Frequency and velocity of people walking

Synopsis

This paper investigates the stepping frequency and velocity of people walking. It considers 800 measurements on two footbridges and two shopping floors. During the measurements, the participants were not aware that they were being observed and walked naturally. The measurements of walking frequency, velocity and step-length were processed using statistical methods and the stepping frequency and velocity of the walking determined. It is found that (a) on shopping floors the people walk with an average frequency of 2.0Hz and a velocity of 1.4m/s, but on the footbridges they walk with an average frequency of 1.8Hz and a velocity of 1.3m/s; (b) the step-length on the shopping floors and the footbridges are almost the same with average values of 0.75m for men and 0.67m for women; (c) the men walk with a higher velocity than the women, while the women walk with higher frequency than the men; and (d) there is a linear relationship between walking velocity and frequency which is different for men and women. The results are compared with data obtained approximately 20 years ago.

Introduction

As footbridges and shopping floors become lighter and their spans become longer, their response to dynamic human loads increases and the vibrations induced by people walking need to be considered for serviceability assessments. There are two approaches to the design of structures subject to walking loads. One relies on ensuring that the fundamental frequency of the structure is sufficiently higher than the load frequency so that the vibration induced by the walking will not be a problem, i.e. resonance is avoided; the other requires calculation of the response of the structure to the walking for comparison with known acceptance levels. Both approaches require knowledge of the frequency of walking loads.

It has been well publicised that the London Millennium Footbridge experienced unexpected and pronounced lateral movement when a crowd of people walked across it. This was induced by the horizontal components of walking loads when the frequency of the load matched one of the lateral frequencies of the bridge. Similar problems have been observed on other footbridges[1,2]. It is known that the frequency of walking loads in the lateral direction is just half of that in the vertical direction. For both footbridges and floors the vertical movement is also important and with modern forms of construction may be a critical factor in their design.

A complete description of walking loads includes the amplitudes of the load components, load frequency and velocity, and phase lags between the load components. An experimental investigation was conducted which examined the amplitudes of the load components and floor response to the load[3]. This paper focuses on the frequency and velocity of walking.

A previous investigation was conducted to examine the frequency ranges and distributions of dance type loads at pop concerts[4]. It reviewed 210 songs ranging from the 1960s to 1990s and including dance, indie, pop and rock. It was found that the average beat frequency of music from successive decades has increased by approximately 0.12Hz since the 1960s. It was also observed that the magnitudes of dance type loads depend on the structure. Similar questions arise when walking is considered:

- Do people walk faster or more slowly on a footbridge than on a shopping floor?
- Do men walk faster than women in terms of velocity and/or

