VARIATIONS IN VERTICAL LOADING FROM WALKING DUE TO SURFACE VIBRATION

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Summary

Walking trials have been carried out on rigid and flexible walkways mounted with a force plate in order to determine how vertical pedestrian loading is influence by these two walking platforms. This paper presents the results of this study. The sample population comprised of seven healthy adults and involved over 40 trial walks at normal pacing velocities. The results report dynamic load factors from both single and continuous loading in terms of both walkways. Furthermore, it presents the relationship between pacing velocity and dynamic pedestrian loading in an endeavour to try and model such loading. It is envisaged that the data contained in this paper could contribute to the improvement of existing numerical load models for simulating pedestrian loading scenarios.

Keywords: Footbridge, flexible, rigid, vertical loading, pedestrian loading, dynamic load factor, pacing velocity, vibrations

1. Introduction

The issue of pedestrian loading on footbridges and more specifically the subject of pedestrian-structure interaction is attracting significant attention from researchers within the engineering community. This is largely in the wake of several notable instances of excessive vibrations in footbridges being recorded in recent times, such as the Millennium Bridge, London and the Eagles Meadow Bridge in Wrexham [1].

Several forcing functions are proposed in the literature to simulate the inducer of such vibrations (i.e., pedestrian walking loads), but have been shown to have varying degrees of success in doing so. It is considered that understanding of the principal properties of human walking actions must contribute to any robust load models. Previously, the authors have investigated vertical loading induced from people walking on a rigid surface ([2]). This paper is a natural progression of this previous work, as it reports the results from an experiment programme of pedestrians walking on a rigid and then a flexible walkway; therefore highlighting the differences in the two. This is particularly important because much of the data on vertical loading due to walking comes from the biomechanical domain, which are results developed from rigid platform walking (as reviewed in [2]).

This paper presents the results of these trials and reports on the difference between loading recorded while walking on a flexible walkway to that of a rigid one; which may be of use in determining such load models.

2. Vertical loading from walking

Walking imparts ground reaction forces (GRF's) in three *orthogonal* planes; namely, a vertical (*inferior*) in the *coronal* (frontal) plane, a *medial-lateral* (or simply lateral) in the transverse (horizontal or axial) plane, and an *anterior/posterior* (longitudinal) in the *mid-sagittal* plane. GRF's can be readily measured for single footfalls using equipment such as force plates. The key focus for this paper - the vertical GRF – is the largest in magnitude[3], followed by the longitudinal and then the lateral force (Fig. 1). Further, unique to walking is a phase known as the double stance phase, where both feet are on the ground simultaneously. The total walking vertical force is derived from a summation of individual footfalls, overlapped by a time period to reflect the double stance phase. [2].

2.1.1 Pedestrian loading from single footfall

The vertical force, Fig. 1, generally has a profile of two peaks and a trough. The first peak occurs at heel-strike (contact phase), while the second occurs due to toe-off (propulsive phase); and the trough occurs at midstance, when both the toe and heel are on the ground simultaneously [4, 5]. Intuitively, anthropometric characteristics (e.g. pedestrian weight and height) and certain gait (walking) parameters such as Step Length, (l_s), Gait Cycle Length/Stride Length (c_s), Pacing Frequency or Cadence (f_s or C) and Pacing velocity (v_s) will influence vertical pedestrian loading.

