The Influence of Spatial Parameters on Pedestrian Lateral Loading

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ABSTRACT: Dynamic loading from pedestrians walking on flexible structures such as footbridges is the subject of much research at present. The interest is stimulated by several notable instances of uncomfortable perceptible vibrations on prominent footbridges in the recent past. Some of this research has revealed that the phenomenon is not entirely due to modern construction techniques with examples of pedestrian-induced vibrations from as early as the 1600s being reported. Such pedestrian-induced vibrations can occur in vertical and lateral directions with the latter being the focus of this paper. Recently published international design guidelines; e.g., Eurocode 5 (NSAI, 2005), ISO 10137 (2007), Setra (2006), FIB (2005), and Hivoss (2008) direct the designer to estimate the response of the footbridge due to crossing pedestrians, and then to measure this against prescribed limits set out either directly or indirectly by the guidelines. Some of these guidelines provide force functions to simulate pedestrian loading, while others are less prescriptive. The load functions that are provided tend to be deterministic in nature and have been shown to be deficient in accurately modelling actual pedestrian loading. Consequently, research is currently being conducted into the exact nature of pedestrian loading and the parameters which influence it. Previous research by the authors has examined the impact of walking velocity and pacing frequency on both vertical and lateral loading. This paper presents the results of recent walking trials, conducted along an 11m walkway to investigate the influence of spatial parameters on pedestrian lateral loading.

KEY WORDS: Pedestrian loading, spatial parameters, lateral, force plate, walking trials

1 INTRODUCTION

Vibrations induced on footbridges due to human loading have increasingly become the focus of considerable research in the structural engineering domain in the past decade. The vibrations induced occur due to two main reasons. Firstly, modern footbridges are elegant and slender, hence quite flexible and lightweight. And, secondly, information and data on the direct nature of the producers of such vibrations – the pedestrians – is somewhat lacking; particularly in the horizontal direction. Currently, designers can monitor actual vibrations post-construction and perform remedial action if required. This approach drove the final cost of The London Millennium Bridge up by 30% [1] (construction cost was €48 million, quoted as a 2010 equivalent by [2]). More desirably, at design stage, there are two approaches to avoiding excessive bridge vibrations; namely the frequency avoidance approach and the vibration limit approach. The former of these approaches is rather restrictive and conservative [3-5]. For these reasons the later approach is the one most often favoured by the design codes; however, it suffers as there is a dearth of knowledge on the nature of pedestrian loading and interaction between pedestrian and moving bridge. Attempts have been made to address this through direct measurement of the forces applied from individual footfall force traces in laboratories, employing techniques and equipment traditionally belonging to the biomechanics domain. These individual footfall force traces are commonly referred to as ground reaction forces (GRFs).

1.1 *Ground Reaction Forces*

Walking imparts forces, GRFs, in three orthogonal planes; namely, vertical, medial-lateral and longitudinal in the mid-sagittal plane. Such forces are generally measured using force plates or sensor mats [6]. Instrumented treadmills have also been used for this purpose, however the loads and walking parameters observed on treadmill devices cannot be used to describe normal walking; as the participant will be forced to walk at a ‘forced’ speed [7, 8]. Bachmann & Ammann [9] report that the vertical force is of greatest magnitude, followed by the longitudinal and then the medial-lateral (M-L) forces (Figure 1).

