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On methods for extending a single footfall trace into a continuous force curve for floor vibration serviceability analysis

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Abstract. An experimentally measured single footfall trace (SFT) from a walking subject needs to be extended into a continuous force curve, which can then be used as load for floor vibration serviceability assessment, or on which further analysis like discrete Fourier transform can be conducted. This paper investigates the accuracy, applicability and parametrical sensitivity of four extension methods, Methods I to IV, which extends the SFT into a continuous time history by the walking step rate, stride time, double support proportion and the double support time, respectively. Performance of the four methods was assessed by comparing their results with the experimentally obtained reference footfall traces in the time and frequency domain, and by comparing the vibrational response of a concrete slab subjected to the extended traces to that of reference traces. The effect of the extension parameter on each method was also explored through parametrical analysis. This study finds that, in general, Method I and II perform better than Method III and IV, and all of the four methods are sensitive to their extension parameter. When reliable information of walking rate or gait period is available in the test, Methods I or II is a better choice. Otherwise, Method III, with the suggested extension parameter of double support time proportion, is recommended.

Keywords: single footfall trace; extension method; motion capture technology; floor vibration serviceability

1. Introduction

Human walking load is a kind of dynamic excitation that may, if not properly considered in the structural design, cause a vibration serviceability problem to structures like footbridges, cantilever stands in stadiums and long-span floors. It may also cause dysfunction of vibration sensitive devices in high-tech factories, labs or hospitals (Pavic and Reynolds 2002, Ebrahimpour and Sack 2005, Han *et al*. 2009, Nguyen *et al*. 2012). One of the well-known examples is the London Millennium Bridge which experienced, on its opening day, excessive vibration when a large number of people were moving on the bridge. The bridge was then closed for almost two years until engineers figured out reasons for the uncomfortable swaying motion and installed some expensive dampers to abate the vibration (Dallard *et al*. 2001, Strogatz *et al*. 2005).

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The floor vibration serviceability is typically assessed by comparing the floor's vibration amplitude under walking load to the acceptable level: the occupant comfort criteria (BSI 1987, Murray *et al*. 1997, ISO 2003, Willford *et al*. 2006). The dynamic properties of walking load are crucial to the accuracy of the assessment and the design of remediation measures or vibration control strategies for questionable floors. Much experimental work has been conducted in the past several decades to investigate the dynamic properties of the walking load. A small sampling are Harper *et al*. (1961), Galbraith and Barton (1970), Ohlsson (1982), Rainer *et al*. (1988), Kerr and Bishop (2001) among many others. A comprehensive literature review regarding experiments and numerical models of human walking load can be found in Racic *et al*. (2009).

Large quantities of experimental records of walking load are needed in order to establish a reliable mathematical model. However, it is not an easy task to measure the walking load in the experiment due to its spatio-temporal variation characteristic. As a result, it was very common in the majority of the previous experimental work single footfall trace (SFT) was recorded by a force plate mounted on the walking path. On the other hand, in disciplines like biomechanics and sports science, there are plenty of records of SFT from normal walking people. These records could be utilized to significantly expand the database for modeling walking loads for civil engineering applications. Fig. 1 demonstrates the SFTs F_x, F_y and F_z measured by a force plate in the x (left-right/perpendicular to the walking path), y (anterial-posterial /walking direction) and z (vertical) direction. F_x and F_z are of particular importance in the vibration serviceability issue, as F_z has the largest amplitude and dominants the vertical vibration, and F_x may cause lateral vibration to line-like structures such as pedestrian bridges to which the stiffness in the lateral direction (x direction) is usually less than that in the walking direction (y direction).

The measured SFT needs to be extended into continuous curve for further analysis of its dynamic properties or for computing a floor's vibration response. Based on the same assumption that both feet perfectly generate the same dynamic force,, several extension methods have been suggested by researchers to extend the SFT. For instance, Ohlsson (1982), Ellingwood and Tallin (1994) obtained the continuous footfall curve by overlapping the measured SFT under the assumption that the SFT remains the same for each step. Kerr and Bishop (2001) converted the

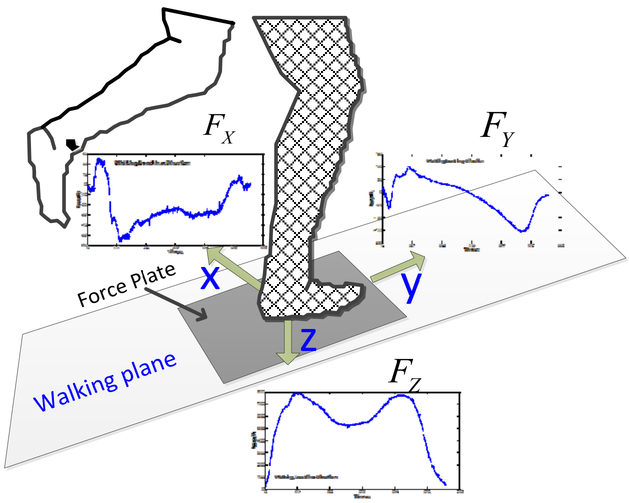


Fig. 1 Single footfall trace measured by a force plate in the *x, y* and *z* direction

measured SFT into a continuous, repeatable time history on which a discrete Fourier analysis could be conducted. Liu (2008) extended SFT by assuming a constant stride time. Since the duration of SFT is very short, generally less than one second, the selection of extension method and the corresponding extension parameters are influential in the dynamic characteristics of the extended results.

Though the extension method is very important in studying and modeling the walking load, comparison of the performance of extension methods is rare. One possible reason is the lack of experimentally obtained reference curves for comparison. Therefore, we explore in this paper the accuracy, applicability and parametric sensitivity of four extension methods by comparing the extended trace with the reference trace in the time and frequency domains, and by comparing the vibration response of a concrete slab subjected to the extended to that of the reference trace. Three of the four extension methods are from the literature and the remaining one is a new extension method suggested by the authors. Based on all the observations in this study, suggestions are given for selecting a proper extension method and its parameters.

2. Methods for extending single foot trace

2.1 The Gait cycle and Gait events

In order to clarify the extension methods in the following parts, it is necessary to introduce some basic terms about the gait cycle and the gait events. Referring to Fig. 2, a gait cycle (or a stride) is defined as the process which starts when one foot first contacts the ground (initial contact, often called heel contact in normal gait) and ends with the next contact of the same foot. A gait cycle can be divided by the occurrence of toe-off into two parts: the swing phase and the stance phase. The period when both feet are on the ground is termed as double support time. It can also be divided into two parts: initial double support (in which the body weight is being transferred from contralateral to ipsilateral) and terminal double support (in which the body weight is being transferred from ipsilateral to contralateral) (Kirtley 2006).