Keller et al.[6] (whilst citing [7-10]) state that pedestrian forces are dependent on factors such as weight, gait velocity, and gait style. Additionally, Keller et al. [6] (whilst citing [11, 12]) explain that the vertical force shows the least variability between and within subjects, and state (without explaining why) the vertical force, being the largest, is the easiest to quantify. Kirtley [13] informs that the shorter the time the foot is on the ground (stance time) the greater will be the force. Drerup et al. [14] indirectly backs up this claim; whilst citing [15-17], by asserting that an effective way to reduce peak pressures on the foot is to reduce speed. Huang [4], meanwhile, notes that the vertical force is affected mostly by the pedestrian's pacing frequency, leaving out pacing velocity and step length; perhaps realising that pacing frequency, step length, and pacing velocity are directly linked to one another. Furthermore, Martin and Marsh [18] observe that a change in step length has negligible effect on the vertical force, so long as the pacing velocity does not change. Probing further into the relationship between pacing velocity and the vertical pedestrian force, Kirtley [13] remarks that pacing velocity has little influence on the toe-off peak. The same author does suggest, however, that the heel peak will be affected by a change in pacing velocity, as the braking force will increase or decrease; accordingly. Moreover, the authors [2, 19] of this paper experimentally investigated the influence of various gait parameters on vertical pedestrian loading; and found velocity to be the most influential parameter. However, this previous study [2, 19] was conducted on a rigid walkway and the relationship was for a single footfall only. This is particularly relevant for this paper because it has been hypothesised that walking on a flexible surface will cause a reduction in the applied vertical force by approximately 10% [20].

2.1.2 Pedestrian loading from continuous walking

As noted a pedestrian will produce two support phases during the gait cycle; i.e., the single support phase and the double support phase. These two support phases cause two vertical force types; namely, a single footfall force and a continuous walking force [21]; Fig. 2. The authors have previously reported that the dynamic force component derived from continuous walking may have a peak amplitude as great as 2.5 times that associated with the single footfall force [2, 19]. Significantly and notwithstanding the fact that the double stance force is significantly larger than the single footfall force most literature tends to focus on the latter. Moreover, many reported findings about vertical pedestrian loading fail to state whether their dynamic force is from the single or double stance phase. The continuous walking force is assumed to be reasonably periodic, with certain defining characteristics. As a result, it is often modelled mathematically as a continuous function, with one or multiple frequency components.

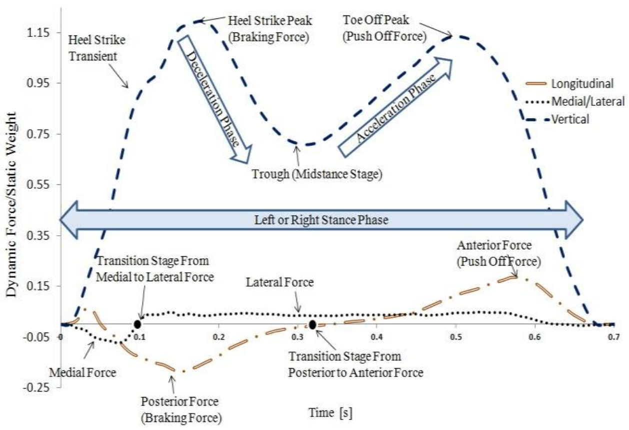

Fig. 1. A diagrammatical representation of the three orthogonal forces from a single footfall

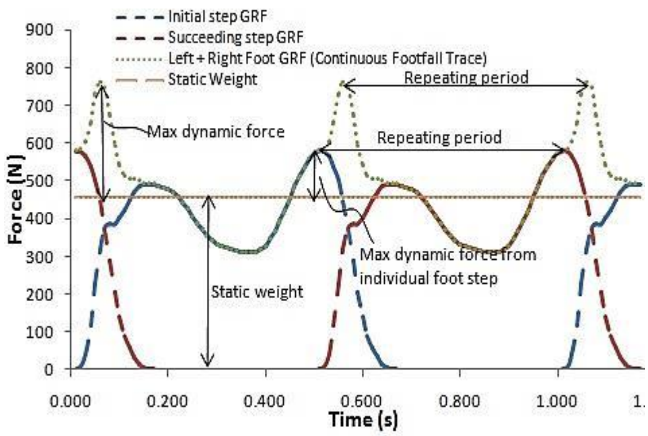

Fig. 2 Vertical GRF caused due to pedestrian walking

2.1.3 Design guide approach

The majority of guides published in the last decade tend to favour a pedestrian load model based on a time-domain approach (e.g. [22-26]), which is normally presented as a *single harmonic sine function* (SHSF). In its basic form the SHSF is presented as a harmonic pulsating point load and as a function of time; $F_v(t)$:

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

Where f_v represents the natural frequency of the bridge; therefore, worst-case scenario is when the pedestrian pacing frequency (f_s) is equal to the natural frequency (f_v) – i.e. when resonance occurs. The dynamic load factor (DLF), which is presented as α_v is defined as the ratio of maximum increase in the vertical pedestrian force from the static weight divided by the static weight of the pedestrian. The **Error! Reference source not found.** presents the vertical DLFs from various guides (e.g. [22-26]) written in the last decade; and is based on a pedestrian weighing 700N – which is the weight used by the majority of the guides. The most intuitive aspect of Fig. 3 is that the DLFs and weight are in most cases a fixed value; which is a ratter narrow ranged approach. For instance, the authors [2, 19] report a DLF value of 0.569 with a high standard deviation of 42% for the double stance at normal paced walking on a rigid surface. Moreover, it is well documented in the literature, (e.g. [27]), that the DLFs can vary depending both intra-subject and inter-subject.

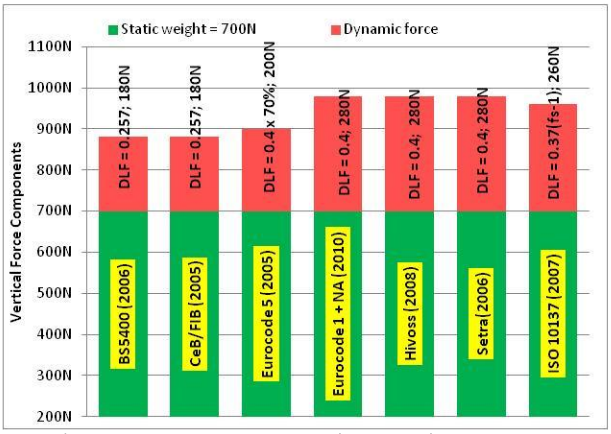

Fig. 3. Vertical DLFs for the 1st harmonic range of walking found within various design guides

3. Experimental Programme

The experimental programme reported herein consists of walking trials involving one female and six male healthy adult participants, aged between 20 and 40 years old. The participants conducted the walking trials in the laboratory on specially constructed rigid and flexible walkways, as described in this section.

3.1 Participants

Participants were recruited from staff and students at Athlone Institute of Technology, Ireland. The ethnical composition of the participant sample were Caucasian Irish. 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 forty two trial walks conducted: twenty one on the rigid walkway and twenty one on the flexible platform.

3.2 Anthropometric data

The following parameters were recorded for each test participant prior to the walking trials being carried out: age; height(with footwear); weight; average leg lengths (measured from the *llilac* crest of the pelvic bone to the base of the lateral *malleolus*). A summary of the recorded values is presented in **Error! Reference source not found.**.

Table 1 Age and antropometric data related to the test participants

Parameter	Mean	Standard deviation
Age (years)	25.9	4.5
Height (m)	1.79	0.06
Mass (kg)	74.73	8.56
Average leg length (m)	0.99	0.03

3.3 Equipment

Two specially constructed walkways were constructed for the experimental programme: a rigid and flexible one.

3.3.1 Rigid walkway

The rigid walkway is 0.9m wide x 11.0m long and is constructed from three 50mm thick 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.

3.3.2 Flexible walkway

The flexible walkway composes of two sheets of 18mm plywood and two 44 x 100 mm timber joists spanning 9m; these are braced longitudinally every 550mm. The flexible deck was found to have a natural frequency of 2.33 Hz when empty; ideally close to the natural frequency of a walking pedestrian; i.e., close to 2Hz. Moreover, the bridge was supported 1m in from each end, providing an effective span of 7m for the walkway.

3.3.3 Data acquisition

For both walkways the same 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, F_z, 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. Walking trials on both rigid and flexible platforms are shown in Fig. 4.