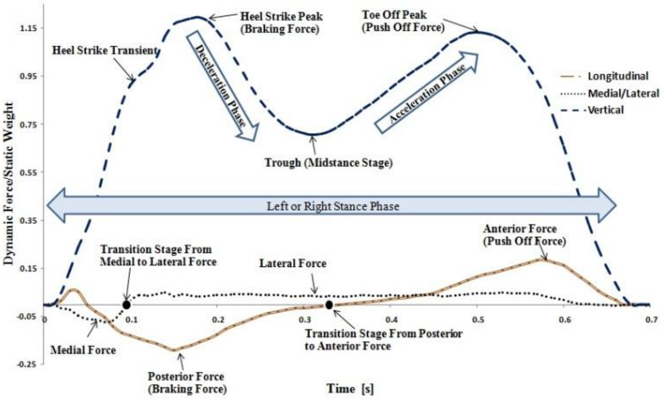

Figure 1 Ground reaction forces traces in three orthogonal planes

In terms of pedestrian loading on footbridges, the longitudinal forces are not considered to be of consequence as the structure will almost certainly be rather stiff in the principal direction of walking. The M-L force pattern is of concern when analyzing relatively flexible structures, even though it is of smaller magnitude than the loading applied in either of the other planes. Moreover there appears to be a dearth of reliable published data on the magnitude and nature of this particular loading regime. Zivanovic et al. [10] carried out a comprehensive review of existing data on pedestrian loading and report only two references ([9, 11]), which provide values for the magnitude of lateral loading in terms of the individual weight of the pedestrian. Further, these two reports vary considerably in their estimation of these values, with the dynamic load factor (the maximum lateral load expressed as a percentage of the static weight) ranging from 3.9% to 10%. Other authors offer values of approximately 4 - 5% as the ratio of peak medio-lateral force to static weight ([12]; [13] cited in [14]). Kirtley et al. [14] also cite [15] who claim that the magnitude of the M-L force increases with step width. A sequential combination of the individual footfall traces will produce the relevant continuous lateral load pattern exerted by humans walking. The exact nature of this continuous lateral load function will be influenced by both gait parameters and anthropometric data for the pedestrians involved. The primary anthropometric data of concern is the static weight of the person, while the gait parameters which have been asserted to influence the lateral load function are described below

1.2 Foot Landing Position

Foot landing position (FLP) is perhaps more commonly referred to as angle of gait, although it has also been termed foot placement angle (FPA) (Kernozek & Ricard, [16]) or angular deviation of the foot ([17] cited by [16]). The term generally refers to the angle made between the centreline of the foot and the forward direction of walking, but exact definitions of the foot reference line can vary between authors [18]. Simpson and Jiang [19] defined this reference line as “a line drawn from the midpoint of the posterior aspect of the calcaneus to the head of the second metatarsal”, a definition which will be used here. The same authors also reported tests, which revealed that FLP influenced the force applied by the pedestrian. They categorised their test participants into categories of "toe-in", "neutral" and "toe-out" depending on their FLP during straight line walking and they claim that toe-out participants exerted significantly greater lateral forces than those in the toe-in category. Values for FLP are reported in degrees, with positive representing toe-out and negative representing toe-in. Reported values for FLP range between $+14.3^0$ (toe-out) and -3.8^0 (toe-in) [19]. This parameter presents the most variability of all of the spatial gait parameters in healthy test subjects. Indeed, [20] citing [21, 22] suggests FLP can be influenced by factors such as walking speed, walking substrate, friction on walkway, hip motion, tibial and malleolar torsion and, adduction or abduction of the foot. Menz et al. [23], as example, report mean FLPs for two trials each on the left and right foot respectively as 6.73^0, 7.32^0, 5.01^0 and 5.02^0 with accompanying standard deviations of 4.96^0, 5.36^0, 5.77^0 and 5.92^0. Nonetheless, Kirtley [14] suggests a neutral foot landing position of $+15^0$, i.e.; slightly abducted or “toe-out” when measured from the plane of walking, while [20] measured a mean value of approximately 9^0. Chung et al. [24] report a mean neutral value of 13.4^0 and claim that toe-out participants exerted significantly greater M-L forces than either toe-in or neutral participants in walking trials.