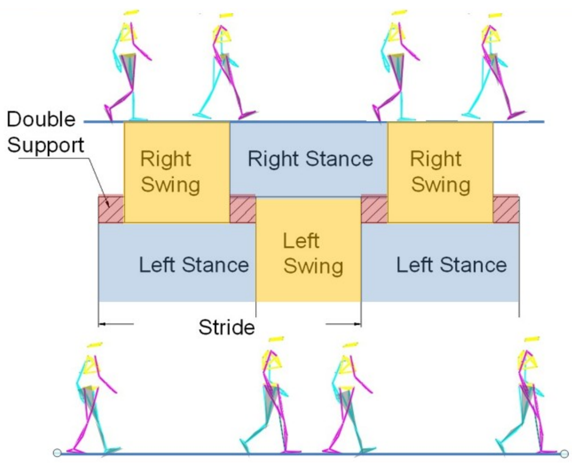


Fig. 2 Gait cycle and gait events

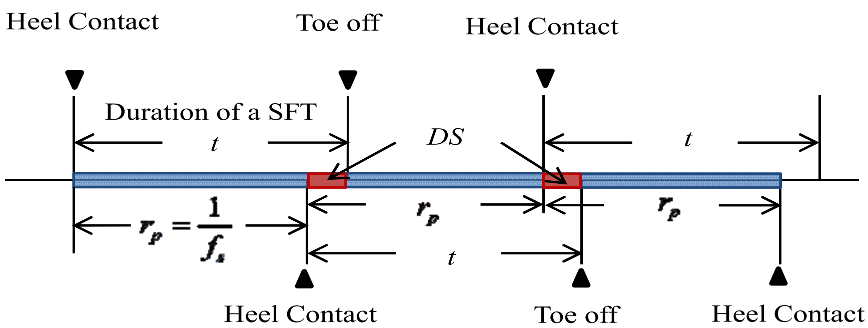
By assuming that both feet perfectly generate the same SFT (F_x, F_y and F_z), the SFT can be extended provided that the double support time is known. Four extension methods, Method I to Method IV (M1, M2, M3 and M4 for short), are compared in this study. The four methods differ from each other in the determination of the double support time.

2.2 Method I (M1): extension based on step frequency

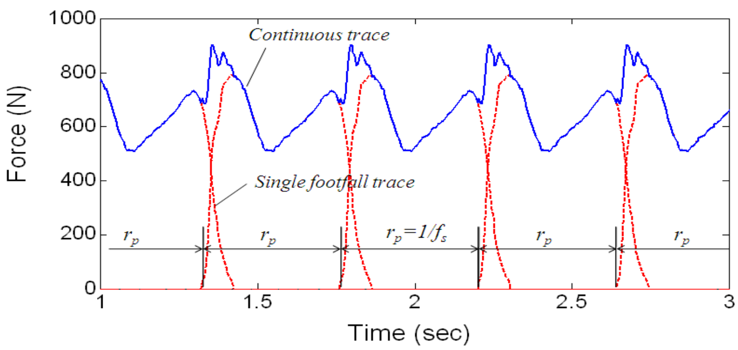
Referring to Fig. 3(a), if the step frequency f_s is known and constant, the double support time (DS) will be the difference between the duration of a single footfall trace (t) and the repeat period (r_p) that defined by the step frequency, $r_p = 1/f_s$. In other words, DS = t-$1/f_s$. Therefore, assuming that human walking is perfectly bilateral symmetric and repeatable, one can overlap a single footfall trace by translating it successively on the timeline with a period of time $r_p = 1/f_s$ and add the translated footfall traces together to get a continuous one. Kerr and Bishop (2001) adopted this method to extend SFT. A sample of extended SFT by M1 is demonstrated in Fig. 3(b).

2.3 Method II (M2): extension based on stride time

As mentioned above, the stride time (T) is the duration of a complete gait cycle (i.e., the time between the same heel continuously making two contacts on the ground). Suppose the stride time T is known and initial heel contact of one foot is taken as zero time instant, the following



(a) Determination of double support time in M1



(b) Example of SFT extended by M1

Fig. 3 Method I: extension method based on step frequency contralateral foot contact will occur at the time instant *T/2* (see Fig. 4). Thus, quite similar to M1, under the same symmetrical and repeatable assumption, *T/2* can be the period r_p for overlapping the single footfall trace. In other words, translate the SFT successively along the timeline with a period T/2 and then add the translated SFTs together. The double support time for M2 can be calculated as *DS=t-T/2*. Liu *et al.* (2008) suggested this approach to extend measured SFT.

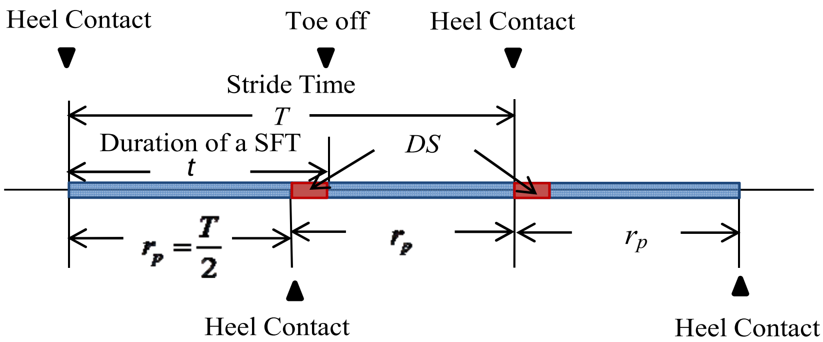
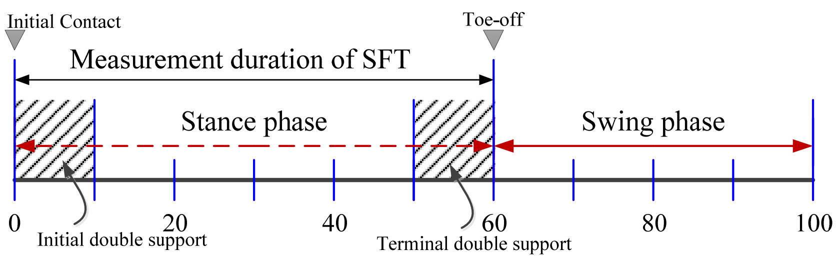


Fig. 4 Method II: extension method based on stride time

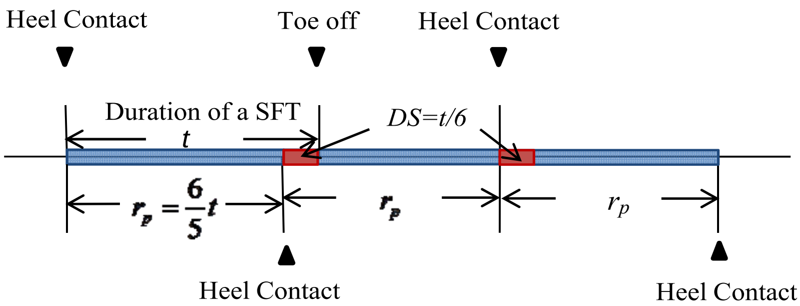
2.4 Method III (M3): extension based on double support proportion

For a subject walking at a normal rate, Kirtley (2006) concluded from experiments that the stance phase (i.e. the time period from the hell contact to toe-off of one foot) and the swing phase each took about 60% and 40% time of a gait cycle respectively, as shown in Fig. 5(a). Since each stance phase is 60%, the double support time is therefore about 2 × 60%−100% = 20% of a gait cycle under the assumption that walking is perfectly symmetrical and repeatable. Because the duration of measured SFT is the same as the stance phase (Fig. 5(a)), the double support time is thus 1/6 of the duration of SFT. Noting this, we suggest the double support time as a fixed proportion of the duration of SFT, for Method III. For example, one can shift the SFT along the timeline at an interval of 5/6 the duration of SFT to construct the continuous walking load time history (Fig. 5(b)).