(a)

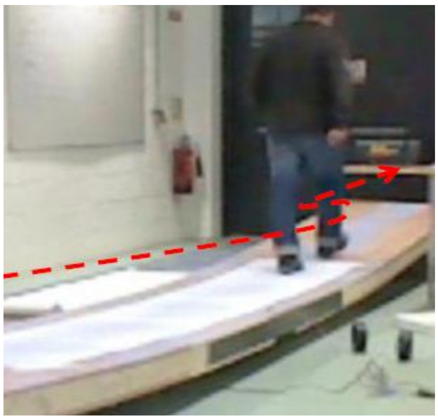
(b)

Fig. 4. Walking trial on (a) rigid walkway and (b) flexible platform

3.3.4 Experimental procedure

The participants were asked to wear their regular clothing and comfortable, flat-soled shoes for both walking trial programmes. Prior to the recorded traversing of the walkways, each participant completed a number of “dummy” runs to ensure they felt comfortable with the process. For these dummy trials and the actual walking trials, the test subjects were requested to walk in a straight line along the length of the walkway at a normal speed, while looking straight ahead – this was aided through using visual targets on the facing walls. Immediately prior to each trial the participant coated the soles of their shoes with blue chalk dust, which aided the recording of the footfall positions and thus measurement of the spatial gait parameters. This procedure has been successfully used by other authors (i.e., [28-30]). Each test subject completed a minimum of three recorded trials on each walkway.

4. Results and discussion

4.1 Vertical forces from single footfall

Fig. 5 presents the single footfall DLF values from both the rigid and flexible walking trials; while Fig. 6 demonstrates the differences in the force profiles between flexible and rigid walking trials. From Fig. 5 it is shown that the mean single footfall DLF value for the rigid trial is 0.277 (SD: 44.7%), which is substantially less than the mean value of 0.363 (SD: 28.0%) from the flexible walking trials. This represents an increase of 31% in the mean value for the flexible walking trial in comparison to the rigid. Conversely, Racic et al. [20] suggests that walking on a flexible surface will cause a reduction by approximately 10%; however they did not make it clear whether this was for single or double stance phase loading.

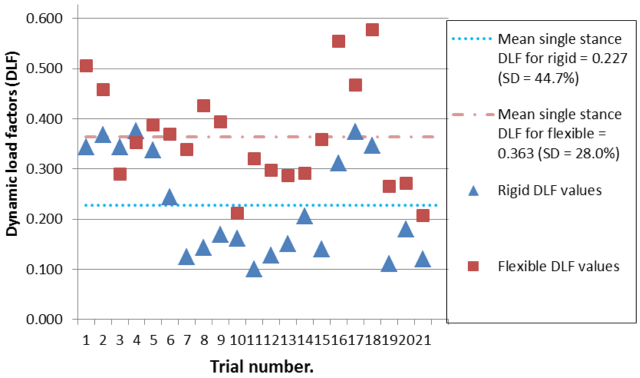

Fig. 5. Single footfall DLF results from rigid and flexible walkway trials

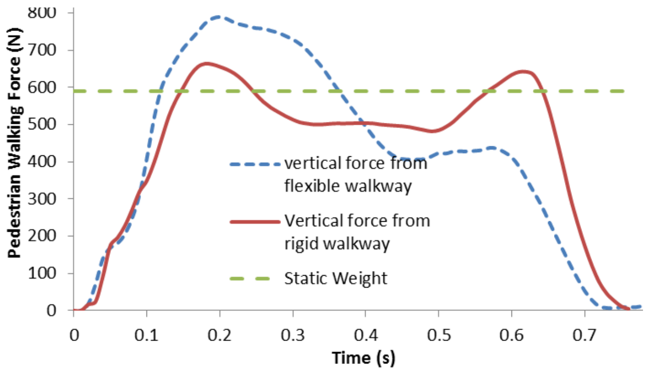

Fig. 6 Comparison of a typical continuous force trace from a flexible and rigid walking trial