1.3 Step Width

Step width, w_s, is defined as the distance between the centre lines of the two feet, perpendicular to the plane of walking. Reported values of step width have proven to be quite variable, with standard deviations up to 30%. Further, there is less reported data on this particular spatial parameter than others such as step length. Archbold & Mullarney [25] report a review of current literature, citing references which yield values between 0.09m and 0.19m for adults, with no apparent link between subject height and step width. Interestingly, values reported by [26, 27] that Korean adults exhibit greater step widths than others reported. Donelen et al. [28] and Bauby & Kuo [29] both linked step width to step length reporting that the step width was approximately equal to 12% and 13% respectively of the step length. However, this relationship has not been found by others. Kirtley et al. [14] reported that step width can vary with age and so recommended normalizing the value by dividing it by the pelvic width. They also stated that step width increases with disequilibrium (lack of balance). As previously stated, [15] have contended that the magnitude of the lateral load is proportional to step width.

1.4 Pacing Frequency

Pacing frequency, f_s, is the most relevant of the temporal gait parameters in terms of pedestrian loading, particularly where resonant effects on structures are to be considered. 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 1.8Hz and 2.2Hz. Keogh et al. [30] reviewed 7 references and derived an average pacing frequency of 1.96Hz, with a standard deviation of 0.21Hz. Archbold & Mullarney [25] present the results based on a survey of a further 20 sources of information and report a mean value of 1.92Hz.

2 LATERAL LOAD SIMULATION

As previously mentioned, there is relatively little published information on direct simulation of lateral loads from walking humans. A number of approaches have been employed however, the most common being the Single Harmonic Sine Function approach.

2.1 Single Harmonic Sine Function (SHSF)

The majority of guidelines and codes define the M-L load pattern as a sinusoidal varying function with a single harmonic, which is a function of the pacing frequency. According to one guideline [31], for instance, there is no hint in the literature that onerous vibration of footbridges due to the second harmonic of pedestrian forces in the lateral direction have occurred. The SHSF approach assumes that the function is perfectly periodic and that the load contribution from alternate footfalls are equal. It also assumes that the use of a single harmonic of the frequency of load application is sufficient to capture the nature and magnitude of the load. It is convenient to note some of the characteristics of such a function at this point. Firstly, the fundamental frequency of application of lateral walking loads is half the pacing frequency as it is related to successive contact of either the left or right foot with the walking surface. Secondly, the magnitude of the force is assumed to be directly related to the static weight of the pedestrian. The magnitude is thus expressed as a proportion of this static weight through use of a dynamic load factor (DLF). The function can thus be represented as follows:

$$F_{(t)} = \mathrm{L_f.G.sin(\pi.f_s.t)} \qquad (1)$$

Where F(t) is the continuous lateral load function, $\mathrm{L_f}$ is the dynamic load factor associated with the function, G is the static weight of the pedestrian, fs is the pacing frequency and t is time. The magnitude of $\mathrm{L_f}$ has been reported as ranging from 0.03 [32] to 0.1 [11]. Archbold [33] asserted that the value of $\mathrm{L_f}$ may also be influenced by individual temporal & spatial parameters such as FLP and not just the static weight of the person. This was used to explain the significant differences in lateral response caused on a lightweight, flexible footbridge by two people of similar weight and height, walking at the same pacing frequency. Erlicher et al. [34] meanwhile demonstrated an increase in the recorded values for M-L force as the pacing velocity increased. The dynamic load factor appears to have increased from approximately 4% while walking at 3.75km/hr up to approximately 6% while walking at 6.0km/hr. Ingolfsson et al. [35] calculated a rms value of the M-L load and equated this to 4.1% of the static weight. While Archbold & Mullarney have shown that higher order harmonics may be significant in term of the overall load function, only the fundamental harmonic will be considered here for simplification.

3 EXPERIMENTAL PROGRAMME

The experimental programme reported herein consists of walking trials involving 14 female and 25 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.

3.1 Participants

Participants were recruited from staff and students at AIT, Ireland. All were aged between 20 and 55 years. The ethnic 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 AIT and its Research Ethics Committee.

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. A summary of the recorded values is presented in Table 1.