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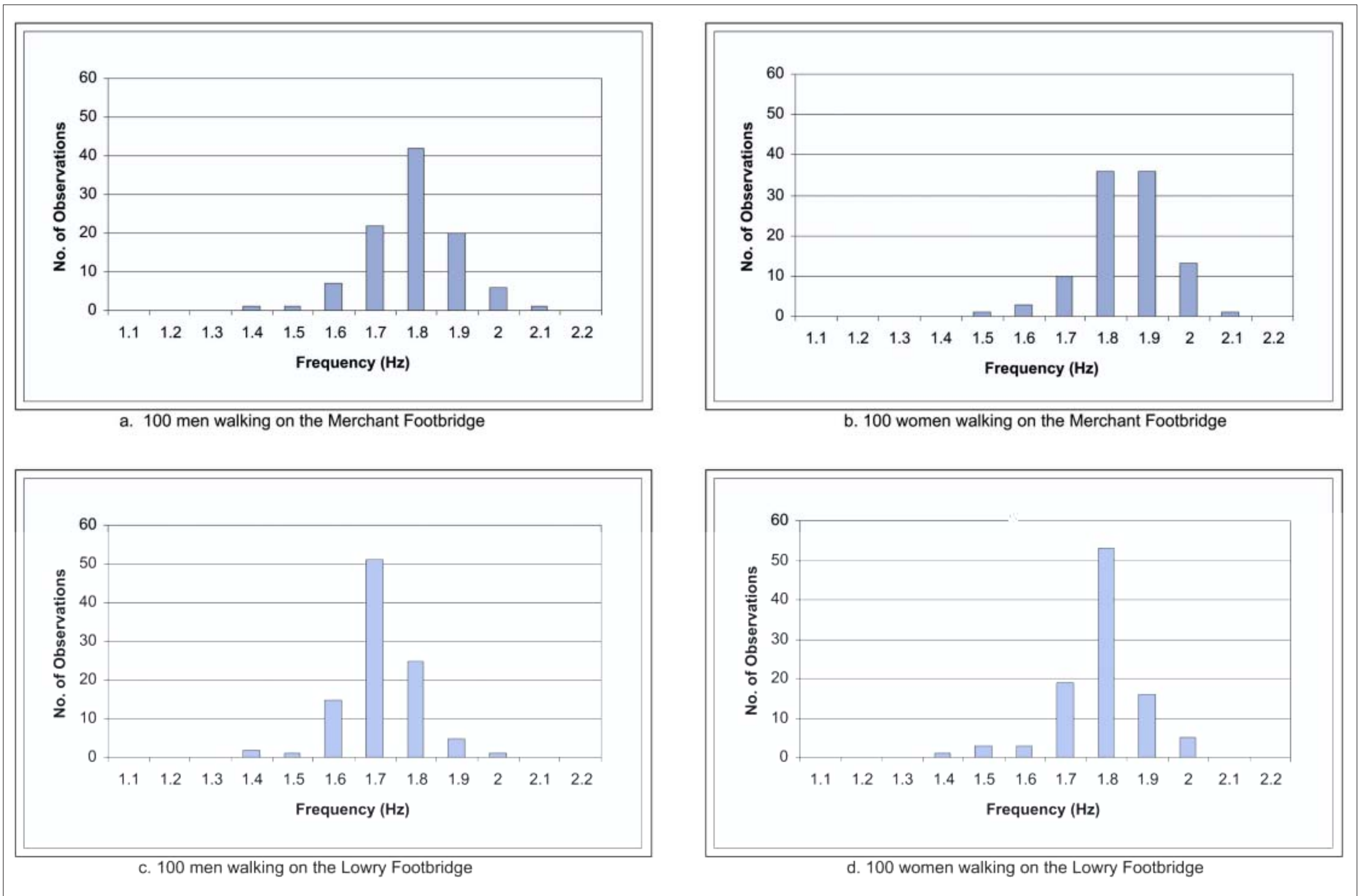


a. 100 men walking on the Merchant Footbridge
b. 100 women walking on the Merchant Footbridge
c. 100 men walking on the Lowry Footbridge
d. 100 women walking on the Lowry Footbridge