Interestingly, throughout the trial programme there was an evident difference between force profiles for walking on a flexible walkway to that of a rigid, a typical example of this is Fig. 6. The rigid walkways force trace has the clearly defined two peaks and a trough (heel strike peak, mid-stance trough, and toe-off peak) profile. In comparison the traces from the flexible walking trials tend to show a relatively large heel strike peak, and a relatively small toe-off peak that is often equal in magnitude to or indistinguishable from the trough. Kirtley [13] suggests that the heel strike peak is a braking force and notes that an increase in velocity will cause an increase in the braking force. The mean pacing velocity in this trial for the rigid walking trial was 1.489 m/s; 11% greater than the flexible walking trial's velocity of 1.343m/s – which does suggest that it is not directly related to the pedestrian pacing velocity; but perhaps instead due to the impact velocity caused by the foot meeting the walkway. To elaborate and as demonstrated in Fig. 6, the flexible walkway was shown to vibrate excessively; therefore as the deck was moving up it came to meet the pedestrian's heel moving down. Moreover, at the stage, where the pedestrian is pushing off, the deck is moving downward; hence the impact force is reduced. To put this hypothesis another way, the pedestrian was walking in resonance with the flexible walkway: he/she is the inducer and receptor of the vibrations. A second theory for the flexible footfall trace profile in Fig. 6 could be related to the sagging of the walkway; i.e. walking on a slope. However, this theory was investigated by Damavandi et al. [31] who measured the vertical force of people walking on the flat, uphill, and downhill at a velocity of 1.43m/s (+/- 0.14m/s) for each case. For the three trial types they found no differences in the toe-off forces and only minimal differences with respect to heel strike forces.

4.2 Vertical forces from continuous walking

The force trace from continuous walking was generated from successive summations of individual footfall traces, separated by a time lag derived from the inverse of the pacing frequency from the respective trials. This assumes complete periodic loading, which may be slightly conservative. The DLF was computed from these simulations as the difference between the maximum vertical force divided by the static weight of the participant. Fig. 7 presents the continuous walking DLF values from both the rigid and flexible walking trials; while Fig. 8 demonstrates the differences in the continuous force profiles between flexible and rigid walking trials. From Fig. 7 it is shown that the mean continuous DLF value for the rigid trial is 0.544 (SD: 43.4%), which is greater than the mean value of 0.403 (SD: 29.0%) from the flexible walking trials. This represents a decrease of 35% in the mean value for the flexible walking trial in comparison to the rigid. This decrease is greater than, Racic et al. [20] suggestion of 10%; however, it is perhaps logical to suggest that this reduction will vary from walkway to walkway. Moreover, Fig. 8 and Fig. 10 suggest that the maximum forces for rigid and flexible platform walking occur at different stages. The maximum rigid walking force occurs at double stance phase, while the maximum force associated with flexible walking occurs at the heel strike phase. Interestingly, the mean DLF associated with the flexible walking trial is 0.4 which is equal to the value given by Eurocode 1 [25], Hivoss [23], and Setra [32]; however, as Fig. 7 and a SD of 29% demonstrates this value can vary considerably.