(a) Definition of double support time in M3 (follow Kirtley 2006)

Fig. 5 Method III: extension method based on double support proportion



(b) Extension procedure of M3

Fig. 5 Continued

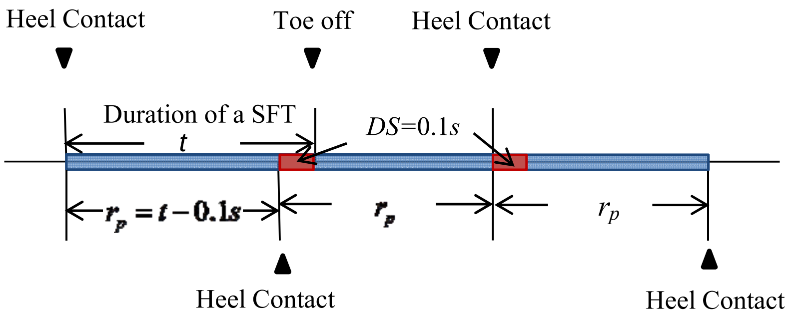


Fig. 6 Method IV: extension method based on double support time

2.5 Method IV (M4): extension based on double support time

Aiming at assessing floor vibration under walking loads, Ellingwood and Tallin (1984) assumed that the double support time in a gait cycle was approximately 0.2 sec for normal walking rates. Under the assumption that each footfall is symmetric and repeatable, one can overlap the single footfall trace with a time period that equals the difference between the duration of the trace and 0.1s and then simply add them together to get continuous traces (Fig. 6).

Effectiveness and applicability of the above four extension methods have been compared by two methods in the following sections. First, the extended footfall curves are compared with the "reference footfall curve" in both the time and frequency domains. Second, the response of a square concrete slab subjected to the extended footfall curve is compared with that from reference footfall curve. The "reference footfall curve" is determined from experiment.

3. Experimental test

3.1 Walking load test using 3D motion capture technology

We have conducted a series of experiments on human walking loads using two force plates in conjunction with the three dimensional motion capture technology. A sketch of the experimental scheme, a photo of the test lab and a test subject are shown in Fig. 7. The experiments were carried

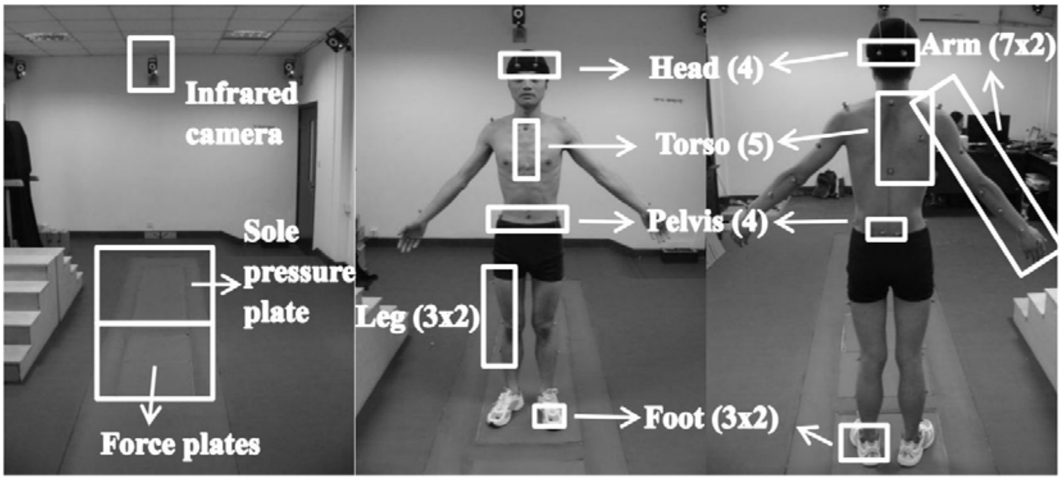


Fig. 7 Experiments on walking load using the 3D motion capture technique

Table 1 Statistics of the test subjects

Gender	Number	Age (y)		Weight (kg)		Height (mm)	
		Mean	Std	Mean	Std.	Mean	Std.
Male	59	23.4	2.34	65.1	4.13	1714.2	74.17
Female	14	22.8	1.15	51.2	8.77	1615.4	25.38

out in the Gait Lab in Shanghai Institute of Traumatology and Orthopaedics, Ruijin Hospital. All measurements have been made in a 15 m by 3.0 m area, where two AMTI OR6-7 force platforms were flush-mounted on the ground, and a 2 m long sole pressure plate was installed on the ground adjacent to the force plates. The movement of the test subject has been measured by the three-dimensional motion capture system, which can acquire, analyze and display three dimensional motion data of the walking people. Reflective markers were attached to the subject's skin to identify bony landmarks of the test subject. Spatial locations of the markers were monitored by optical camera, and the kinematic quantities such as displacement- of each body segment could be measured. The Vicon Motion Capture System with ten infrared cameras has been installed in the lab. The motion capture system was integrated with analog data acquisition systems of the force plate to enable simultaneous measurements. Moreover, a video recorder was employed to record the test process for future visual check of the experimental data.

3.2 Test procedure

Up to now, we have completed walking experiments for 73 subjects (59 male and 14 female). Statistics of the age, body weight and height of all the test subjects are given in Table 1.

Each test subject, after warm-up and rehearsal, was asked to perform seven tests, which were three self-chosen walking rates (slow, normal and fast walking speed without sound instruction) and four fixed walking frequencies 1.5, 1.75, 2.0 and 2.25 Hz guided by an electronic metronome. Every test case was repeated several times to ensure valid measurements, which meant in a gait cycle each foot fully stepped on the surface of one force plate while not having the other foot in contact with the same plate. Thus, each force plate successfully recorded the SFT of one foot at a 1000 Hz sampling frequency. Thirty-nine reflective markers were attached to each test subject, see Fig. 7. In particular, three markers were placed on each foot in order to precisely monitor the movement of the foot. The spatial locations of all the markers were monitored by Vicon System with the sampling frequency of 200 Hz (200 frames per second). A more comprehensive description of the experiment can be found in Chen *et al*. (2011, 2012) and Wang *et al*. (2012).

3.3 Reference footfall trace

Based on the markers' movement, the gait parameters, such as cadence, walking frequency, stride length and the double-support time of each step were calculated following the biomechanical definition using the post-processing software of Vicon System. Using these gait parameters we can extend the measured force trace into a 'reference footfall curve'. In the test, each force plate recorded the SFTs of one foot in the *x*, *y* and *z* directions. Thus, the footfall trace in a complete gait cycle could be developed by overlapping the SFTs of each foot. The heel contact time instant (i.e. the start time of the next double-support period) could be determined by marker's displacement records. Then, the reference footfall curves were constructed by repeating the footfall trace of the gait cycle under the assumption that every cycle is repeated periodically. Fig. 8 illustrates the procedure for developing the reference footfall trace. For every test case of each test subject, the reference footfall curve was constructed. Comparison between Fig. 3(b) and Fig. 8 shows that the reference curve is based on footfall traces of both feet in a stride and the overlap time instant of the next stride is decided by the marker's record. In other words, the reference curve uses measured double support duration while the extension methods use assumed double support duration.

