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THE IMPACT OF FOOTWEAR ON GROUND REACTION FORCES AND GAIT CHARACTERISTICS OF WALKING PEDESTRIANS

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Abstract: *Vibration serviceability of lightweight and long-span structures is an area of research, which is attracting increasing attention in recent years. A common source of dynamic excitation in such structures is the interaction between the structure and its human occupants. Pedestrian loading is relatively small in magnitude compared to other forms of structural loading, but the dynamic nature of the force application complicates its understanding. Further complexity is added through the dearth of knowledge in relation to the interactive relationship between pedestrian loading and structural vibration, commonly referred to as human-structure interaction. This lack of understanding has contributed to several well-known cases of excessive structural vibration in bridges, stadium grandstands and even long-span floors in commercial buildings. Approaches to simulating interactive pedestrian loading are both deterministic and stochastic and encompass a range of simulation techniques from equivalent force methods to interactive elements such as spring-mass-damper systems and inverted pendulum models. At the core of all of these methods is the necessity to better model the forces applied by walking pedestrians and the parameters, which can influence these forces. This paper reports on the results of walking trials aimed at investigating the influence of footwear on the gait characteristics and associated ground reaction forces generated by people walking at several walking velocities. Participants were asked to walk on an instrumented walkway, at a range of pre-designated walking velocities and wearing different types of footwear. The influence of the footwear type on the gait characteristics such as walking velocity, pacing frequency, stride length and stride width are reported. Moreover, the influence of footwear on the ground reaction forces generated while walking are analysed.*

1. Introduction

The issue of pedestrian loading on flexible structures such as footbridges, grandstands and lightweight floors is an area, which is receiving significant attention from the research community. Of particular interest is the interaction between the pedestrian loading and the structural response of the loaded structure. This interest has been instigated by several noteworthy examples of high-profile structures, which have vibrated considerably under dynamic pedestrian loading under specific conditions.

In order to address the issue, a variety of modelling strategies have been developed, including moving force models, moving spring mass damper (SMD) models, inverted pendulums and others, which aim to mimic the interaction between the force and the structure to varying degrees. Irrespective of the model proposed, each depends on the use of a force function to simulate pedestrian walking loads, of which a number are regularly employed. Typically these functions can be characterised by parameters including pacing frequency (rate of load application); step length or pacing velocity (spatial distribution of loads), pedestrian mass and dynamic load factors (force magnitude) to represent the dynamic nature of the force application. These load models are covered in some detail in Mullarney (2018) and elsewhere. Interestingly, none of these methods consider the potential impact of ground surface or footwear on the load application. This paper aims to address the impact of various footwear types on the forces and gait characteristics of walking pedestrians.

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1.1 Pedestrian loading

Pedestrians create three near periodic ground reaction forces (GRFs) whilst walking; namely, a vertical, medial-lateral, and a longitudinal force (Figure 1). The vertical and medial-lateral force components tend to be of greatest concern to footbridge designers.

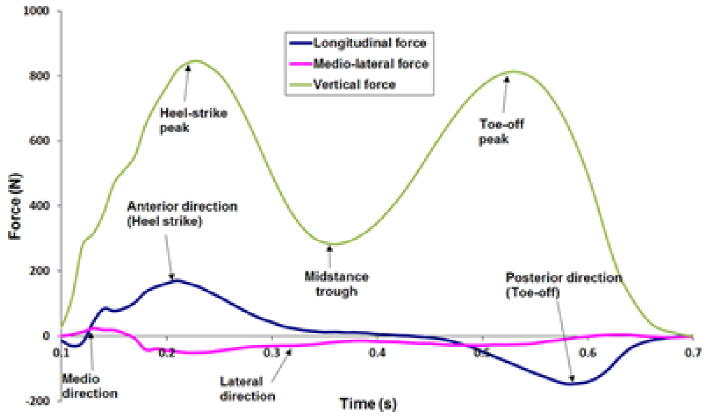


Figure 1. Ground reaction forces from single footfall.

