THE INFLUENCE OF SELECTED GAIT PARAMETERS ON VERTICAL PEDESTRIAN LOADING

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Summary

Walking trials have been carried out on a rigid surface mounted with a force plate in order to determine the influence of selected gait parameters on vertical pedestrian loading. This paper presents the results of this study. The sample population comprised thirteen female and fourteen male healthy adults walking at normal pacing velocities. Relationships between gait parameters and between these parameters and the vertical forces exerted by the pedestrians on the walking surface are reported herein. 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: Pedestrian loading; walking trials; force plate; vertical load; gait parameters.

1. Introduction

The issue of pedestrian loading on footbridges and more specifically the subject of pedestrian-structure interaction is beginning to attract 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.

Several forcing functions are proposed in the literature to simulate this type of loading, 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 or gait must contribute to development of any robust load models.Current work is focussing on trying to predict the load behaviour from crowds of pedestrians. One approach being undertaken is developing stochastic load models based on statistically accurate information in relation to individual pedestrian behaviour within crowds [1]. In order to verify and calibrate these statistical models, accurate and reliable data on the actions and processes involved in human locomotion are required.

Gait refers to the typical walking behaviour of pedestrians and can be broadly defined by a number of parameters. There is currently a dearth of reliable information in relation to these gait parameters due to the fact that much of the work on gait analysis up to now has been carried out in the field of biomechanics.

Recent work carried out by the authors involved determination of several gait parameters for a population of healthy male and female test subjects through a series of walking trials. Ground reaction forces from the pedestrians were also recorded for each walking trial.

This paper presents the results of these tests and reports on the inter-relationships that exist between certain parameters and their influence on the vertical forces exerted by the pedestrians.

2. Gait Parameters

Although human locomotion is a very complex process, Davis et al. [2] describe walking or 'gait' as a cyclic activity for which certain discrete events have been defined as significant. In biomechanical terms, these parameters are classed as either spatial or temporal and a list of these parameters is contained in Table 1. In terms of pedestrian loading on structures, the gait parameters of relevance depend on whether vertical or lateral excitation is being considered. Step length, pacing frequency, and the resultant vertical ground reaction force are the parameters which influence vertical loading.

Table 1 Spatial and temporal gait parameters

Spatial Gait Parameters	Temporal Gait Parameters
Step Length	Pacing Frequency/Cadence
Step Width	Swing Phase
Foot Landing Position (Toe-in/Toe-out Angle)	Stance Phase/Support Phase
	Pacing Velocity

2.1 Step Length

Step length, l_s, refers to the distance from the heel strike of one foot to the heel strike of the other foot. There has been some confusion in the literature between step length and stride length, which is actually the distance between the heel strike of one foot and the next heel strike of the same foot. Stride length can simplistically be taken as approximately twice the step length, but this may hide the fact that there can be variability between the right and left step lengths respectively. Hence, to avoid confusion it may be best to avoid using the term ‘stride length’, and instead refer to right step length plus left step length as cycle length. Some authors claim that step length increases with age up to a point and then begins to diminish [3]. In a review of over one-hundred papers the authors [3] have previously shown that the mean reported value for step length to be 0.59 m for children and young adults, 0.67 m for mature adults, and 0.61 for persons over 60 years; with standard deviations of 8%, 11%, and 9% respectively.

2.2 Pacing Frequency

Pacing frequency, f_s, is the most relevant of the temporal gait parameters in terms of pedestrian loading. It is defined as the inverse of the time taken from the initial contact of the left foot with the ground to the initial contact of the right foot immediately thereafter and corresponds to the rate of application of vertical forces. In biomechanical terms, this parameter is often measured as cadence, which is the number of steps per minute rather than the number per second.