4. Comparison of extension results and discussion

4.1 Comparison of one test subject's result: time domain

Using experimental records of the normal walking case for a male test subject (weight = 72kg, height = 1790mm), Fig. 9 (a) to (c) compares the extended time histories from the four methods

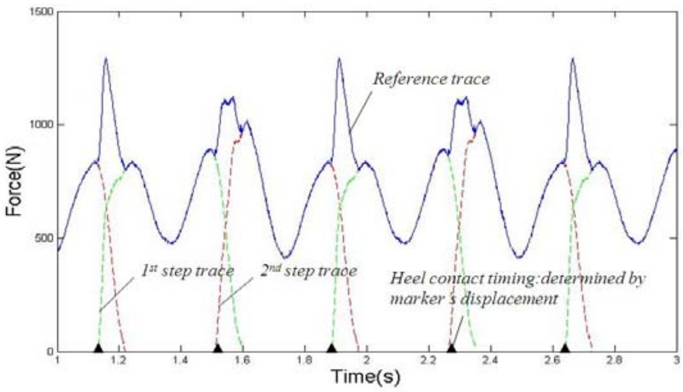
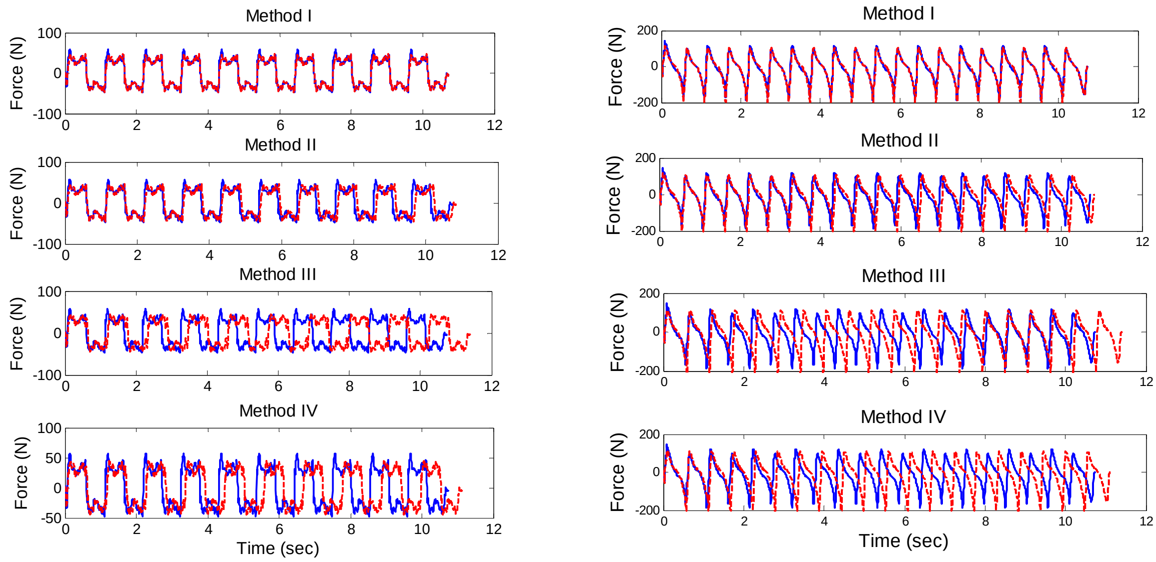
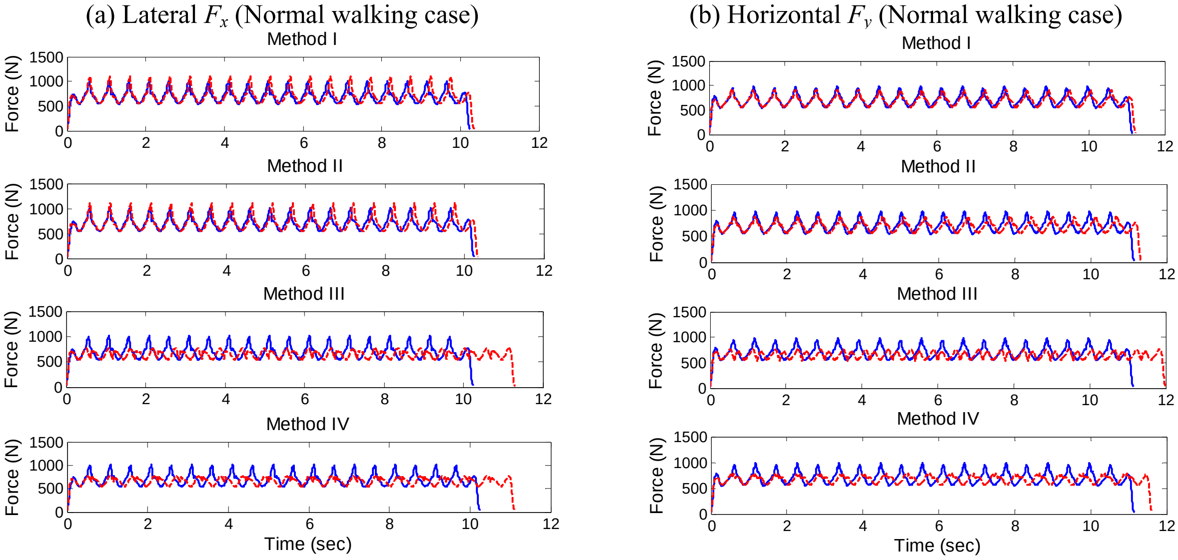


Fig. 8 Construction of reference footfall curve

with the reference traces in the x, y and z directions respectively. For the same test subject, Fig. 9 (d) further shows the comparison in the z direction for the test case of a guided walking rate of 1.75 Hz. Visual inspection of Fig. 9 indicates that the extended curves by M1 and M2 match quite well with the reference curves in three directions, while the extension results by M3 and M4 are not good compared with M1 and M2. The results for other test subjects are similar. Period elongation can be seen in M3 or M4. M3 and M4 roughly estimate double support time by duration proportion or a constant, leading to unsatisfied estimation of repeat period and eventually resulting in elongation or shortening of the extended time history. It will be shown later that M3 and M4 can be improved when proper extension parameter is adopted.