However, in walking there is a stage where both feet touch the ground simultaneously, and this is referred to as the double stance or 'continuous walking' phase. This phase produces the continuous walking force, which is again near periodic in time; as presented in Figure 2. This force is modelled by the guides using a function similar to that in Equation 1.

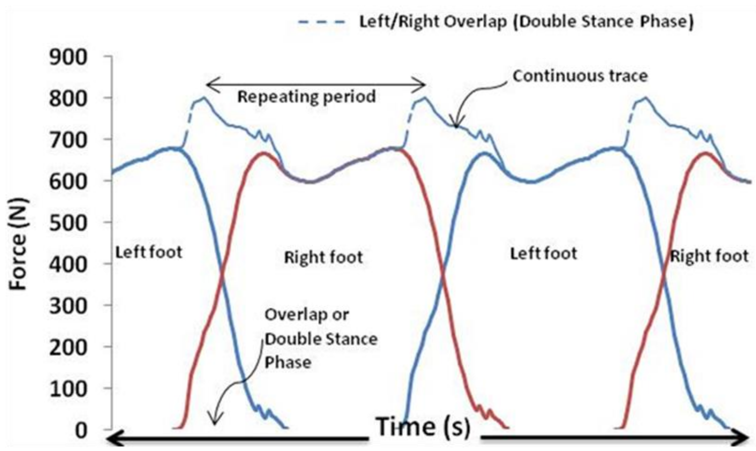


Figure 2. Continuous vertical walking force.

$$F_v(t) = W + \alpha_v . W . \sin(2.\pi.f_s.t) \text{ [N]} \qquad (1)$$

Where $F_v(t)$ is the vertical, pulsating point force; W is the pedestrian's static weight, and is generally presented as a fixed value within design guides. More, f_s is the pacing frequency, and t time, while a_v is the dynamic load factor (DLF) associated with vertical walking; and is defined as the ratio of maximum increase in vertical force from the static weight divided by the static weight of the pedestrian. The guides generally present this as a fixed value; however, Mullarney (2012) and Mullarney (2018) found it to be dependent on pacing velocity (a product of height and pacing frequency), pacing frequency, and the flexibility of the bridge. As footwear may influence the effective leg length of a person (flat versus high heels) and can potentially alter the damping properties of the pedestrian (through the material of the sole and through kinematic changes to the foot upon ground strike), the authors posited that its influence on pedestrian loading is worth investigating.

1.2. Footwear

Rodgers (1988) cites Cavanagh (1982) when she makes the point that footwear attenuates the peak GRF, and Katoh et al (1983) when she elaborates that different footwear types generate different force profiles. Majumdar et al. (2006) found that the wearing of military boots in comparison to slippers and barefoot, greatly increased step length and pacing velocity, but reduced step width and pacing frequency; some key parameters which influence GRFs.

Mario et al. (2009) suggests that wearing footwear constrains the natural barefoot motion. It is therefore reasonable to suggest that any such constraint of motion will cause a change in gait and therefore a change in GRF; but how significant this change is in terms of modelling pedestrian loading in a civil engineering context needs to be explored in both a kinematic (movement) and kinetic (force)context.

1.3 Footwear and Kinematic Effects

Menant et al. (2009) note that footwear is likely to influence balance control and the risk of experiencing slips and trips when walking. Mario et al. (2009) investigate whether footwear restricts the foot motion. In their kinematic investigation, Mario et al. (2009) present results that indicate the wearing of sandals constrained the natural foot motion in terms of adduction amplitude, eversion slope, eversion amplitude, metatarsal bases and metatarsal heads. They explain that differences in foot motion between barefoot and shoe conditions were induced by the sole and the forefoot spreading by the strap of the sandals.

These results are in agreement with Wolf et al. (2008) who carried out trials involving eighteen children walking with shoes and walking barefoot. Wolf et al. (2008) describes the wearing of a 'commercial' shoe as having a significant influence on the motion patterns particularly at the forefoot. Interestingly, Menant et al. (2009) points out that the 'interface' (or sole of the shoe) is likely to influence balance control walking; again impacting on gait. Moreover, Hansen and Childress (2004) in their results discussion claim that a walker will adapt when wearing shoes of different heel heights to maintain similar rollover characteristics (i.e., rollover shapes). Furthermore, Schaefer and Lindenberger (2013), whilst citing Ebbeling et al. (1994) and Lee et al. (2001), explain that wearing high heels have been shown to change various gait and posture characteristics by, for example, increasing trunk and knee flexion angles and by leading to more asynchronous joint actions of the lower extremities.