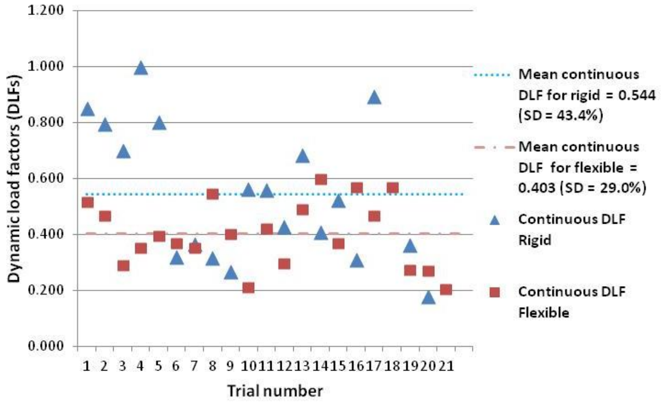

Fig. 7. Continuous DLF results from rigid and flexible walkway trials

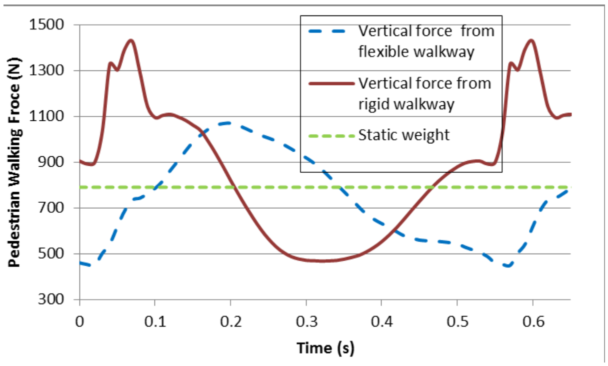

Fig. 8 Comparison of a typical continuous force traces from flexible and rigid walking trials

4.3 Variation between single and continuous DLFs

A comparison between the continuous and single stance DLFs is presented in Fig. 9. An intuitive aspect of Fig. 9 is how close in magnitude the single and continuous DLF mean values are for the flexible walking trials; as there is only an 11% difference. Moreover, for the majority of flexible walking trials, the difference between continuous and single stance DLF's was zero; a typical example is shown in **Error! Reference source not found.**0. This is in contrast to rigid walking where the continuous DLF is over twice that of the single stance value (Fig. 10). The reason for the negligible difference between double and single stance DLF's when walking on a flexible walkway can be linked to the large heel strike peak and small toe-off peak (as explained in section 4.1) that occurs as a result of the single stance phase. To elaborate, the heel strike peak is so large relative to the toe-off peak the resulting double stance maximum peak is only influenced by the heel strike peak.