Table 1 Age and anthropometric data for each gender group

	Male		Female	
Parameter	Mean	SD	Mean	SD
Age (Year)	32.1	18.2	27.0	3.5
Height (m)(with footwear)	1.81	0.06	1.65	0.06
Weight (kg)	81.31	11.68	62.25	8.61

3.3 Equipment

A rigid walkway was specially constructed to carry out the walking trials. The 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. 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 level with the top surface of the walkway. In the vertical direction, Fz, the force plate has a natural frequency of 150Hz and a loading capacity of 1334N 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@80Hz, 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 3.5m 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 from the trials. A schematic layout of the test set-up is shown in Figure 2.

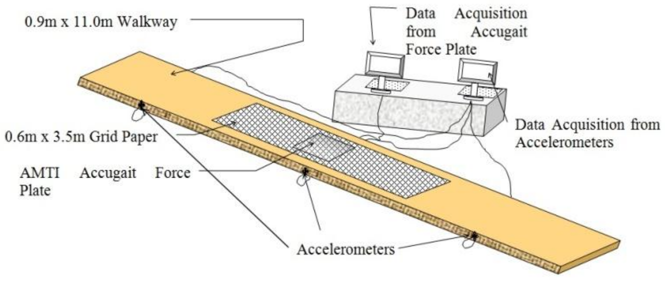

Figure 2 Schematic representation of walkway and set up

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 their normal speed and gait, 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 [20], [36],and [37]. In addition [20] citing [21, 38-41] and by conclusion of their own experimental work suggests the footprint method of assessing gait parameters easy, reliable, valid, inexpensive and clinically feasible. Each test subject completed a minimum of two recorded trials at their normal speed and gait. A quarter of the participants then carried out additional trials; i.e., they walked with an exaggerated toe-out, toe-in, and/or natural (close to zero degrees) foot landing position. The type of foot landing position the participants used depended on their normal style, e.g., if the participant had a relatively straight foot landing position he/she then carried out a minimum of two toe-out and toe-in foot landing position trial sets. The spatial and temporal gait parameters recorded for each trial were step length, step width, FLP, and pacing frequency. Step length is measured as the distance from the heel strike of one foot to the next heel strike of the opposite foot and is measured in the direction of walking. Step width is measured as the distance between the centrelines of consecutive heel strikes and is measured normal to the direction of walking as shown in Figure 3. This figure also shows the measurement of the FLP, which is defined as the angle made by a line drawn from the centre of the heel, through the head of the second metatarsal and a line drawn parallel to the direction of walking.

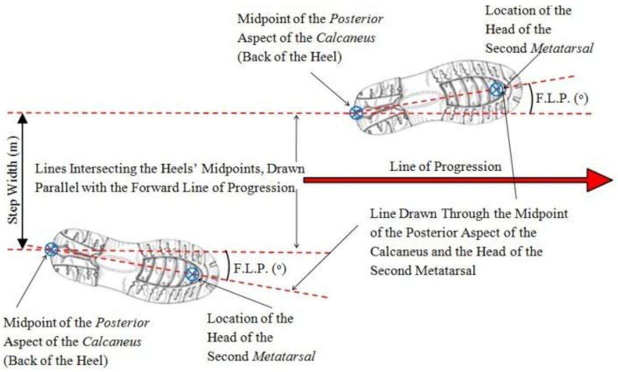

Figure 3 Measurement of spatial parameters.

The spatial and temporal gait parameters recorded for each trial were step 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 (GRFs) in all three orthogonal directions were measured for the instance of a footfall striking the force plate. These GRF traces also enabled the determination of the single foot stance support phase.