Fig 1. Frequency distributions of walking loads on two footbridges

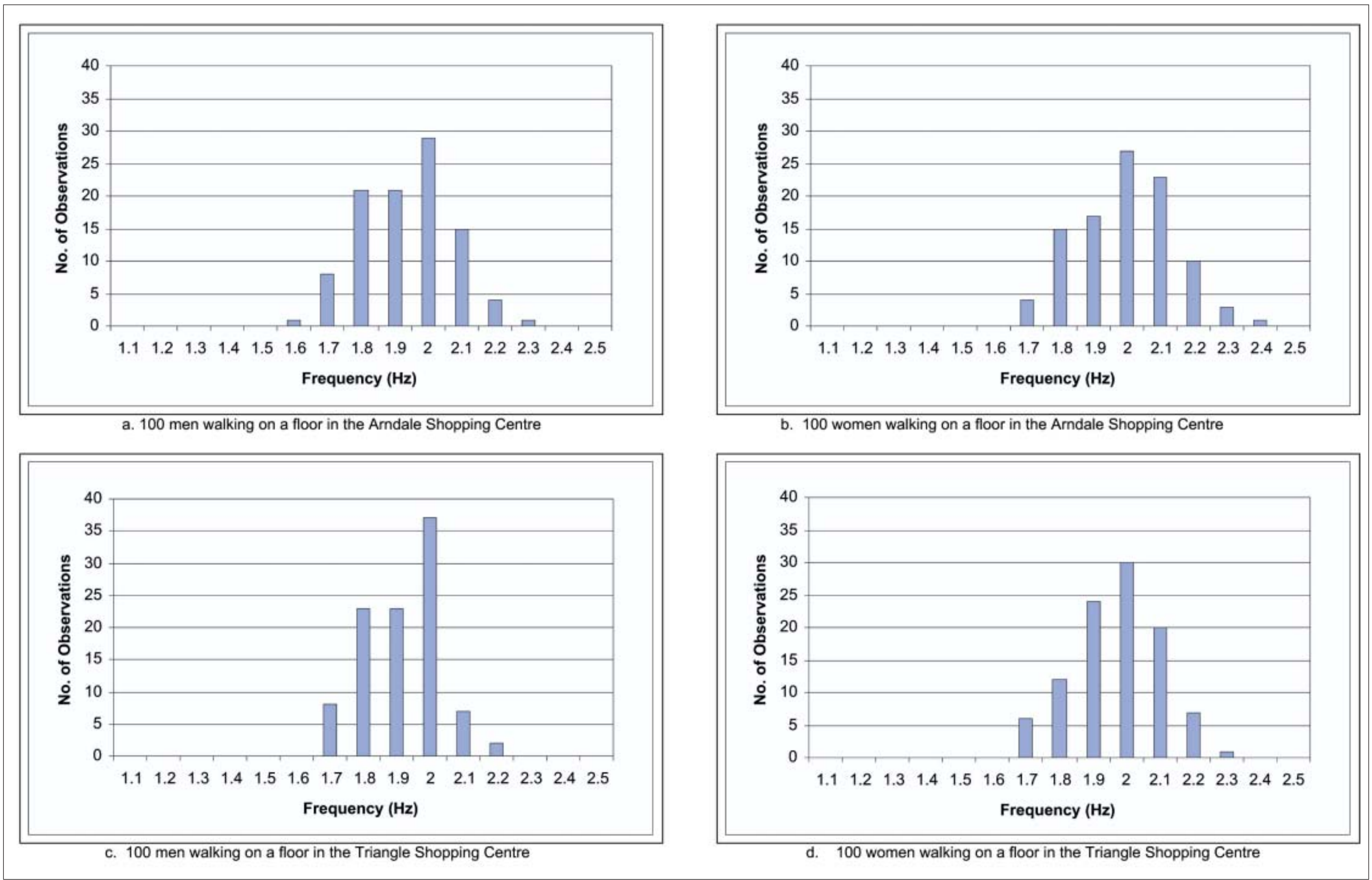


Fig 2. Frequency distributions of walking loads on two shopping floors

frequency?

- What is the norm and distribution of the walking frequency and velocity?
- Do people walk faster or more slowly today than they did 20 years ago?

To answer these questions the frequency and velocity and their distributions of walking loads are investigated.

For this investigation measurements of the number of steps and time taken to walk a given distance were recorded when 100 men and 100 women walked across each of two footbridges and two shopping floors. The statistical characteristics of the walking frequency and velocity were then determined. The investigation is relatively straightforward, but the results are useful for the design and analysis of structures subject to walking loads.

Table 1: Statistical results of 400 people walking on two footbridges

1	Merchant footbridge			Lowry footbridge			The two footbridge	
2	100 men	100 women	200 men and women	100 men	100 women	200 men and women	200 men	200 women
3 Mean value of step length ($L_{s.a}$) (m)	0.78	0.70	0.74	0.72	0.64	0.68	0.75	0.67
4 Curve fitting value of step length ($L_{s.cf}$) (m)	0.78	0.70	0.74	0.72	0.64	0.68	0.75	0.67
5 Mean value of walking frequency (f) (Hz)	1.84	1.89	1.86	1.76	1.84	1.80	1.80	1.86
6 Mean value of walking velocity (v) (m/s)	1.43	1.32	1.38	1.27	1.18	1.23	1.35	1.25
7 Equation 4 $v = L_{s.cf} \times f$ (m/s)	1.43	1.32	1.38	1.27	1.18	1.22	1.35	1.25
8 Standard deviation of walking frequency (σ_f) (Hz)	0.11	0.11	0.11	0.086	0.10	0.10	0.11	0.11
9 Standard deviation of walking velocity (σ_v) (m/s)	0.12	0.11	0.13	0.070	0.084	0.090	0.13	0.12
10 Frequency range (Hz)	1.41–2.13	1.56–2.12	1.41–2.13	1.50–2.01	1.48–2.06	1.46–2.06	1.41–2.13	1.48–2.12
11 Velocity range (m/s)	1.03–1.78	0.99–1.62	0.99–1.78	1.00–1.52	0.93–1.41	0.93–1.52	1.00–1.78	0.93–1.62
12 Coefficient of correlation (ρ)	0.78	0.73	0.54	0.59	0.66	0.30	0.74	0.69