Reported values of normal pacing frequencies indicate that the average pacing rate is between 1.8 Hz and 2.2 Hz. Keogh et al. [1] reviewed 7 references and derived an average pacing frequency of 1.96 Hz, with a standard deviation of 0.21 Hz. The authors of this current paper have previously reported a decrease in pacing frequency with age based on a review of current literature [3]. The under 20 age group have an average of 2.02 Hz, while 20-60 year olds and the over 60’s display 1.92 Hz and 1.91 Hz respectively. Interestingly, results from Oberg et al. [4] indicate that there may be a gender consideration relating to pacing frequency, with women walking at an average of 2.1 Hz and men at an average of 1.98 Hz for normal walking velocity. However, Kirtley [5] hypothesises (citing data from Sutherland [6]) that this can be explained by variations in limb lengths.

2.3 Pacing Velocity

The pacing velocity, v_s, is defined as the distance travelled by a pedestrian in any direction over time. Intuitively, pacing velocity has a direct relationship with step length and pacing frequency. Kirtley [5] proposed that pacing velocity increases linearly with pacing frequency, and has a logarithmic relationship with step length. This means that pacing velocity can be increased at lower velocities by quickening the pacing frequency and/or increasing the step length, however at higher velocities it can only be increased by quickening the pacing frequency as there is a limit on the maximum step length possible [5]. Some normal velocity values reported during walking trials include 1.27 m/s, 1.50 m/s, and 1.46 m/s, with standard deviations of 9%, 10%, and 7% respectively; carried out, in order, by Dubost [7], Morris [8], and Bilney et al. [9].

2.4 Inter-relationship of Gait Parameters

Some researchers have attempted to make correlations between step length, pacing frequency and anthropometric data. Kerr and Bishop [10] for example reported a relationship between the height of the test subject, h, and the step length, l_s, as:

$$l_s = 0.45h \quad (1)$$

Grundmann and Schneider [11] meanwhile report tests carried out by Inman [12] and Andriacchi et al. [13], which both give similar results. Andriacchi et al. [13] recorded time-distance measurements and ground reaction forces in relation to pacing velocity for normal test subjects and patients with knee disabilities. These measurements yield a relationship between the mean values of step length, l_s, the body height, h, and the pacing frequency as:

$$l_s = 0.24hf_s \quad (2)$$

Kirtley [5] citing Sekiya and Nagasaki [14], meanwhile, asserts that most people seem to maintain a constant 'walk ratio' (defined as step length divided by pacing frequency) throughout adult life.

2.5 Ground Reaction Forces

Essentially, ground reaction forces (GRF's) measure the forces applied to a surface by a person walking across it. As such, ground reaction forces are the primary interest in studying loading applied by persons traversing a structure. Walking imparts forces in three orthogonal planes – forward/backward, lateral and vertical. In biomechanics literature, these three planes are labelled the saggital, medio-lateral and vertical respectively. Bachmann & Ammann [15] reported that vertical force is of greatest magnitude, followed by the saggital and then the medio-lateral forces. In terms of pedestrian loading, the saggital plane is not considered to be of consequence as the structure will almost certainly be rather stiff in the direction of walking.

The vertical force (Figure 1) generally has a profile of two peaks and a trough. The first peak occurs at heel strike, while the second occurs due to toe off (when the foot pushes off the ground); and the trough occurs at midstance, when both the toe and heel are on the ground at the same time [16]. The vertical force is believed to be influenced by a pedestrian's step length, a spatial parameter; pacing velocity and pacing frequency, two temporal parameters; and weight. Kirtley [5] explained that the shorter the time the foot is on the ground (stance time) the greater will be the force. Huang [16] stated that the vertical force was affected mostly by the pedestrians 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.

In terms of pedestrian loading, the load pattern caused by variations in the vertical GRFs from successive footfalls is of primary concern. The dynamic load factor has been defined as the ratio of maximum increase in GRF from the static weight divided by the static weight of the pedestrian. It has been proposed that this is proportional to the pacing frequency, f_s, and represented as:

$$r_n = 0.25f_s - 0.1 \quad (3)$$

for pacing frequencies in the range from 1.6 Hz to 2.4 Hz [18].