Ebbeling et al. (1994), for instance explain that the wearing of heels greater than 50.8mm can greatly influence lower extremity mechanics which may affect the energy cost of gait. It is further noted by Ebbeling et al. (1994) that they wearing of heels while walking is 'unnatural' and will alter the angular patterns of both the ankle and knee. Lee et al. (2001) in their results conclusion note that the wearing of high heels causes several deleterious effects; for instance, the lumber spine flexion angle decreases significantly as heel height increases, which creates a more unstable posture because of the increase in the height of the centre of body mass. In addition, there is a compensatory increase in erector spine activity to maintain the abnormal posture (Lee et al. 2001).

1.4 Footwear and Kinetic Effects

The movement of the body is intrinsically linked to the pressure created by the foot as explained by Burnfield et al. (2004) whilst citing Eils et al. (2002) and Rosenbaum et al. (1994). Initially, body weight is loaded solely on the heel region resulting in high peak pressures in this area (Burnfield et al. 2004, Eils et al. 2002, Rosenbaum et al. 1994). Peak heel pressure dissipates once the forefoot contacts the ground (flat foot) and body weight is distributed over a larger surface area (Burnfield et al. 2004).

In late stance, as the body progresses anterior to the ankle joint and the heel elevates from the ground, force is once again concentrated over a relatively small region, the forefoot (Burnfield et al. 2004, Eils et al. 2002). High forefoot pressures in late stance are a consequence of this posture (Rosenbaum et al. 1994, Burnfield et al. 2004) To elaborate, Ebbeling et al. (1994) explains that the wearing of heels causes the centre of mass to be raised and shifted forward; therefore increasing the vertical GRF. This claim is backed up by Li et al. (2010) who found that the maximum forces and pressures increased in the medial forefoot area as heel height increase, which as noted by the same researchers is consistent with results by Lee et al. (2005), Speksnijder et al. (2005), and Mandato et al. (1999).

Moreover, the medial forefoot has being identified by Morag et al. (1999), and Speksnijder et al. (2005) as the most sensitive area with change of heel height (Li et al. 2010). According to Lee et al. (2005) that by Increasing heel height medial forefoot pressure, impact force, and perceived discomfort during walking will increase. Significantly, Ebbeling et al. (1994) stresses that kinematic changes will preclude attenuating this vertical force since balance becomes an important factor at higher heel heights.

In their investigative study Burnfield et al. (2004) report that faster speeds and walking barefoot results in higher mean and peak plantar pressures. They (Burnfield et al. 2004) explain that faster walking is generally associated with higher pressures, primarily due to increased peak force values. They hypothesis given by Burnfield et al. (2004) for the greater planter pressure with barefoot in comparison to shod walking is that during barefoot walking there will be most likely a reduced contact area during this form of gait. Burnfield et al. (2004), however, does stress the point that for this latter hypothesis they have not found any data in the literature to back up this claim. Hallander et al. (2014), from their running trials involving children, report that the wearing of shoes resulted in an increase in pacing frequency but also an increase in step lengths in comparison to barefoot walking.

This work set out to explicitly measure the impact of various types of footwear on the loading applied while walking.

2. Experimental Programme

Participants conducted walking trials in the laboratory on a specially constructed rigid walkway. These trials involved participants walking in three different scenarios - barefoot, in flat shoes, and in high heels. In each scenario, gait parameters and ground reaction forces were recorded.

2.1 Participants

This walking trial set involved three adult participants off Brazilian background. Persons were excluded from participation if they had a history of previous injury with ongoing symptoms, or significant previous injury that would hamper their gait. In total there were eighteen trial walks conducted: six trial walks in barefoot, six with flat soled shoes, and six with high heel shoes. This amounted to each participant carrying out two trials walks for each foot type arrangement.