Table 2: Statistical results of 400 people walking on two shopping floors

1	Arndale shopping floor			Triangle shopping floor			Two shopping floors	
2	100 men	100 women	200 men and women	100 men	100 women	200 men and women	200 men	200 women
3 Mean value of step length ($L_{s.a}$) (m)	0.74	0.67	0.71	0.74	0.68	0.71	0.74	0.68
4 Curve fitting value of step length ($L_{s.cf}$) (m)	0.74	0.67	0.71	0.74	0.68	0.71	0.74	0.68
5 Mean value of walking frequency (f) (Hz)	1.98	2.05	2.01	1.96	2.02	1.99	1.97	2.03
6 Mean value of walking velocity (v) (m/s)	1.47	1.38	1.43	1.45	1.37	1.41	1.46	1.37
7 Equation 4 $v = L_{s.cf} \times f$ (m/s)	1.47	1.38	1.42	1.45	1.37	1.41	1.46	1.37
8 Standard deviation of walking frequency(σ_f) (Hz)	0.14	0.15	0.15	0.11	0.13	0.12	0.12	0.14
9 Standard deviation of walking velocity (σ_v) (m/s)	0.14	0.13	0.14	0.10	0.13	0.12	0.12	0.13
10 Frequency range (Hz)	1.70–2.31	1.74–2.48	1.70–2.48	1.72–2.22	1.70–2.32	1.70–2.32	1.70–2.31	1.70–2.48
11 Velocity range (m/s)	1.11–1.82	0.99–1.71	0.99–1.82	1.15–1.66	0.99–1.71	0.99–1.70	1.11–1.82	0.99–1.71
12 Coefficient of correlation (ρ)	0.59	0.58	0.46	0.50	0.68	0.49	0.56	0.69

Evaluation method

In this study it is assumed that people walk at a constant frequency and velocity for a specified distance. This assumption simplifies the evaluation of the stepping frequency and walking velocity.

If a person walks at a constant velocity v and frequency f for a given distance L with footsteps n_s in a time period t then the walking frequency is

$$f = n_s/t \qquad \text{...(1)}$$

The walking velocity is

$$v = L/t \qquad \text{...(2)}$$

The step-length is

$$L_s = L/n_s \qquad \text{...(3)}$$

Substituting equations 1 and 3 into equation 2 and eliminating L, t and n_s gives

$$v = L_s f \qquad \text{...(4)}$$

Equation 4 indicates that walking velocity and frequency have a linear relationship with a positive constant of the step-length.

When a large number of measurements of walking frequency and velocity are obtained, statistical methods can be applied for determining their mean value and standard deviation.

When there are two variables, x and y, the coefficient of correlation between the two variables is defined as[5]:

$$\rho = \frac{n\sum xy - \left(\sum x\right)\left(\sum y\right)}{\sigma_x \sigma_y} \qquad \text{...(5)}$$

The correlation coefficient ρ lies between –1 and +1, and describes how closely the two variables are related. Values of $\rho = -1$ and $\rho = 1$ indicate that y is a function of x. A value $\rho = 0$ shows that there is no relationship between x and y, i.e. x and y are independent variables. The variables x and y are defined as the walking frequency and velocity in this study.

Design of experiments

The walking frequency and velocity of individuals may vary due to the differences between male and female, age, fitness, the venue, lighting, temperature, weather etc.

This study focuses on:

- footbridges and shopping floors: These are the venues where excessive vibration may occur due to normal walking. Footbridges are normally outdoors while shopping floors are indoors. People may feel differently when crossing these two types of structure, and this may affect their walking frequency and velocities.
- men and women aged approximately between 20 and 50: This is because they are the main users of footbridges and shopping floors, and normally exert larger walking loads than other age groups. As men are normally taller than women, they may have larger step-lengths; however, it is not clear whether men walk with a higher frequency and/or velocity than women.

