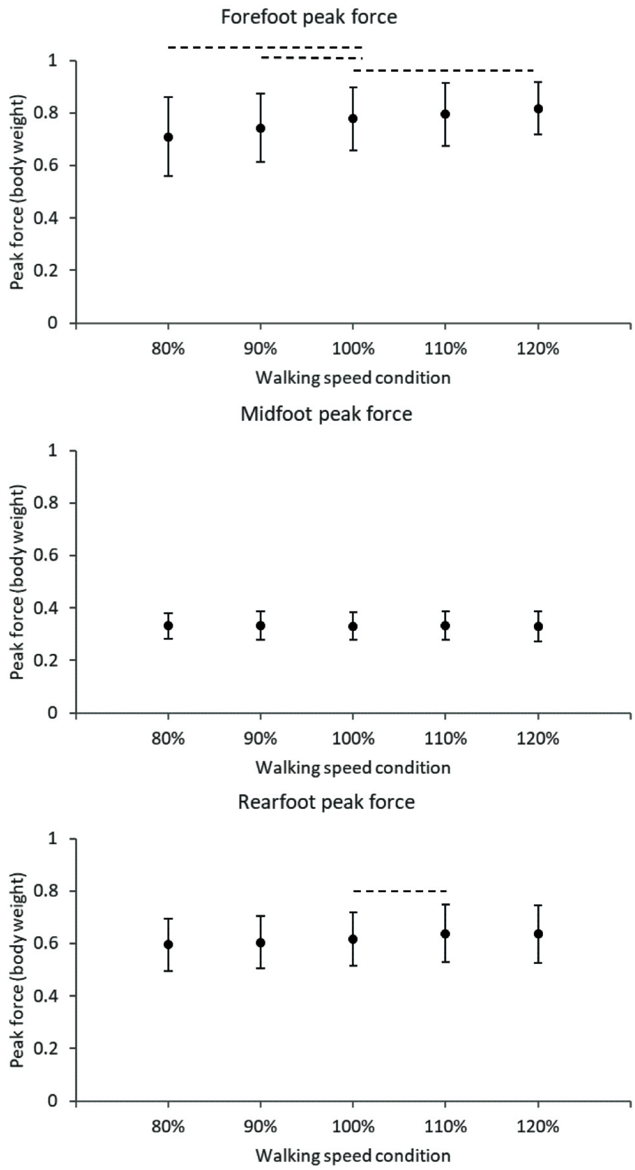


Figure 4. Peak force – Scatter plots for each speed and foot region. Solid vertical error bars represent standard deviations. Broken horizontal lines indicate significant differences between 100% and any other speed ($p < 0.05$). The peak force for forefoot and rearfoot peak tended to be lower at slower conditions and higher at faster conditions, but for midfoot did not

the different patterns of changes of the plantar peak forces between the forefoot or rearfoot and the midfoot regions could reflect region-specific biomechanical shock absorption functions. Bohanno et al. [2] reported that a contoured prefabricated foot orthosis was more effective at reducing pressure than some heel inserts. This finding suggests that the peak forces did not change with increased walking speed only in the midfoot region, which implies that the midfoot with its medial longitudinal arch more effectively attenuates shock than other regions.

The current study provides novel information by investigating the effects of walking speed on plantar forces in three foot regions, but it also has limitations. First, the self-paced normal speeds of the present participants were relatively slower than those of previous studies [3, 12, 22]. Therefore, generalizability of the study findings should be limited to slow walking speeds. Future studies should investigate the effects of changing speed on plantar forces in the three foot regions under faster walking conditions. Second, we did not assess the effect of foot posture (e.g., pronated, neutral, or supinated), and it is possible that foot posture may alter the regional plantar force along with their speed dependence. However, Rosenbaum et al. [28] previously reported that foot posture dose not affect how peak plantar pressure changes as walking speed increases. Therefore, varying foot posture among participants would not impair the ability to detect a foot regional-specific pattern. Finally, caution should be applied when comparing these data to those collected from overground walking trials as it has been reported that gait characteristics can differ between treadmill and overground walking [1, 31].

The present study investigated the effects of changing speed on plantar forces in three foot regions during treadmill walking using triple-sensor insoles. The repeatability ICC results demonstrate good to excellent repeatability for assessing plantar regional forces across different walking speeds The results showed that walking speed affected contact time of all foot regions and peak force only in the forefoot and rearfoot regions, but not in the midfoot region. This suggests that while walking speed influences plantar force in the forefoot and rearfoot, but it may not have the same effect in the midfoot. The triple-sensor insole's ability to measure plantar force data across three foot regions and different walking speed has potential to broaden the scope of research questions and explore various clinical applications. This finding may be useful as basic information to evaluate region-specific function of the foot for absorbing shock. Future studies should assess the arches of the foot and include comparisons with participants with foot disorders. In these studies, it would also be prudent to control for or monitor other factors that could affect regional-specific patterns such as pronated/supinated foot posture, abnormal bony structure, plantar tissue characteristics.

Conflict of interest: Authors state no conflict of interest.

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