2.2 Anthropometric data

The following parameters (Table 1) were recorded for each test participant prior to the walking trials being carried out: age; height (with and without footwear footwear); weight (with and without footwear).

Table 1. Anthropometric data of pedestrians with and without shoes

Parameter	Mean	Standard deviation
Age (years)	22.67	0.47
Height – barefoot(m)	1.58	0.038
Height – flat shoes (m)	1.61	0.045
Height – high heels (m)	1.64	0.057
Mass – barefoot (kg)	59.29	0.13
Mass – flat shoes (kg)	60.59	0.14
Mass – high heels (kg)	60.63	0.14

2.3 Equipment

2.3.1 Walkway

The walkway is 0.9m wide x 11.0m long and is constructed from three 50mm laminated fibreboard panels framed with timber battens and cross members at 600mm centres, which were bolted together longitudinally and placed directly on the laboratory floor.

2.3.3 Data acquisition

A 500mm x 500mm AMTI AccuGait balance platform (force plate) was mounted at the mid-point of the walkway to record the ground reaction forces: the top surface of the force plate was made flush with the top surface of each walkway. In the vertical direction, Fz, the force plate has a natural frequency of 150Hz and a loading capacity of 1334N: the force plate was calibrated prior to the walking trials through measurement of static forces. A Monitran MTN1800 accelerometers, with a sensitivity of 1.020 V/g@80Hz, were mounted to the side of the walkway at midspan. Data were recorded from the accelerometers through a virtual instrument (VI) developed in National Instruments (NI) LabView 8.5. These data were used to determine the time interval between consecutive footsteps on the rigid walkway; and to determine the natural frequency of the flexible walkway. The trial participants walking frequency during the flexible walking trials were determined via video analysis; this method was calibrated during the rigid trial walks against the accelerometer readings. Grid paper measuring 4.2m x 0.6m and containing a 20mm x 20mm grid size was placed over the middle section of the walkway to assist in recording the spatial parameters such as step length, step width and foot landing position. A schematic layout of the testing set-ups is shown in Figure 3.

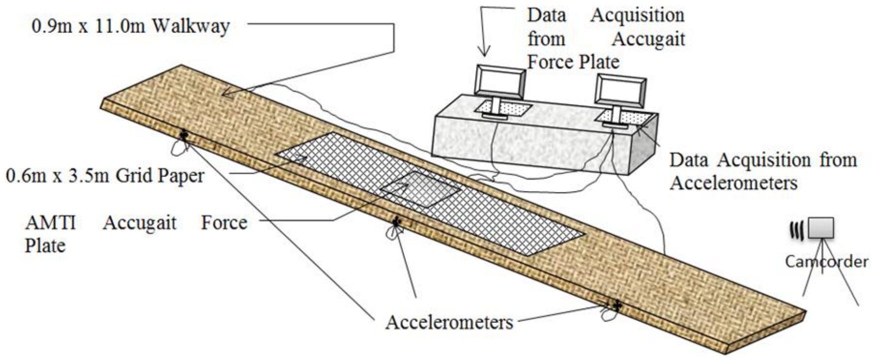


Figure 3. Schematic layout of equipment used in trial

2.4 Experimental procedure

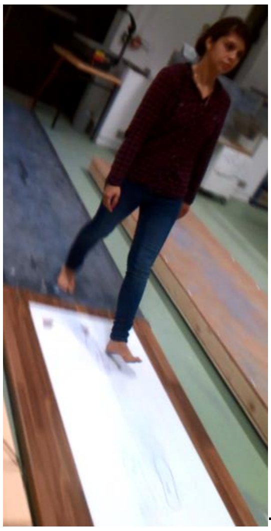
Each participant was asked to carry out the trials using 3 different types of footwear; namely to carry out two walking trials each in bare feet, flat soled shoes and in high heels. Dummy runs were carried out prior to each trial to allow the participant to become familiar with the walkway and surroundings. Spatial parameters (step length and width) were recorded via blue chalk dust and paper. For all trial walks, the participants were asked to walk in a straight line along the length of the walkway at a self-regulated "normal" speed, while looking straight ahead; Figure 4.