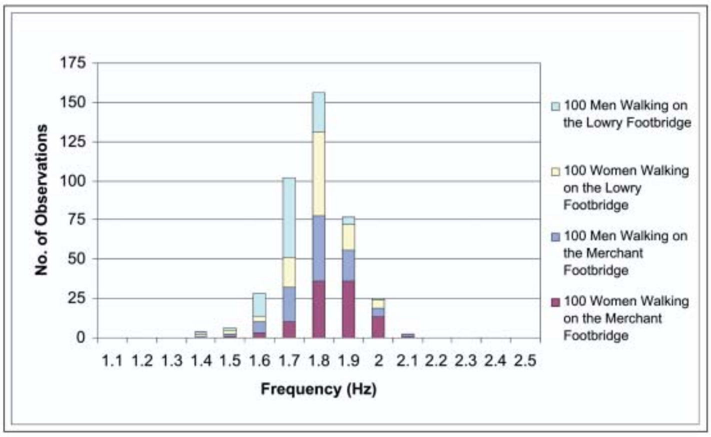
Therefore two footbridges and two shopping floors in Manchester were selected for the tests. The two footbridges were the Merchant Footbridge and the Lowry Footbridge. The two shopping floors were in the Arndale Shopping Centre and the Triangle Shopping Centre. 100 men and 100 women were randomly selected for the tests at each of the venues. Therefore, a total of 800 measurements were taken.

Before taking measurements, the lengths of the test venues were determined. The walking distances were 65.1m and 92m for the two footbridges and 21m for the two shopping floors. A stopwatch was used to record the time taken to walk the given distance and the number of steps taken was counted at the same time. Thus the walking frequency, velocity and step-length can be determined using equations 1-3.

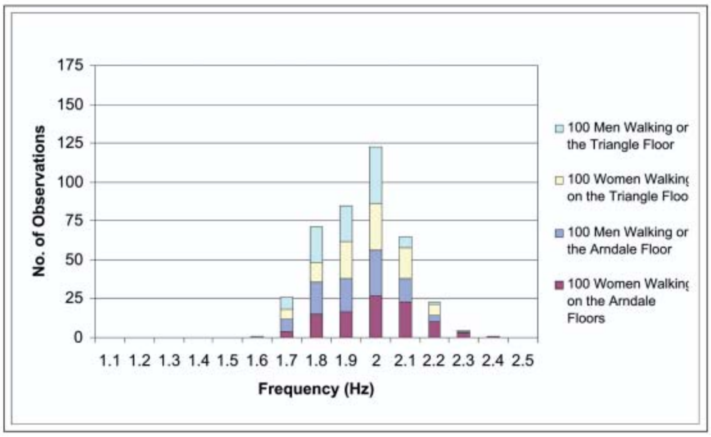
Earlier trial experiments were conducted within the UMIST campus and students were invited to take part in the tests. It was found that the students did not walk naturally because they knew that they were being observed[6]. In the current study, one of the authors followed a walker to record the time period and counted the number of steps for the given distance while the walker did not realise that he/she was being observed. In this way many samples were obtained. Any data that did not satisfy the assumption given in the last section was excluded from the analysis. These exclusions resulted from the following causes:

- While walking on footbridges, people stopped walking to view the surroundings.
- While walking on shopping floors, people stopped in order to look at the shops or changed direction in order to avoid others or to enter shops.

An inaccuracy in counting the number of steps arises from



a. 400 people walking on the Footbridges.