(a) Lateral F_x (Normal walking case) (b) Horizontal F_y (Normal walking case)



(c) Vertical F_z (Normal walking case) (d) Vertical F_z (Guided walking 1.75Hz)

Fig. 9 Comparison of extended footfall curves (dashed line) with the reference curve (solid line) (male subject: Weight = 72kg, Height = 1790mm)

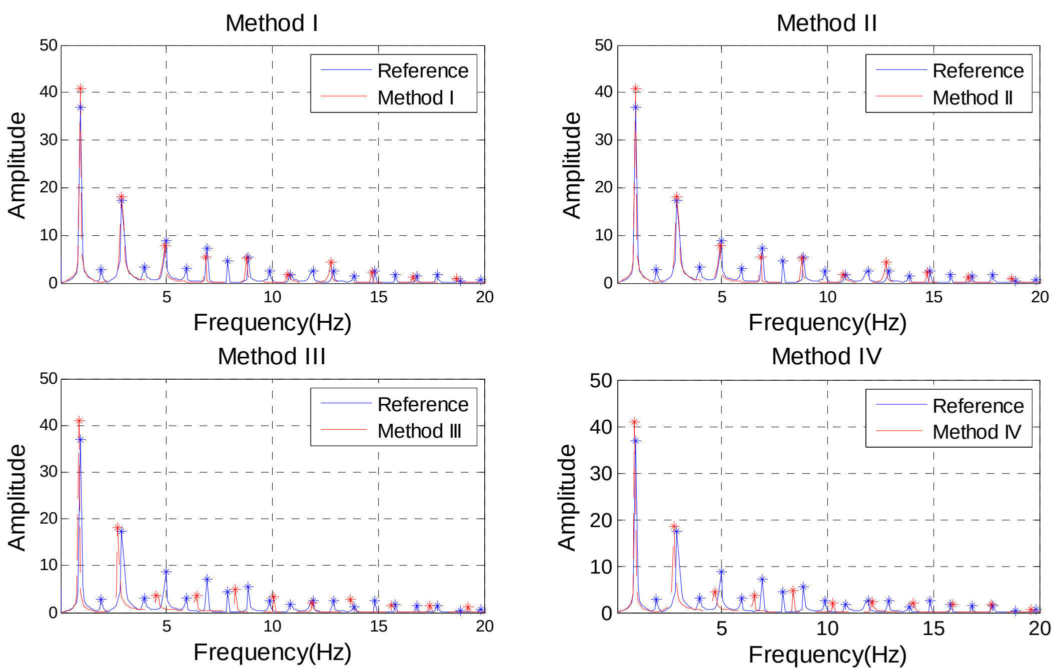
4.2 Comparison of one test subject's result: frequency domain

For the extended and reference curves shown in Figs. 9(a) and 9(c), Figs. 10(a) and Fig. 10(b) depicts their Fourier amplitude spectrum in the *x* and *z* directions, respectively. Results in the *y* direction are similar to the *z* direction and therefore are not presented. The results are consistent with those in time domain: M1 and M2 are better than M3 and M4 in reproducing the main characteristics of the spectrum. Extension curves from M1 and M2 in the *x* and *z* directions have all dominant harmonics close to those of the reference curve. Extension curves from M3 and M4, on the other hand, have only the first dominant harmonic that is close to that of the reference curve. The conclusion is the same for all the other test subjects' results.

From results of M1 and M2, it is seen that the reference trace and the extension traces all have dominant harmonics in the odd multiples of half walking rate in the *x* direction and multiples of walking rates in the *z* direction. However, the reference traces still have sub-harmonics between every two dominant harmonics while all extended traces do not manifest this characteristic. This phenomenon is not surprising since the extension methods ignore the imperfect symmetry of left and right step in a gait cycle. In other words, all the SFT extension methods with the perfect symmetrical assumption are inevitably neglecting the energy of actual walking load between two dominant harmonics.

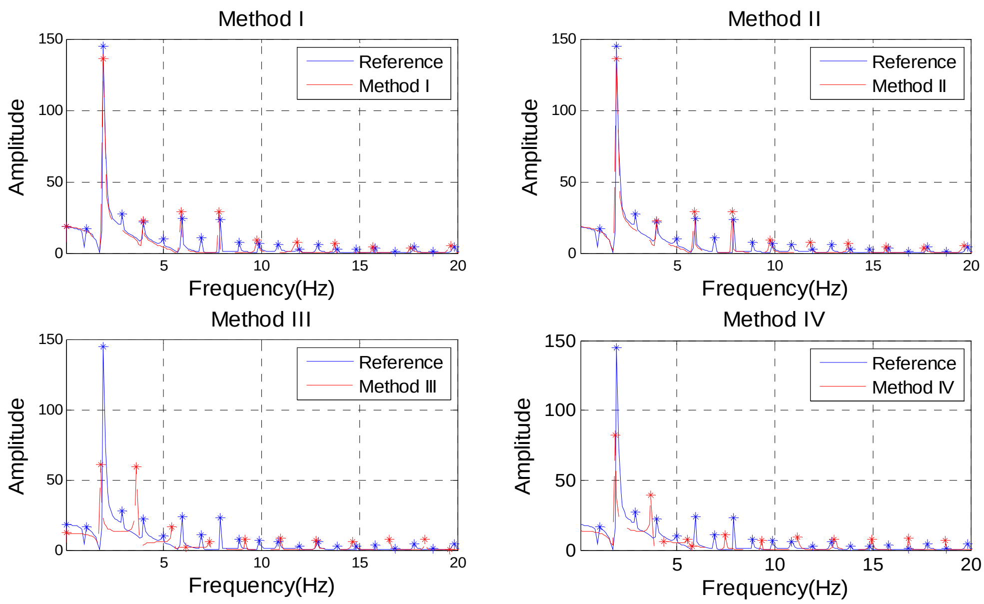
4.3 Comparison of one test subject's result: floor's response

Besides comparison with reference footfall curves, the extended footfall time histories were also applied to a simply-supported concrete slab and the acceleration responses of the slab were



(a) *x* direction

Fig. 10 Comparison of the spectrum of extended and reference curves computed by the modal superposition approach (Song and Jin 2004). The parameters of the slab are: dimensions of 12m × 12m × 0.305m (side length × side length × thickness); mass density of 2500kg/m^3; a Rayleigh damping model (α = 2.6162, β = 5.3176e-4 for damping ratio 0.05), and a walking stride length of 0.75m. The human-structure interaction hasn't been considered in the response calculation.