2.5 Parameters measured

Table 2 lists the parameters recorded during each trial.

Table 2. Parameters measured

Gait parameter	Force	Anthropometric data
Step length (m)	Vertical GRF (N)	Mass (kg)
Pacing velocity (m/s)	Continuous GRF (N)	Height (m)
Pacing frequency (Hz)		Heel height (m)
Step width (m)		
Foot landing position (^{0})		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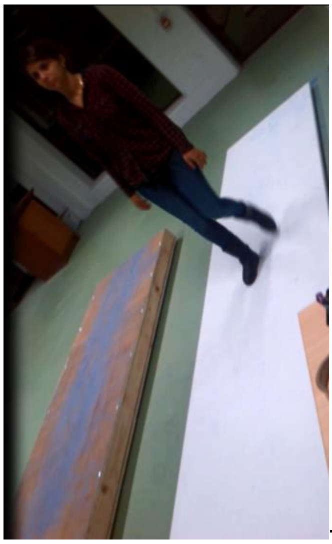
-b

- c

Figure 4. Walking trials, a – barefoot walking, b – flat shoe walking, c – high heel shoe walking

Figure 5. Sample of shoe types used

3. Results and Discussion

3.1 Gait Parameters

Figure 6 presents the spatial and temporal parameter results from the walking trials conducted. Pacing velocity from barefoot to flat shoe walking shows a 4.03% increase (1.323 m/s to 1.380 m/s), and a 0.23% decrease (1.323 m/s to 1.320 m/s) from barefoot walking to high heel shoe walking.

In terms of pacing frequency, barefoot to flat shoe shows a decrease of 0.60% (1.989 Hz to 2.001 Hz), while bare foot to high heel shoe walking showed an increase of just 0.45% (1.989 Hz to 1.980 Hz). Step length presents a 4.07% (0.662 m to 0.689 m) and a 0.76% increase from barefoot to flat shoe walking and barefoot to high heel walking; respectively.

Table 3 Recorded parameters from walking trial

Parameter	Barefoot		Flat shoe		High Heel	
	Mean	SD	Mean	SD	Mean	SD
Heel height [m]	0	0	0.030	53.33	0.060	36.67
Step length [m]	0.662	6.34	0.689	5.52	0.667	7.95
Pacing frequency [Hz]	1.989	6.69	2.001	2.60	1.980	1.72
Pacing velocity [m/s]	1.323	12.70	1.380	7.03	1.320	7.73
Step width [m]	0.074	22.97	0.065	32.31	0.076	18.42
FLP [^{0}]	10.16	27.60	9.600	26.95	8.767	38.60

3.2 Step length, pacing frequency, and height

Andriacchi et al. (1977) proposes that step length is proportional to a product of both the participant height and the pacing frequency, *fs*, with a coefficient of 0.24. The results recorded by Archbold and Mullarney (2011) showed a good comparison with Andriacchi et al. (1977) coefficient, as a value of 0.23 was determined (Equation 2 and 3). The coefficient from this experimental programme reveals a value of 0.21 for all footwear types as shown in Figure 6. More plotting height versus step length reveals a value of 0.43 (R^2: 0.8).