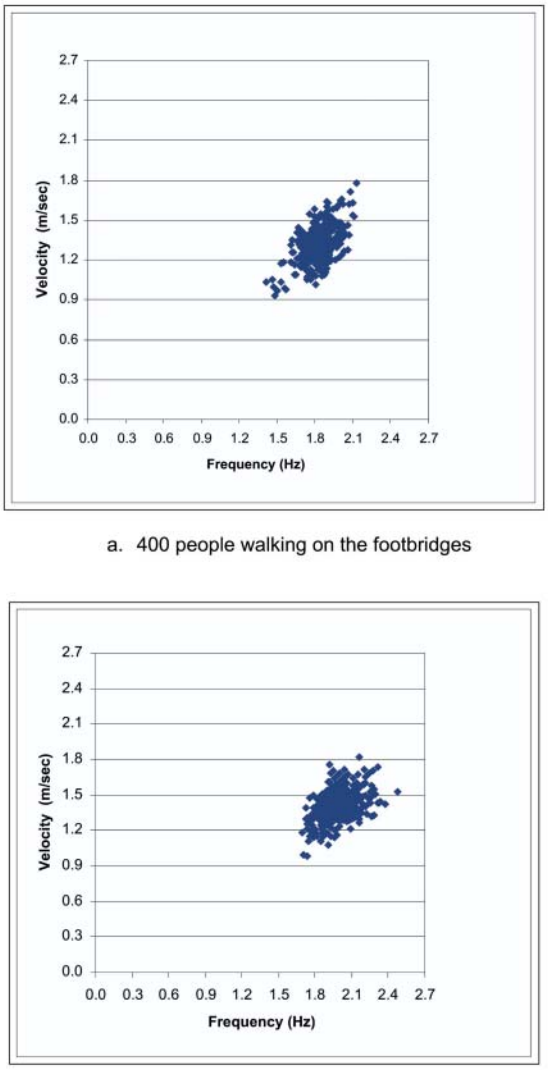


b. 400 people walking on the Shopping Floors.

Fig 3. Frequency distributions on footbridges and shopping floors

Table 3: Summarised results of 800 people walking on footbridges and shopping floors

	Footbridges	Shopping floors
Frequency range	1.4–2.1Hz	1.7–2.5Hz
Velocity range	0.93–1.8m/s	0.99–1.8m/s
Mean value of step length ($L_{s.a}$)	0.71m	0.71m
Curve fitting value of step length ($L_{s.cf}$)	0.71m	0.71m
Mean value of walking frequency (f)	1.8 Hz	2.0Hz
Mean value of walking velocity (v)	1.3m/s	1.4m/s
$v = L_{s.cf} \times f$	1.3m/s	1.4m/s
Standard deviation of walking frequency (σ_f)	0.11Hz	0.13Hz
Standard deviation of walking velocity (σ_v)	0.13m/s	0.13m/s
Coefficient of correlation (ρ)	0.51	0.47



a. 400 people walking on the footbridges

b. 400 people walking on the floors

Fig 4. Relationship between walking velocity and frequency

the possibility of half a step being missed or added at the start or end of the distance. As the walking distance is sufficiently large, this has a negligible effect on the results.

The experimental study allows the frequency and velocity ranges to be determined and comparison of the results obtained from different venues and different groups of walkers.

Ranges and distributions of frequency and velocity

On footbridges

Fig 1 shows the frequency distributions of 100 men and 100 women walking on each of the two bridges. Table 1 provides the corresponding statistical results for each group of 100 people on each of the two footbridges and four combinations of 200 people. Several characteristics can be observed from Fig 1 and Table 1:

a) Generally, men walk with a larger step-length than women (3rd and 4th rows, Table 1).
b) The mean values of step-length for both men and woman are almost the same as that obtained from the curve fitting (3rd and 4th rows, Table 1).
c) Men walk with a higher velocity than women (6th and 11th rows, Table 1) while women walk with higher frequency than men (5th and 10th rows, Table 1).
d) As men and women have different walking characteristics, the correlation coefficient is lower when the two sets of data are processed together (12th row, Table 1).
e) The mean values of velocity for both men and women can be accurately predicted using Equation 4 where the mean values of walking frequencies are adopted (7th row, Table 1).

Table 4: Comparison with published data on footbridges

	Type of distribution	Mean value of frequency (Hz)	Standard deviation (Hz)	Frequency range (Hz)	Mean value of velocity (m/s)	Average step length (m)
Matsumoto *et al*[7]	Normal	2.0	0.13	1.5–2.5	–	–
Bachmann[8]	Normal	2.0	0.18	1.5–2.5	–	–
Wheeler[9]	–	2.0	–	–	1.5	0.75
Bachmann[10]	–	2.0	0.175	1.65–2.35	–	–
This study[11]	Normal	1.8	0.11	1.4–2.1	1.3	0.71*
This study[11] (for shopping floors)	Normal	2.0	0.13	1.7–2.5	1.4	0.71*

* 0.75m for men and 0.67m for women

f) The frequency distributions basically follow normal distributions (Fig 1).
g) The stepping frequencies for the 400 walkers are between 1.41Hz and 2.13Hz, while 388 of the 400 people walked at frequencies between 1.6Hz and 2.1Hz (10th row, Table 1 and Fig 1).
h) People walk more slowly on the Lowry footbridge than on the Merchant footbridge. This may be because the Lowry footbridge is located at a more attractive site and the passengers walk more slowly to view the surroundings (6th and 11th rows, Table 1).