(b) z direction
Fig. 10 Continued

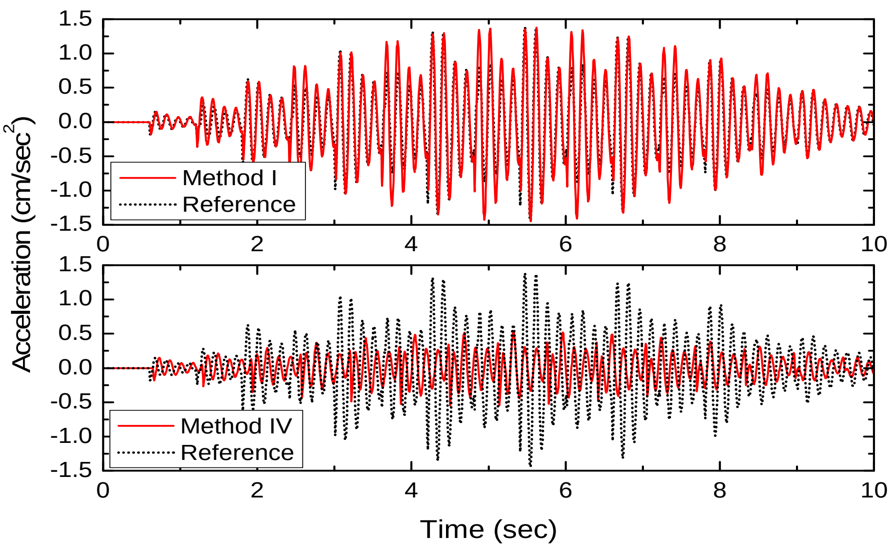
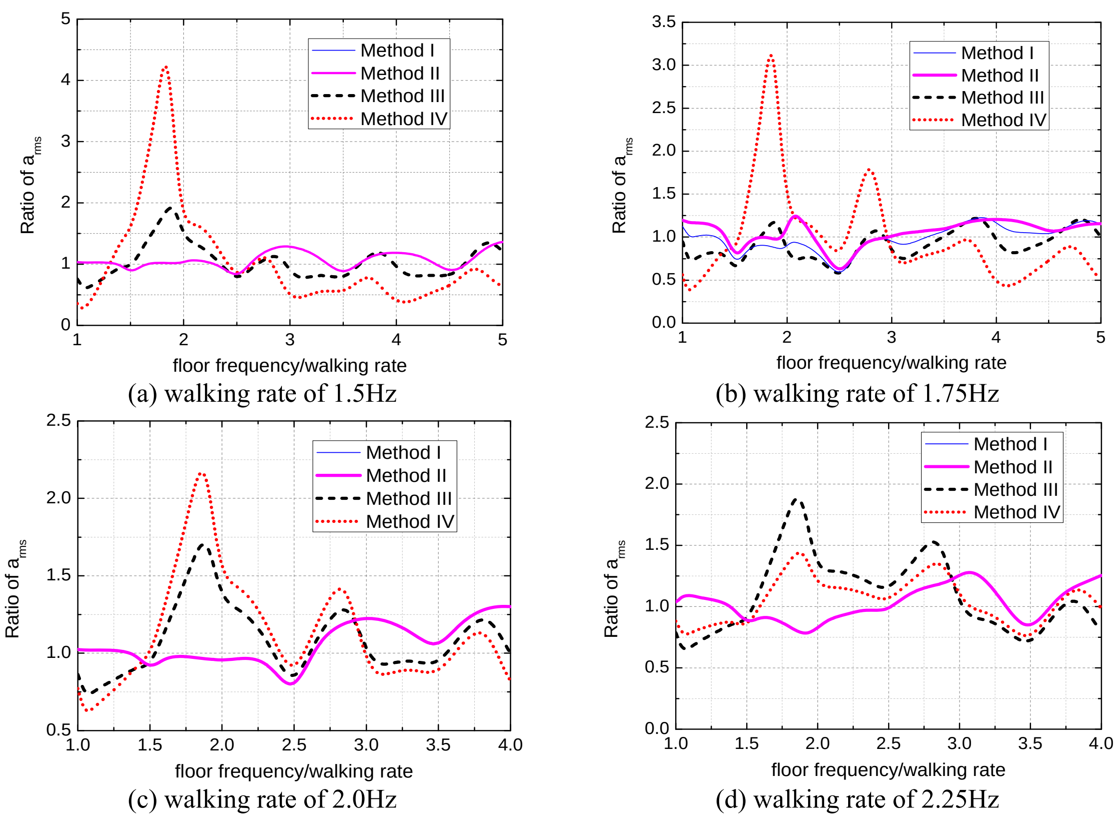


Fig. 11 Time histories of the floor acceleration response under the reference trace and extended traces by M1 and M4

After applying the extended and reference vertical load traces in Fig. 9(c) to the concrete slab, the root-mean-square (RMS) values of acceleration response at the floor's central point were calculated as 0.462, 0.542, 0.387 and 0.178 cm/s^2, respectively, under reference trace and extended traces by M1 to M4. The relative error is 17%, 17%, -16%, and -61% for M1 to M4. Fig. 11 further shows the time history of acceleration responses under reference and extended traces by M1 and M4. It is seen that the acceleration response under extended trace by M1 has the same variation trend with and slightly larger amplitudes than the reference acceleration response. The acceleration response for M4, on the other hand, differs significantly from the reference response. The difference between the reference and each method's acceleration responses are also computed, and the RMS values of the difference for M1 to M4 are, respectively, 0.1839, 0.2637, 0.4867 and 0.5960 cm/s^2.

To learn the effect of slab frequency on the effectiveness of those four methods, we applied the extended and reference footfall traces of walking rates 1.5, 1.75, 2.0 and 2.25Hz of one subject to square slabs of various fundamental frequencies, ranging from 1 to 5 times the walking rate, to calculate the floor acceleration responses at the center. The results are shown in Fig. 12(a) to 12(d) where the abscissa is the ratio of floor frequency over walking frequency, and the ordinate is the acceleration response ratio of the RMS value of the extended curve against the RMS value of the reference trace. Overall, performance of M1 and M2 are relatively robust to the frequency ratio whilst M3 and M4 are sensitive to the frequency ratio. In Figs. 12(a), (c) and (d), the results of M1



(a) walking rate of 1.5Hz
(b) walking rate of 1.75Hz
(c) walking rate of 2.0Hz
(d) walking rate of 2.25Hz

Fig. 12 Effect of floor frequency on the extension method and M2 are almost the same. It is seen from all these figures that acceleration responses from M1 and M2 are close to the reference response; M3's extended result is the next closest, and M4 is the worst in most cases.

4.4 Statistical results of all test subjects

To quantify the difference of the extended and reference curves, the correlation coefficient γ of the two curves were calculated by the following equation

$$\gamma = \frac{\sum_{i=1}^{n}(y_{si}-\overline{y}_s)(y_{ri}-\overline{y}_r)}{\sqrt{\sum_{i=1}^{n}(y_{si}-\overline{y}_s)^2}\sqrt{\sum_{i=1}^{n}(y_{ri}-\overline{y}_r)^2}} \quad (1)$$

where the y_s and y_r are the extended curve of method s (s = 1,2,3,4) and the reference curve, and an overhead bar denotes the mean value; n is the total number of points in the curve and subscript i denotes the i th point. By definition, the closer to 1 index γ is less difference exists between the two curves. Taking results in Fig. 9(d) as an example, the correlation coefficients for M1, M2, M3 and M4 are 0.8584, 0.8584, 0.5973 and 0.3782, respectively.

Table 2 illustrates for each walking case, the averaged correlation coefficient of index gama for all test subjects. Results in Table 2 are consistent with the visual observation that M1 and M2 have the best correlation coefficients for all cases in three directions, and M3 is slightly better than M4. The γ values are lower than 0.75 in the z direction and lower than 0.65 in the x direction for all the four methods. Note that the absolute value of correlation coefficients changes with the extension duration (i.e. the number of gait cycles) because of the accumulation of errors in each cycle. A shorter duration may lead to a better correlation. Nevertheless, observations from Table 2, together with the comparisons of responses in section 4.3, once again emphasize the importance of choosing a proper extension method.