There appears to be contradictory theories in relation to the impact of velocity on vertical ground reaction forces. Martin and Marsh [17] argued that a change in step length has negligible effect on the vertical force, so long as the pacing velocity does not change. On the other hand, an increase in pacing velocity is reported to have little influence on the toe-off peak, but it does tend to increase the heel peak due to an increase in braking at heel contact [5].

This paper presents the findings from a series of walking trials aimed at establishing relationships between the above gait parameters, the anthropometric data of the participants and the resulting vertical ground reaction forces.

3. Experimental Programme

The experimental programme reported herein consists of walking trials involving thirteen female and fourteen male healthy adult participants. The participants conducted the walking trials in the laboratory on a specially constructed rigid walkway as described in the following section.

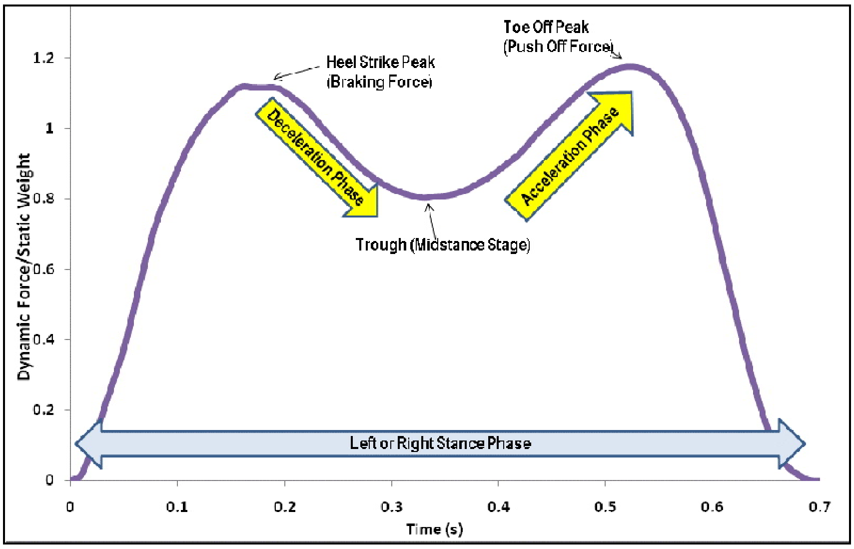

Fig. 1 Typical trace of the vertical GRF occurring from walking

3.1 Participants

Participants were recruited from staff and students at Athlone Institute of Technology, Ireland. All were aged between twenty and forty years. The ethnical composition of the participant sample was predominantly Caucasian with a small proportion being of African and Chinese 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. All participants gave written consent according to the ethical procedures approved by Athlone Institute of Technology and its Research Ethics Committee. Twenty-seven individuals participated in the trials, fourteen male and thirteen female.

3.2 Anthropometric Data

The following parameters were recorded for each test participant prior to the walking trials being carried out: age; height (with and without footwear); weight; right and left leg lengths (measured from the *superior palpable* of the *greater trochanter* to the base of the *lateral malleolus).* A summary of the recorded values is presented in Table 2.

Table 2 Age and anthropometric data for each gender group

	Male		Female	
Parameter	**Mean**	**S.D**	**Mean**	**S.D**
Age (Year)	27.7	5.2	25.0	2.8
Height (m) (with footwear)	1.78	0.06	1.62	0.05
Weight (kg)	82.04	13.50	62.17	14.19
Right leg length (m)	0.86	0.06	0.87	0.05
Left leg length (m)	0.80	0.05	0.80	0.05

3.3 Equipment

A rigid walkway was specially constructed to carry out the walking trials. The walkway is 0.9 m wide x 11.0 m long and is constructed from three 50 mm thick laminated fibreboard panels framed with timber battens and cross members at 600 mm centres, which were bolted together longitudinally and placed directly on the laboratory floor. A 500 x 500 mm 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 level with the top surface of the walkway. In the vertical direction, Fz, the force plate has a natural frequency of 150 Hz and a loading capacity of 1334 N and the force plate was calibrated prior to the walking trials through measurement of static forces. Three Monitran MTN1800 accelerometers, with a sensitivity of 1.020 V/g@80 Hz, were mounted to the underside of the walkway at approximately one-third span, mid-span, and two-third span respectively.