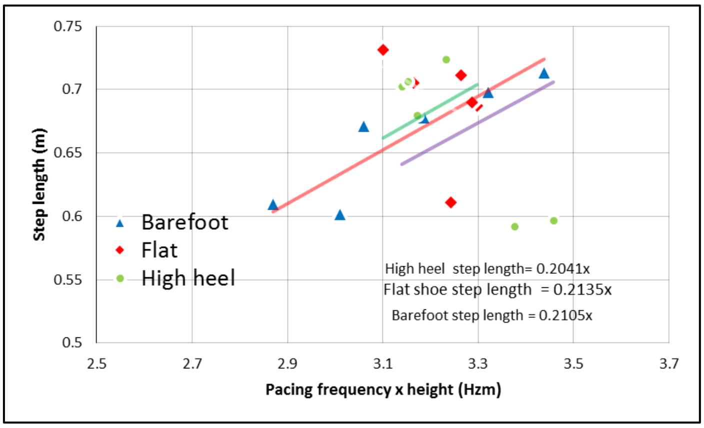

Figure 6. Relationship between step length, pacing frequency, and height

$$v_s = 0.23hf_s^2\ [m/s] \tag{2}$$

$$f_s = \sqrt{\frac{v_s}{0.23h}}\ [Hz] \tag{3}$$

3.3 Single Stance Ground Reaction Force

Figure 7 presents the single footfall DLFs for each trial walk and ranges from a maximum of 0.271, occurring during high heel walking, to a minimum of 0.080, occurring during flat shoe walking. Mean values are presented also, and are 0.191 (SD: 17.80%), 0.164 (SD: 32.32%), and 0.229 (SD: 15.72%) for barefoot, flat shoe, and high heel shoe walking; respectively. Another important point of note is that for each participant the maximum DLF occurred during high heel walking. The reason for this is unclear, but maybe due to the extra medial forefoot forces that commonly occurs due to high heel walking as explained by Ebbeling et al. (1994). This is illustrated in **Error! Reference source not found.** 8, which shows how the toe-strike force is largest for the high heel walking in comparison to barefoot and flat shoe walking.

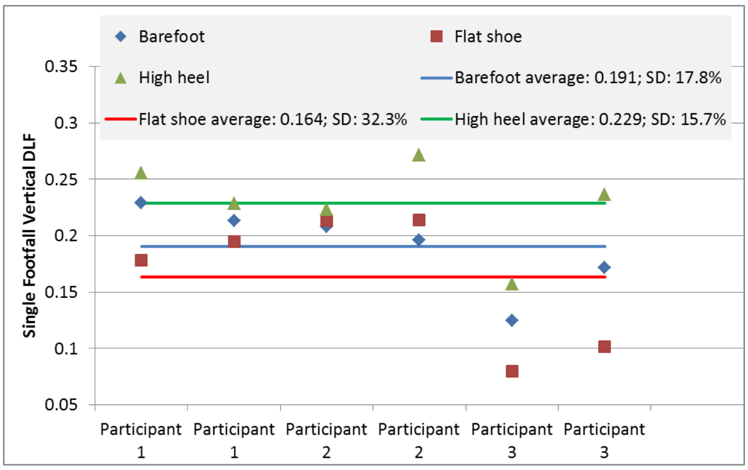

Figure 7. Single stance DLF for each participant and footwear type

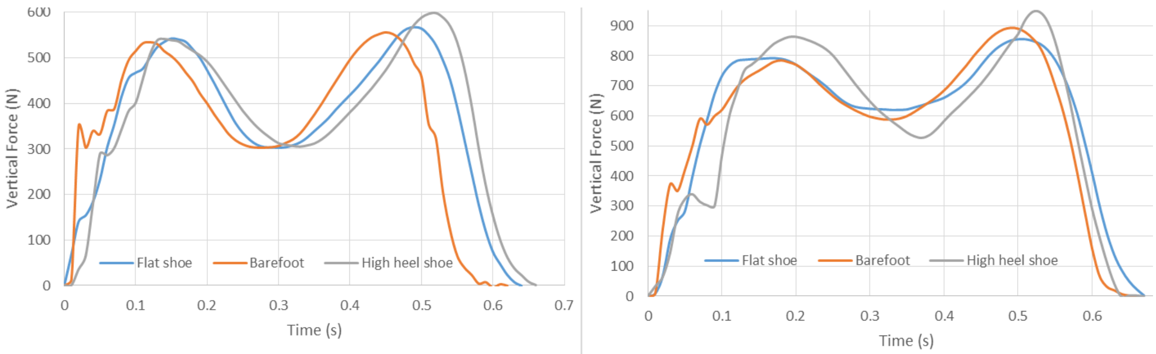

Figure 8: Force profiles for participant 2 trial 2, left; and participant 3 trial 2 right