On shopping floors

The data obtained from shopping floors were processed in the same way to those from the footbridges. Fig 2 shows the frequency distributions of 100 men and 100 women walking on each of the two floors. Table 2 provides the corresponding statistical results for each group of 100 people on each floor and four combinations of 200 people. Similar characteristics as (a-f) observed from the data on footbridges in the previous section are valid on the shopping floors. However, other characteristics are:

g) The stepping frequencies for the 400 walkers are between 1.70Hz and 2.48Hz, while 393 of the 400 people walked at frequencies between 1.7Hz and 2.3Hz (10th row, Table 2 and Fig 2).
h) People walk slightly more quickly on the floor in the Arndale Centre than they do on the floor in the Triangle Centre, but this difference is very small (6th and 11th rows, Table 2).

Comparison between the results on footbridges and shopping floors

There are many common features between the results obtained from footbridges and those from shopping floors. However, some differences are also apparent. Fig 3 shows the walking frequency distributions on footbridges and shopping floors and each of the two figures consists of 400 observations. Fig 4 gives the measurements showing the correlation between walking velocity and frequency. Table 3 provides a statistical summary of 400 people walking on footbridges and shopping floors respectively. It is found from Fig 3, Fig 4 and Table 3 that:

- the distributions for walking frequency on the footbridges and floors follow a normal distribution, with standard deviations of 0.11Hz and 0.13Hz respectively;
- people walked faster on the shopping floors, with a mean frequency of 2.00Hz and a velocity of 1.42m/s, than on the footbridges, where a mean frequency of 1.83Hz and a velocity of 1.30m/s were determined;
- statistically 95.5% of the surveyed people walked on the footbridges within the frequency range between $1.83 - 2\sigma_f$ and $1.83 + 2\sigma_f$, i.e. between 1.61Hz and 2.05Hz, and the velocity range between $1.30 - 2\sigma_v$ and $1.30 + 2\sigma_v$, i.e. between 1.04m/s and 1.56m/s;
- statistically 95.5% of the surveyed people walked on the shopping floors within the frequency range between 1.74Hz and 2.26Hz, and the velocity range between 1.16m/s and 1.6 m/s;
- the step-lengths on the footbridges and the shopping floors were similar.

Comparison with published results

Table 4 provides a comparison between the related data from literature and this study on footbridges. It shows that the average values of walking frequency and velocity obtained from this study are about 8.5% and 13% smaller than those in the literature published approximately 20 years ago.

However, the values in the literature for footbridges are close to the measurements from the shopping floors, which are also given in Table 4.

Conclusions

800 measurements have been taken on two footbridges and two shopping floors. The assessment of these measurements has led to several conclusions, which will be useful for designing and analysing footbridges and shopping floors. They are:

1. People walk faster on the shopping floors, with an average frequency of 2.0Hz and a velocity of 1.4m/s, than on the footbridges, which encounter an average frequency of 1.8Hz and a velocity of 1.3m/s. The ranges of walking frequency and velocity are given in Table 3.
2. The mean values of the step-length on the footbridges and the shopping floors are similar with 0.75m for men and 0.67m for women.
3. There is a linear relationship between walking velocity and frequency. The relationship can be expressed as

$$v = L_s f = \begin{cases} 0.75f & \textit{for men} \\ 0.67f & \textit{for women} \end{cases} \qquad \text{...(6)}$$

4. The experiments indicate that men walk with higher velocities than women, while women walk with higher stepping frequencies than men.
5. The walking frequency distributions on the footbridges and the shopping floors follow normal distributions with standard deviations of (0.11Hz, 0.13m/s) and (0.13Hz, 0.13m/s) respectively.

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