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. Grid paper measuring 3.5 m x 0.6 m and containing a 20 mm x 20 mm 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 from the trials. A schematic layout of the test set-up is shown in Fig. 2.

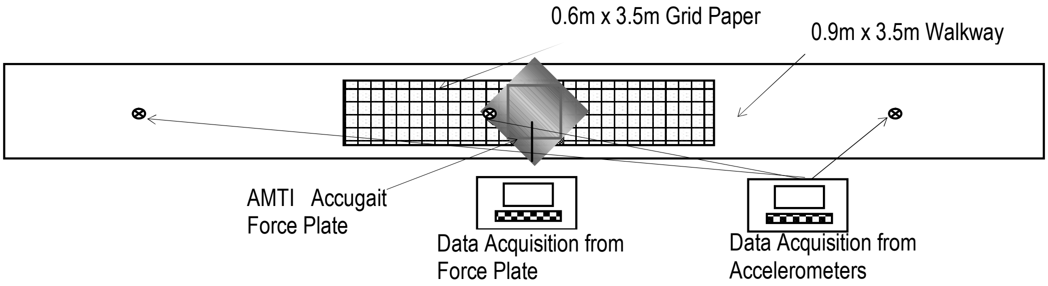

Fig. 2 Schematic representation of walkway and test set-up (not to scale)

3.4 Experimental Procedure

The participants were asked to wear their regular clothing and comfortable, flat-soled shoes for the walking trials. Prior to the recorded traversing of the walkway, 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 [19], [20],and [21]. Each test subject completed a minimum of four recorded trials. Immediately after each trial was completed, the stationary or static step width and foot landing position were also recorded, although they are not relevant to this paper. Fig. 3 shows a recorded trial in progress.

The spatial and temporal gait parameters recorded for each trial were step length, stride length, step width, foot landing position, and pacing frequency. Pacing velocity was determined from the product of pacing frequency and step length. Also, the ground reaction forces (GRF's) in three orthogonal directions were measured for the instance of a footfall striking the force plate. The vertical GRF trace also enabled the determination of the single foot stance support phase.

4. Results & Discussion

4.1 Step Length

Figure 4 shows the comparison between the average step lengths measured in the walking trials carried out in this study with those provided by the same authors [3] of this paper when reviewing published data from over 20 other sources. The mean step length, l_s, recorded for the entire group was 0.75 m, with 0.71 m recorded for females, and 0.78 m measured for males. The standard deviations of 9%, 9%, and 6% respectively. These values, as shown in Figure 4, compare well with previously published data, however the overall mean and the mean of the male participants appear to be slightly higher than found by others [3]. The reasons for this are unclear, but may relate to the overall height of the male participants. Interestingly, while many subjects displayed relatively equal left and right step lengths, for some there was a difference of up to 7.5% between the respective values. This is of interest to engineers in determining the uniformity of load application from people walking. Step length ratio is defined as the shortest step length divided by the longest step length of each participant. The mean value for the entire group was 0.97, with a standard deviation of 3 %. Current load models for pedestrian loading assume a step length of 0.90m, which is considerably larger than that measured here and reported previously.