3.4 Single DLF versus Pacing velocity

Mullarney (2012) showed that during slow, normal, and fast walking pacing velocity has a greater influence then step length and pacing frequency on the single DLF; as R^2 of 0.75, 0.57, and 0.61, respectively testify. **Error! Reference source not found.** presents pacing velocity plotted against single stance DLF for all three footwear types; respectively. It again suggests that the faster you walk the high the DLF tends to be. Nothwithstanding this, however, is that high heeled shoe type tends to produce higher DLFs that both barefoot and flat shoe types; but its R^2 value is much less. The reason for this but may be due to the different kinematic characteristics associated with this form of gait as explained by Ebbeling et al. (1994), i.e. heel high walking offers a different form of gait to that of barefoot and flat shoe walking. This is illustrated in **Error! Reference source not found.** where all three shoe type's walking DLFs are plotted against pacing velocity and compared with the equation presented in Mullarney (2012). For instance, only three DLFs (one barefoot and two flat shoe DLFs) are non-adjacent to the equation put-forth by Mullarney (2012); yet all of the high heel walking data points are non-adjacent.

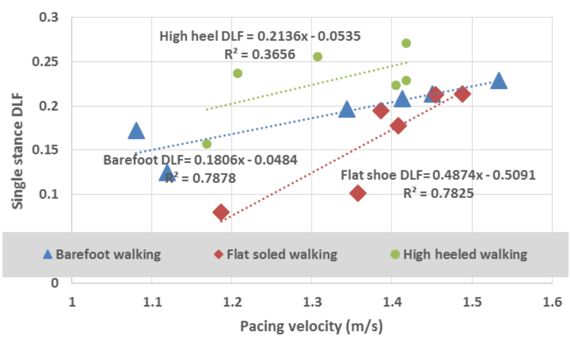

Figure 9. Pacing velocity plotted against single stance DLF

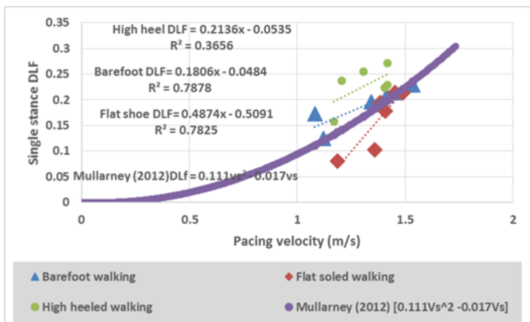

Figure 10. Pacing velocity plotted against single stance DLF, and Mullarney (2012) equation

3.5 Continuous DLF versus pacing velocity

Figure 11 presents the continuous DLFs for each trial walk and ranges from a maximum of 0.749, occurring during high heel walking, to a minimum of 0.172, occurring during flat shoe walking. Mean values are presented also, and are 0.427 (SD: 34.19%), 0.432 (SD: 26.85%), and 0.539 (SD: 25.97%) for barefoot, flat shoe, and high heel shoe walking; respectively. Interestingly, both barefoot and flat shoe means are approximately equal, but less than the mean value for high heel walking.