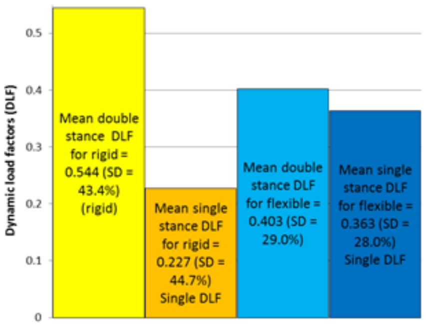

Fig. 9. Comparison between mean DLFs for rigid and flexible walking trials

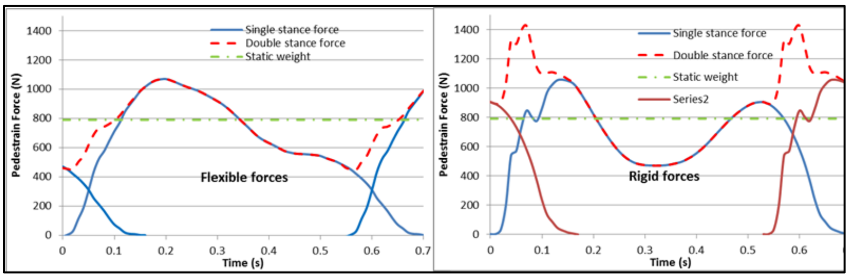

Fig. 10 Comparison between mean DLFs for rigid and flexible walking trials

4.4 Relationship between DLFs and pacing velocity

Pacing velocity was determined to be the parameter most closely related to both the single and continuous DLFs when walking on a rigid surface; Fig. 11 and Fig. 12. However, no apparent relationship exists between pacing velocity (or any gait parameter) and the DLF generated from walking on a flexible walkway; Fig. 11 and Fig. 12. The mean pacing velocity for the rigid walking trials was 1.45m/s (SD = 0.17m/s) with a value of 1.38m/s (SD = 0.12m/s) for the flexible walking trials. Focusing on Fig. 11 it is shown than an r^2 value of 0.02 was found for the flexible DLF, while the trendline for the rigid's DLF confirms well with [2,19], which is from a much larger data set. Moreover and from Fig. 12, the rigid continuous DLF reveals an r^2 of 0.62, which shows quite a strong relationship; which is in contrast to the r^2 of 0.02 for the flexible continuous DLF. This leads to the conclusion that there is greater uncertainty associated with simulating the vertical walking force generated on a flexible surface than for a rigid surface. This corresponds well with observations that human-structure interaction is subjective rather than objective and varies both inter- and intra-subject. This also advances the argument for any approach to attempting to model these forces must be stochastic rather than deterministic.

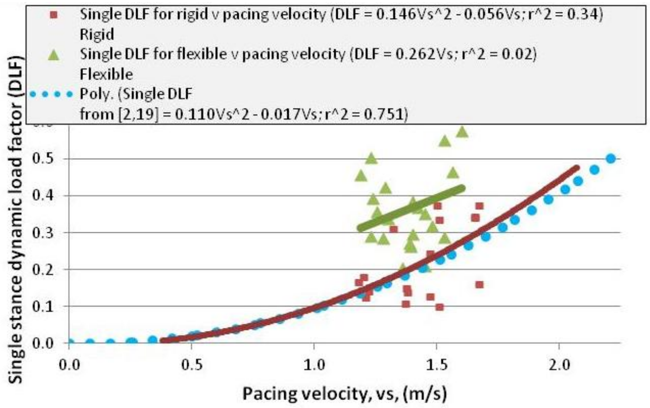

Fig. 11. Single stance DLF plotted against pacing velocity

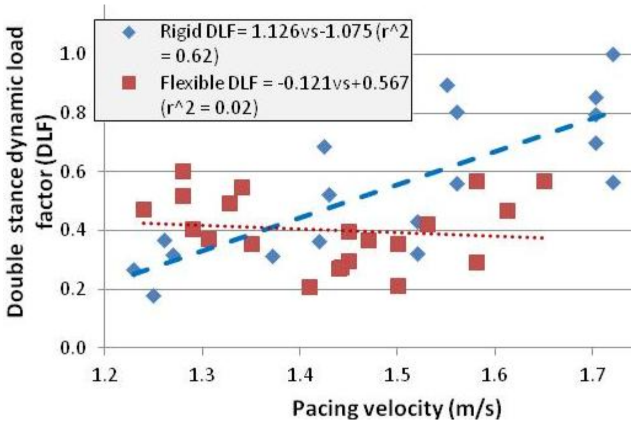

Fig. 12 Continuous DLF plotted against pacing velocity

5. Conclusion

Over 40 walking trials have been conducted on a sample of seven healthy adults. The aim of the work was to investigate the differences between walking on a flexible and rigid walkway in terms of vertical pedestrian loading and whether this loading was influenced by the nature of the walking (pacing frequency or velocity). The results reveal a mean single stance DLF of 0.277 (SD: 44.7%) for rigid walking and 0.363 (SD: 28.0%) for flexible walking. In terms of the continuous DLF, values of 0.544 (SD: 43.4%) and 0.403 (SD: 29.0%) were determined for rigid and flexible platforms respectively. Interestingly, these results reveal that the continuous DLF increases only marginally from the single stance value in terms of the flexible platform, but significantly in terms of the rigid surface. Moreover, the result of 0.403 (SD: 29.0%) for the mean continuous DLF compares well with the value of 0.4 presented in the guides, albeit a large scatter of values was recorded. Mean pacing velocities of 1.45m/s (SD = 0.17m/s) and 1.38m/s (0.12m/s), were determined for rigid and flexible walking respectively. In terms of rigid walking the DLF is shown to vary linearly with pacing velocity in terms of both the single stance and continuous loading. However, there was no apparent relationship between pacing velocity (or any other gait parameter) and the DLF for flexible walking.

6. References

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