5. Computational parameter sensitivity analysis

5.1 Parametric analysis of extension methods

Comparisons in the previous section demonstrate that M1 and M2 are more reliable and

Table 2 Correlation coefficient of extended and reference footfall curve

No. Test Conditions (pace rate)	Correlation coefficient (z/x/y)			
	Method I	Method II	Method III	Method IV
1:Free walk (Slow)	0.73/0.63/0.70	0.73/0.63/0.70	0.59/0.41/0.56	0.48/0.29/0.44
2:Free walk (Normal)	0.58/0.46/0.55	0.58/0.46/0.55	0.58/0.46/0.57	0.57/0.44/0.56
3:Free walk (Fast)	0.49/0.39/0.46	0.49/0.38/0.46	0.55/0.46/0.57	0.51/0.42/0.52
4:Guided walk (1.5Hz)	0.73/0.65/0.70	0.73/0.64/0.70	0.58/0.39/0.55	0.37/0.17/0.34
5:Guided walk (1.75Hz)	0.72/0.64/0.71	0.72/0.63/0.71	0.61/0.46/0.59	0.49/0.30/0.45
6: Guided walk (2.0Hz)	0.65/0.56/0.64	0.65/0.56/0.64	0.61/0.49/0.60	0.59/0.47/0.58
7: Guided walk (2.25Hz)	0.62/0.54/0.62	0.62/0.54/0.62	0.59/0.49/0.60	0.58/0.48/0.58

accurate than M3 and M4 in extending SFT. However, sensitivity of the extension accuracy to the gait parameters (i.e. the extension parameter) remains an issue for M1 and M2. Besides, most previous experimental work only recorded SFT and didn't record the gait parameter, such as in the traditional force-plate-only experiment where kinematic data were not available which, in turn, necessitates the other extension methods like M3 and M4. Consequently, it is essential to analyze the parametric sensitiveness of M1 to M4 and to determine appropriate extension parameters for them.

Since M1 to M4 all rely on single extension parameter, we then varied the extension parameter of each method within a range of ±10% and accordingly extended the footfall trace of all test subjects again by the four methods. For instance, the extension parameters of M1 for 1.5Hz walking test were 1.35, 1.3875, 1.425, 1,4625, 1.5, 1.5375, 1.575, 1.6125 and 1.65 Hz. For each parameter variation level, Table 3 shows the average value of correlation coefficients for the seven test cases of all the test subjects. Figs. 13 and 14 show the variation of correlation coefficients γ with computation parameters in the x and z directions, respectively. It is clear from Table 3 that M1 and M2 are sensitive to the extension parameter. The correlation coefficient is reduced to 0.26 and 0.25 for 10% parameter variation for M1 and M2. Based on the above results, it is recommended that when M1 or M2 is utilized for extension, the gait parameter (step frequency or stride time) should be accurately recorded and its measurement error is better controlled within 5%.

Table 3 Variation of the correlation coefficient with extension parameters

Parameter variation	Correlation coefficient (*z/x/y*) (average value of 7 test conditions)			
	Method I	Method II	Method III	Method IV
-10%	0.16/0.08/0.14	0.34/0.14/0.27	0.49/0.32/0.45	0.39/0.24/0.35
-7.5%	0.25/0.08/0.20	0.47/0.28/0.42	0.51/0.35/0.48	0.43/0.27/0.40
-5%	0.36/0.14/0.27	0.61/0.50/0.60	0.54/0.39/0.52	0.46/0.31/0.43
-2.5%	0.50/0.31/0.42	0.70/0.64/0.71	0.56/0.42/0.55	0.49/0.34/0.47
0	0.65/0.55/0.63	0.64/0.55/0.62	0.59/0.45/0.58	0.51/0.37/0.50
2.5%	0.70/0.64/0.71	0.50/0.32/0.43	0.61/0.48/0.60	0.53/0.39/0.52
5%	0.62/0.52/0.62	0.37/0.15/0.28	0.63/0.51/0.63	0.54/0.40/0.52
7.5%	0.49/0.32/0.46	0.27/0.09/0.21	0.64/0.53/0.64	0.54/0.40/0.52
10%	0.38/0.18/0.31	0.19/0.08/0.16	0.65/0.55/0.66	0.53/0.39/0.51

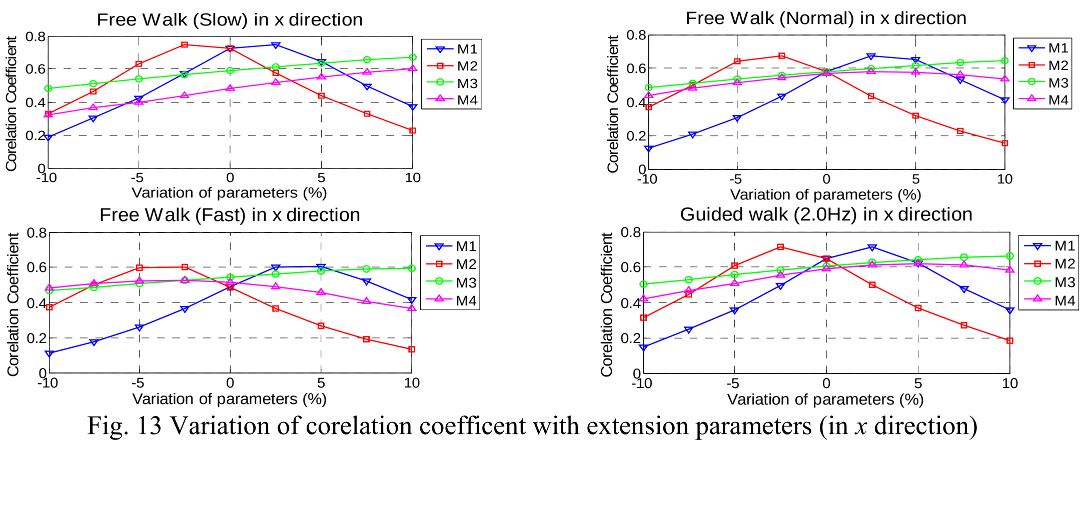


Fig. 13 Variation of corelation coefficent with extension parameters (in x direction)