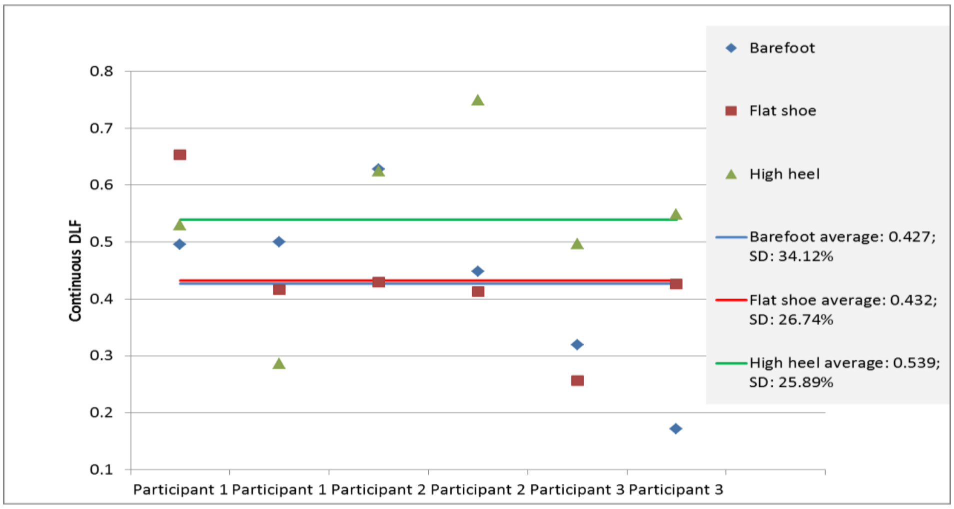

Figure 11. Continuous DLFs for each walking trial, coupled with mean values

During Mullarney's (2012) trial programme it was noted that the continuous walking DLF is typically 2.5 times larger than the single stance DLF. Figure 12 presents the difference between the single stance and continuous walking DLFs for the three footwear types, and reveals differences of 2.23, 2.63, 1.80, and 2.40 for barefoot, flat shoe, high heel, and overall walking; respectively. Again most values are close to the 2.5 as presented by Mullarney (2012) apart from high heel walking. For this reason the continuous DLF presented in Mullarney (2012) is plotted against pacing velocity and the continuous DLFs results here; Figure 12.

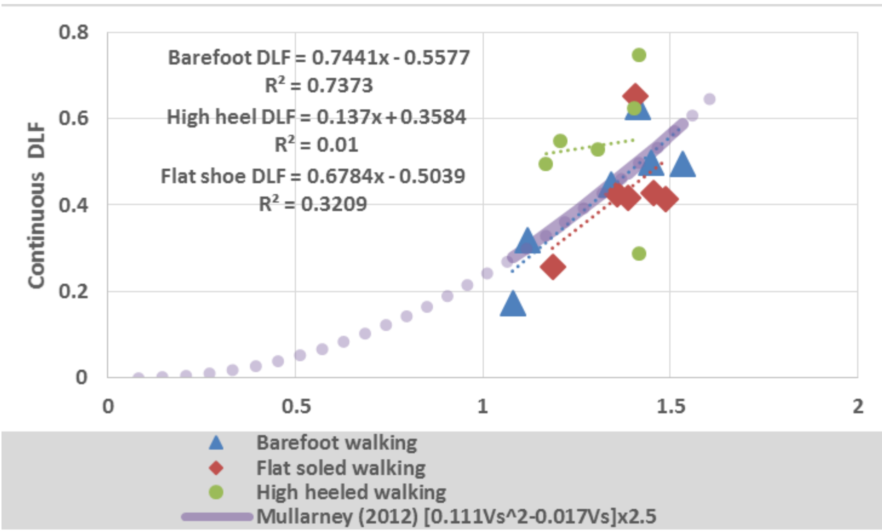

Figure 12: Mullarney (2012) equation plotted against pacing velocity and the continuous DLFs

Table 4. Summary of DLFs from the trials

	Single stance DLF		Continuous DLF	
	Mean	SD (%)	Mean	SD (%)
Flat shoe walking	0.164	32.32	0.432	26.85
Barefoot walking	0.191	17.8	0.427	34.19
High heel walking	0.229	15.72	0.539	25.97
Overall	0.194	25.77	0.466	30.9

Table 4 presents a summary of the DLF's from the walking trials. The increase in DLF (both single stance and continuous) is most pronounced for high heel walking, with values up to 40% higher for high-heeled shoes. This is an important consideration in determining load functions for crowds of pedestrians.

4. Conclusions

Much work is being carried out in the area of human-induced loads on flexible structures. Much of this work focuses on methods for simulating the interaction between pedestrian loading and structural response. At the core of these methods is the load function which is employed to simulate pedestrian loading. Generally, generic models are used, which do not consider parameters such as type of footwear. This paper reports on walking trials carried out on an instrumented, rigid walkway, aimed at investigating the impact of footwear on both ground reaction forces and gait characteristics. It was found that there is little difference between the parameters for barefoot and flat soled walking, but high- heeled walking led to significantly greater vertical ground reaction forces. The spatial parameters were not as greatly affected. This increase in GRF is an important consideration for those developing load models for pedestrians.

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