4 RESULTS & DISCUSSION

4.1 Temporal & spatial parameters

Table 2 presents a summary of the mean and standard deviations (SD) results for both the temporal & spatial gait parameters recorded during the normal walking trials. Also recorded in Table 2 are the Mean and SD M-L DLF results. The overall mean pacing frequency for the trials was 1.90 Hz; males had a mean of 1.85 Hz and females 2.00 Hz. The females meanwhile had a shorter step length than their male counterparts; 0.72 m versus 0.78 m respectively. Interestingly the pacing velocity for both genders sets were the same, 1.46 m/s; these three sets of results are in close agreement with results published previously by the authors [6] in a different trial set and by [42]. Moreover, the hypothesis suggested by [14] (citing data from [43]) that females will have on average a higher pacing frequency than males due to their shorter on average limb length. Step width for the entire group was 0.07m; 0.08m for males and 0.07m for females. It must be remarked however that the SDs were quite high, for instance; the overall group value was 57 %. Foot landing position, although normally distributed overall (Figure 5), shows a large difference between genders, i.e; females had an average of 3.16^0 versus 6.92^0 for males. Again the SDs recorded are quite high. Interestingly, from these results, most people in the test population did not walk with a toe-in FLP.

Table 2 Temporal & spatial gait parameters recorded

		Medial-Lateral DLF	Step length (m)	Step width (m)	Foot landing position (^{0})	Pacing frequency (Hz)	Pacing velocity (m/s)
Male	Mean	0.085	0.78	0.08	6.92	1.85	1.46
	SD	0.026	0.06	0.03	4.46	1.17	0.14
Female	Mean	0.059	0.72	0.07	3.16	2.00	1.46
	SD	0.025	0.07	0.04	5.49	0.20	0.20
Overall	Mean	0.076	0.76	0.07	5.45	1.90	1.46
	SD	0.028	0.07	0.04	5.22	0.19	0.16

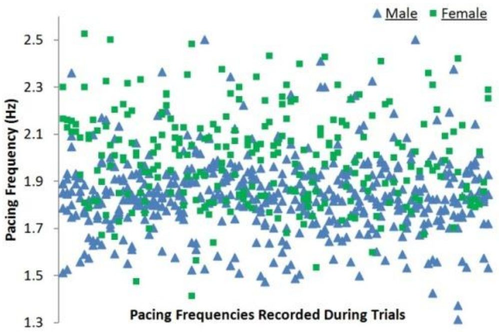

Figure 4 Male and female pacing frequencies recorded during trials

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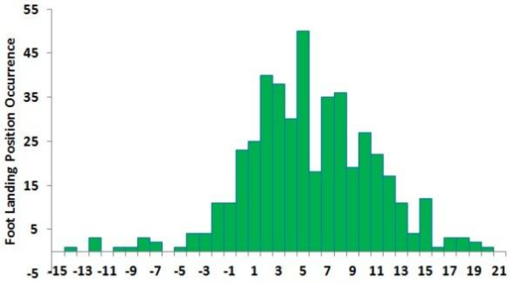

Figure 5 Distribution graph for foot landing positions recorded during trials

4.1 Gait & anthropometric relationships

As noted earlier some authors [28, 29] have suggested that step width is approximately 12 to 13 % of step length. In the case of these trials, however, the approximation is 10% with a rather low co-relationship.

4.1 Medio-lateral load & gait relationship

The M-L DLF or L_f was obtained by dividing the maximum M-L dynamic force by the subject's static weight for each trial run. The maximum dynamic force is the maximum force form a continuous walking trace, i.e, once the left and right foot overlap have been summed; Figure 6. This approach assumes the force form each footstep is the same. The overall average M-L DLF is shown in Table 2 to be 0.073, which is close to a previous value, 0.066, provided by the authors [6].