Fig. 3 Walking trial in progress

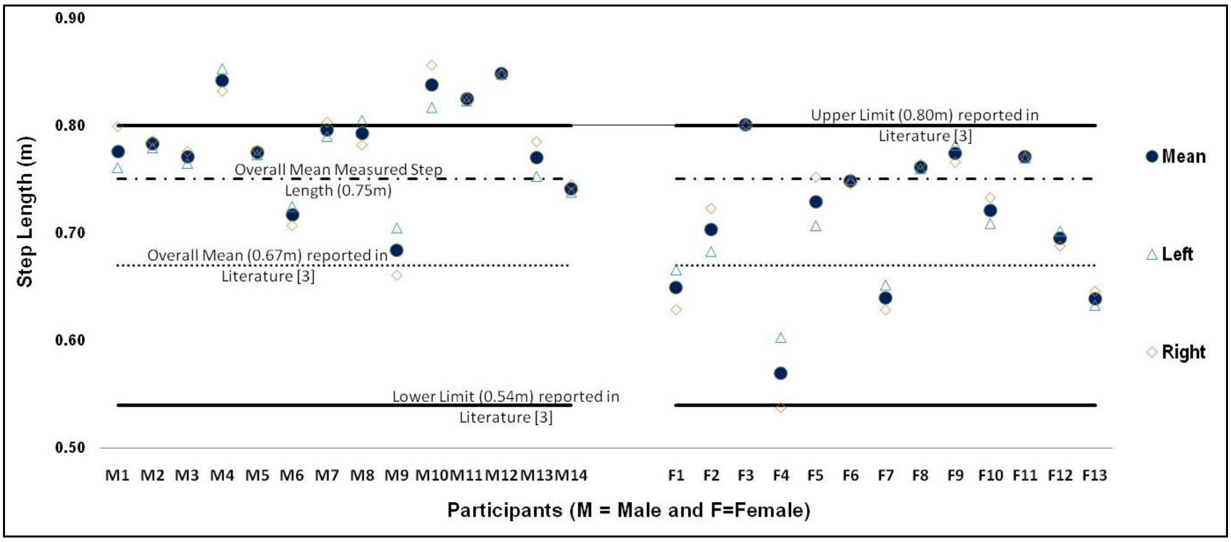

Fig. 4 Measured and previously reported step lengths

4.2 Pacing Frequency

Figure 5 shows the comparison between the pacing frequencies in the walking trials carried out in this review with those provided by the same authors [3] of this paper when analysing over 20 reported trials. The average pacing frequency, f_s, was 1.88 Hz for the entire group, 1.95 Hz for females, and 1.82 Hz for males; with standard deviations of 7%, 7%, and 5% respectively. The overall average pacing frequency, 1.92 Hz, reported in [3] is close to both the female and overall averages here, but 5.5% larger than the male pacing frequency. The relative pacing frequency (pacing frequency over height) showed large variations between females and males, with values of 0.91 Hzm^{-1} for the entire group, 0.98 Hzm^{-1} for the females, and 0.50 Hzm^{-1} for the males.