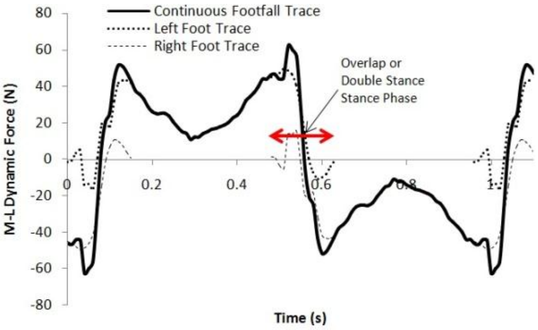

Figure 6 Continuous Footfall Trace

Potential relationships between gait parameters, anthropometric data, and the DLF were explored. In terms of straight and toe-out FLPs the M-L DLF, L_F, appears proportional to step length (Figure 7), while for toe-in FLP L_f appears to be proportional to step width (Figure 8). Analysis of the distribution of FLP's (Figure 5) reveals that the majority of people will walk with a FLP of between -2^0 and $+11^0$, as the female and male means are $3^0 \pm 5^0$ and $7^0 \pm 4^0$; respectively. In the range of common FLP's therefore the magnitude of the overall peak lateral force appears to be related to the step length as opposed to the step width, as would have been expected. This relationship is shown in Figure 9.

5 CONCLUSIONS

This paper reports on data form over 140 walking trials by a healthy adult test population involving 25 males and 14 females. Trials involved walking at a 'self selected' gait style and speed, and then walking with exaggerated FLPs (toe-in, toe-out, and straight) along an 11 m fixed walkway.

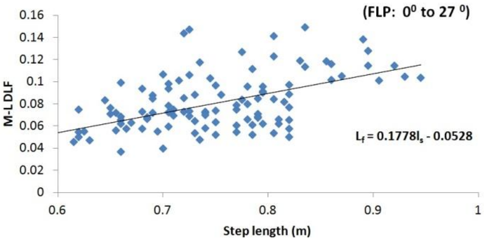

Figure 7 Step length, M-L DLF, and FLP relationship

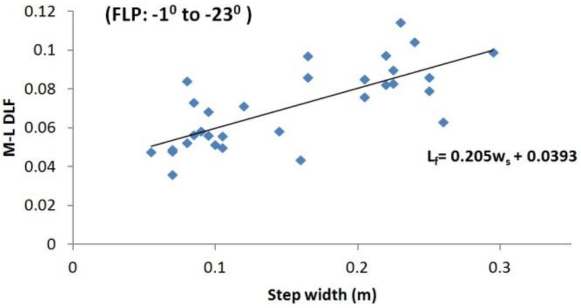

Figure 8 Step width, M-L DLF, and FLP relationship

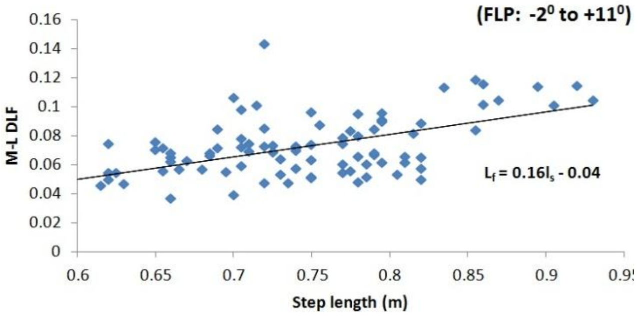

Figure 9 Step length and M-L DLF relationship for the 'average' range of FLPs

The mean FLP, step width, step length, pacing frequency, and pacing velocity for normal or 'self selected' walking was 5.45^0, 0.07m, 0.76m, 1.9Hz, and 1.46m/s; respectively. Mean values for the M-L dynamic load were 7.6%, 8.9%, and 8.5% of the static weight of the subject for the overall, female, and male groups; respectively. Various gait parameters and anthropometrics data relationships were explored and proved consistent with previous findings such as [44].

A relationship exists between step width an L_F for toe-in subjects, while for toe-out and neutral subjects, L_F, was related to step length. Given the vast majority of all recorded and published FLP's are in the normal to toe-out range, a relationship between step length and L_F has been established. This relationship may provide the footbridge designer with an easily quantifiable way in which to determine the peak value of the M-L dynamic walking load. Moreover, this relationship between step length and medio-lateral force is novel and has not been reported previously in published research. For this reason it may be worth investigating this parameter's relationship with the M-L DLF more closely.