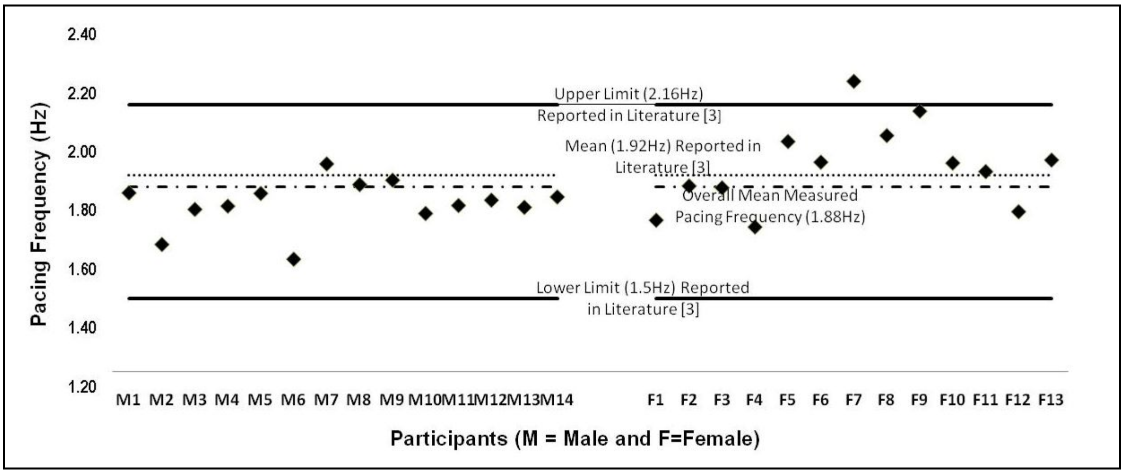

Fig. 5 Measured and previously reported pacing frequencies

4.3 Pacing Velocity

The average pacing velocities of the participants and the overall normal distribution of pacing velocities for the group are presented in Figure 6. The pacing velocities ranged from 1.00 m/s to 1.65 m/s with an overall mean of 1.41 m/s, with mean female and male participant pacing velocities recorded as 1.38 m/s and 1.43 m/s respectively. The standard deviations for the overall, female and male groups were 11%, 13%, and 8% respectively. The relative pacing velocity, defined as the height divided by velocity [5], was 0.83 $ms^{-1}m^{-1}$ for the entire group, with variations between the relative values of the male (0.81 $ms^{-1}m^{-1}$) and the female (0.85 $ms^{-1}m^{-1}$) participants. Figure 6(b) shows that over 80% of participants had mean pacing velocities between 1.3 m/s and 1.7 m/s.

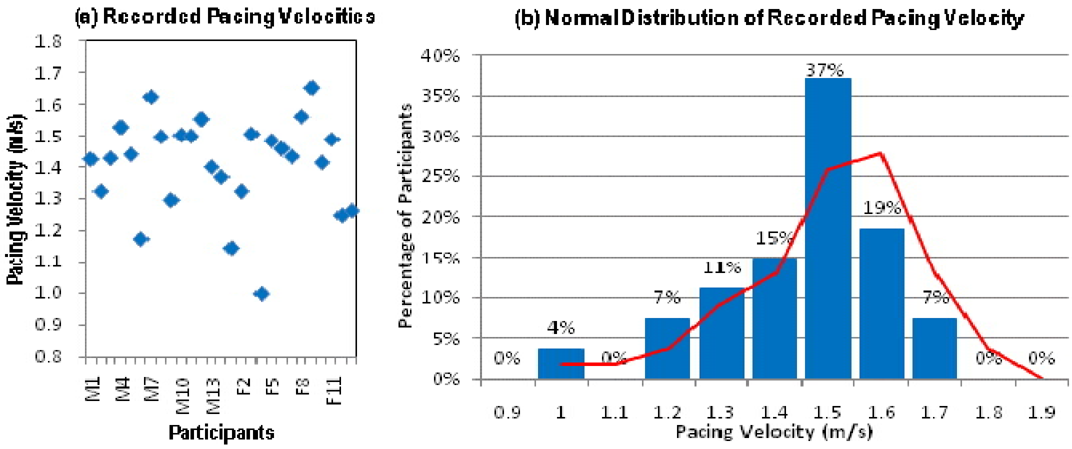

Fig. 6 Range and Distribution of Recorded Pacing Frequencies for 'Normal' Walking

4.4 Inter-relationship of Gait Parameters

Kerr & Bishop [10] report a linear relationship between step length and participant height (Equation 1), with a coefficient of 0.45. Analysis of these results yields a similar relationship with a coefficient of 0.44 (Equation 4), however, there was considerable scatter in the measured values. This relationship was identical for both male and female test subjects.

$$l_s = 0.44h \quad (4)$$

Andriacchi et al. [13] meanwhile, proposes that the step length is proportional to a product of both the participant height and the pacing frequency, f_s (Equation 2). The results recorded here and presented in Figure 7 show quite a good comparison with the relationship from equation 2, this time with a coefficient of 0.23 rather than 0.24.

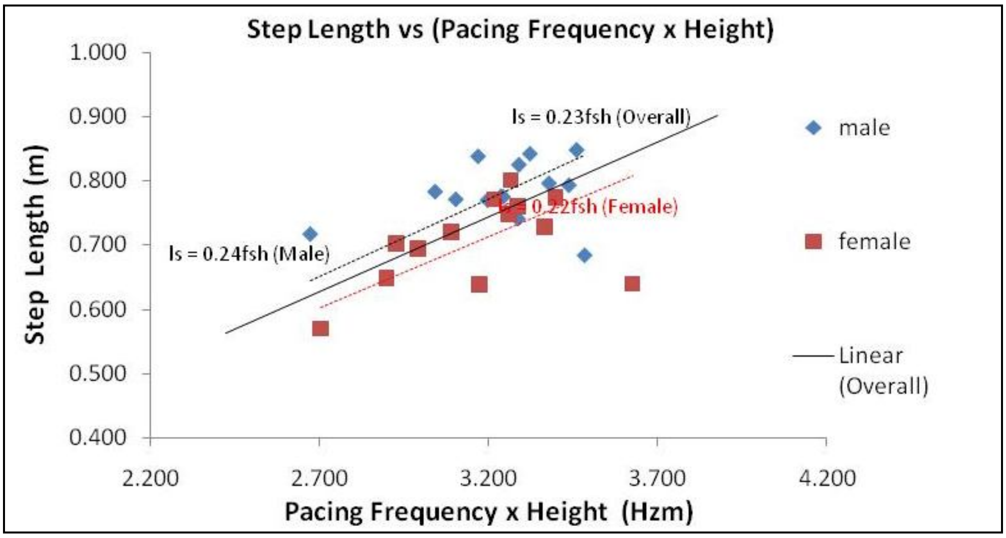

Fig. 7 Relationship between step length, pacing frequency and height

Other notable relationships were observed in this study. Single stance phase is seen to increase with pacing frequency, indicating a decrease in the swing phase of gait. Further, the theory from Kirtley [5], whilst citing data from Sutherland [6], that pacing frequency, f_s, reduces with increased leg length, was also noticed.

In summary, there exists a relationship between step length, height, pacing velocity and pacing frequency. As pacing velocity is the product of step length and pacing frequency, this relationship can be expressed as:

$$v_s = 0.23hf_s^2 \quad (5)$$

Inverting this may yield a useful tool for estimating pacing frequency based on participant height and pacing velocity, which is very simple to measure:

$$f_s = \sqrt{\frac{v_s}{0.23h}} \quad (6)$$

4.5 Ground Reaction Forces

Typical GRF traces recorded from each of the participants are represented in Figure 1. In terms of pedestrian loading, the key characteristic of this curve is the maximum vertical force applied to the walking surface. The increase in vertical force over the static weight of the person is termed the vertical dynamic load factor.

4.5.1 Vertical Dynamic Load Factor

As described in Section 2.5, it has been proposed that the vertical dynamic load factor, r_n, varies linearly with pacing frequency in the range from 1.6 Hz to 2.4 Hz. Figure 8(a) shows the variation in vertical dynamic load factor related to different measured pacing frequencies. A linear regression analysis yields a relationship as follows:

$$r_n = 0.25f_s - 0.3 \quad (7)$$

This is similar in form to that previously proposed in the literature, however, the magnitude is considerably lower than expected. For example, at a pacing frequency of 1.9Hz, this relationship estimates a dynamic load factor of 0.175, as opposed to 0.375 which would have been obtained previously. This may suggest that current load models employ an overly conservative vertical dynamic load factor. It is acknowledged that the results here are from a relatively small sample population of 27 people and also that there is considerable scatter in the measured results. Nonetheless they do constitute the mean values from over 100 walking trials.

Figure 8(b) presents the change in vertical dynamic load factor as a function of change in pacing velocity. It is noted that there appears to be less scatter in these results and there is improved correlation when subjected to linear regression analysis. The relationship between vertical dynamic load factor, r_n and pacing velocity, v_s as determined from this study can be represented as:

$$r_n = 0.411v_s - 0.387 \quad (8)$$

within a velocity range of 1.00 m/s ≤ v_s ≤ 1.65 m/s. It is noted that as the velocity reduces below the lower limit of this range, the vertical dynamic load factor will tend towards zero, with very slow velocities inducing negligible dynamic force. This compares with a linear relationship in the higher velocity range of 1.5m/s ≤ v_s ≤ 3.5m/s reported by Keller et al [22] of:

$$r_n = 0.614v_s - 0.792 \quad (9)$$

The higher velocity range may account for some of the difference between the two proposed relationships and this may merit further investigation. Due to the improved correlation between the values, it is suggested here that walking velocity may therefore be the parameter that primarily influences vertical ground reaction forces rather than pacing frequency specifically.

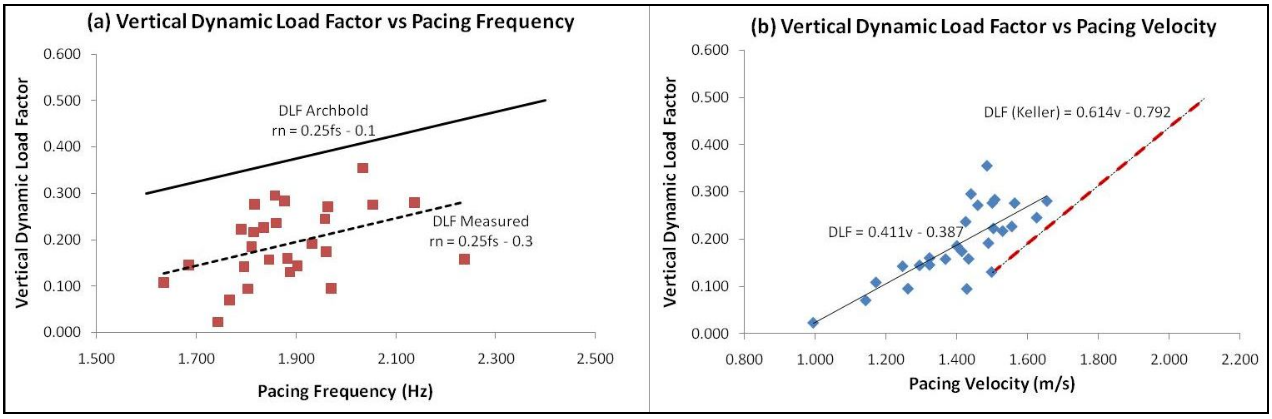

Fig. 8 Relationship between vertical dynamic load component and (a) pacing frequency and (b) pacing velocity

5. Conclusions

Over 100 walking trials have been conducted on a sample healthy adult population of thirteen males and fourteen females. The aim of the work was to investigate inter-relationships between gait parameters and their influence on vertical forces imparted by pedestrians when walking at normal velocities. The results reveal a mean pacing frequency of 1.88 Hz, with a mean step length of 0.75 m and a mean pacing velocity of 1.41 m/s. These results compare well with previously published data. There exists a relationship between pacing frequency, pacing velocity, step length and height, which may be used to estimate pacing frequencies from measured pacing velocities. The vertical dynamic load factor is shown to vary linearly with pacing velocity. This offers better correlation than comparison between vertical dynamic load factor and pacing frequency, as has been suggested in the literature. Moreover, the vertical dynamic load factor derived from these trials is considerably lower than that suggested by other authors and used in current load models. This is worthy of further investigation.

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