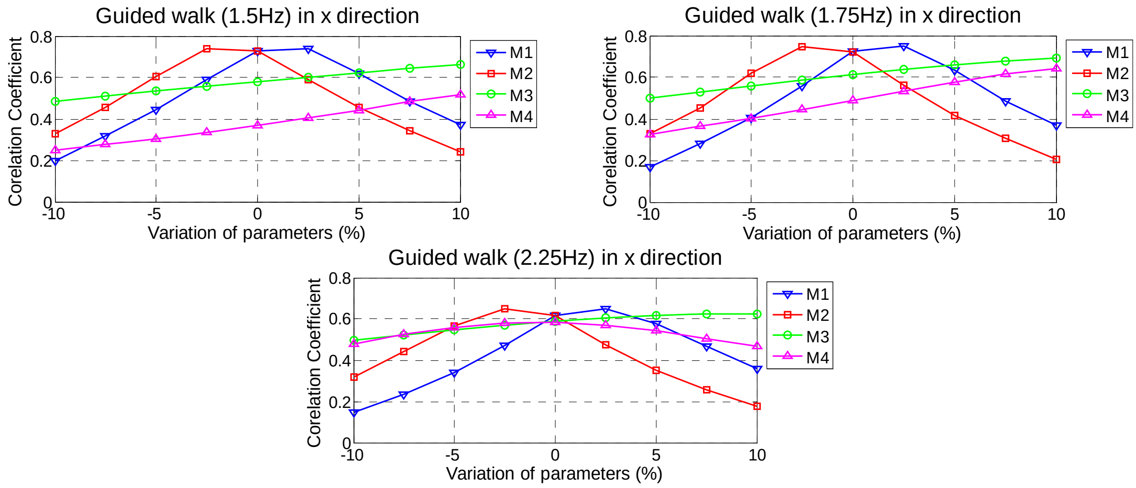


Fig. 13 Continued

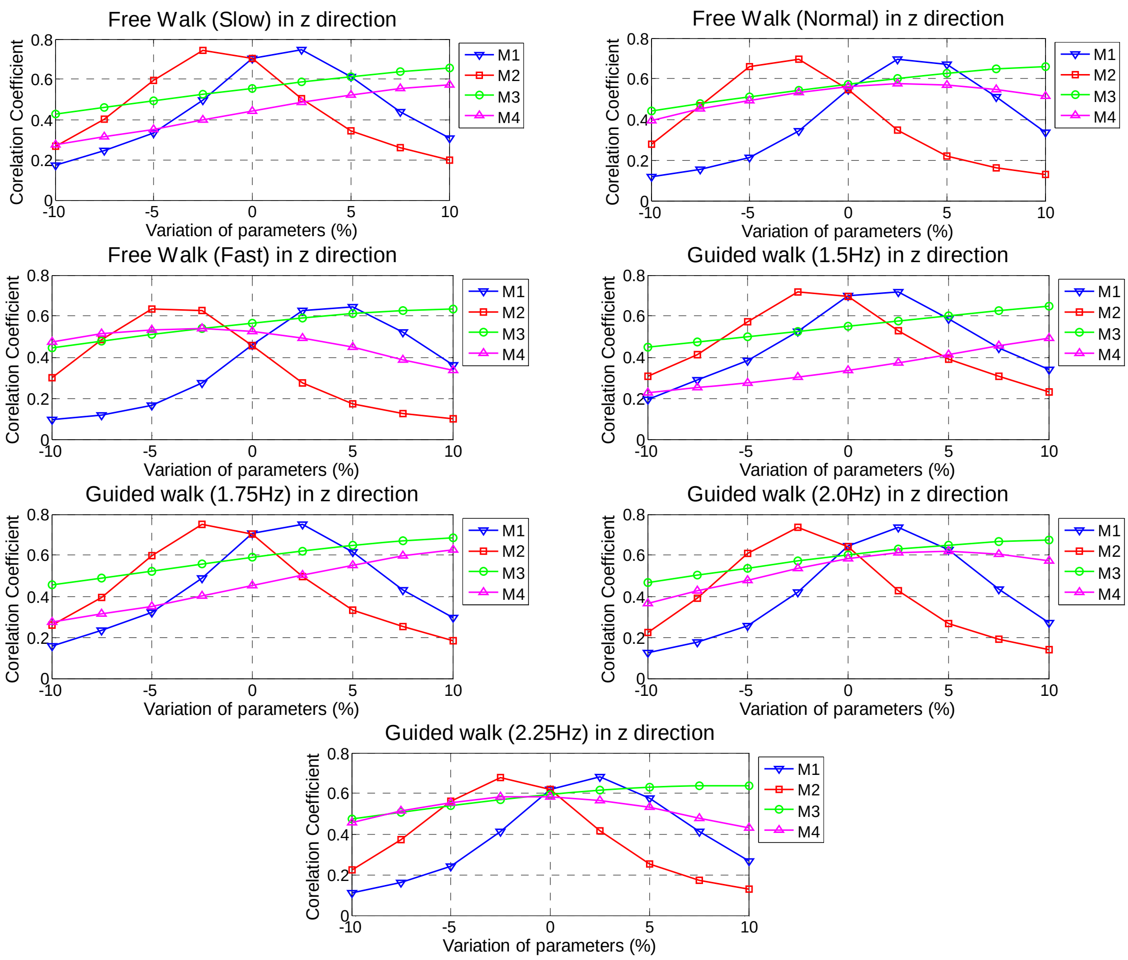


Fig. 14 Variation of corelation coefficent extension parameters (in *z* direction)

5.2 Recommended calculation parameter for M3

Table 3 demonstrates that M3 and M4 are also sensitive to the extension parameter. However, compared to M1 and M2, M3 and M4 seem to be relatively robust to parameter variation. Table 4 shows the statistical results of the double support time and double support portion for all subjects of different cases. In our experiment, the double support proportion was found to be 22.76% on average, and the double support time was 0.2344 sec on average. Also it is clear that the double support portion is approximately constant for all test cases. The independency of double support portion from walking rate was also reported in Ebrahimpour *et al.* (1996). If we take the double support proportion/2 = 22.76%/2 = 11.38% as the extension parameter for M3 and double support time/2 = 0.2344s/2 = 0.1172 sec as the parameter for M4, we calculate the correlation coefficients again, and the results are illustrated in Table 5. Note that with the recommended extension parameters the correlation between the extended traces and reference traces have been improved, especially for test cases with fixed walking frequency.

6. Conclusions

This study investigates the performance of four methods (Method I to IV) of extending the

Table 4 Statistical results of double support time and double support proportion

Test Condition		Total valid cases	Double Support Time		Double Support Proportion	
			Mean	Standard Deviation	Mean	Standard Deviation
Free Walk	Slow	376	0.2586	0.0496	0.2374	0.0343
	Normal	363	0.2139	0.0448	0.2214	0.0393
	Fast	344	0.1849	0.0870	0.2142	0.0901
Guided Walk	1.5Hz	374	0.3007	0.0473	0.2389	0.0331
	1.75Hz	381	0.2576	0.0355	0.2335	0.0303
	2.0Hz	371	0.2222	0.0352	0.2249	0.0343
	2.25Hz	367	0.2029	0.0315	0.2234	0.0348

Table 5 Correlation coefficient determined by suggested parameters

No. Test Conditions (pace rate)	Previous parameter: Double Support Time0.2s for M4; Double Support Proportion20% for M3		Suggested parameter: Double Support Time0.2344s for M4; Double Support Proportion22.76% for M3	
	Method III	Method IV	Method III	Method IV
1:Free walk (Slow)	0.59/0.41/0.56	0.48/0.29/0.44	0.69/0.56/0.68	0.57/0.40/0.55
2:Free walk (Normal)	0.58/0.46/0.57	0.57/0.44/0.56	0.65/0.56/0.67	0.57/0.44/0.56
3:Free walk (Fast)	0.55/0.46/0.57	0.51/0.42/0.52	0.60/0.52/0.63	0.42/0.32/0.41
4:Guided walk (1.5Hz)	0.58/0.39/0.55	0.37/0.17/0.34	0.69/0.57/0.67	0.47/0.27/0.44
5:Guided walk (1.75Hz)	0.61/0.46/0.59	0.49/0.30/0.45	0.70/0.60/0.70	0.60/0.45/0.58
6: Guided walk (2.0Hz)	0.61/0.49/0.60	0.59/0.47/0.58	0.67/0.58/0.68	0.62/0.51/0.61
7: Guided walk (2.25Hz)	0.59/0.49/0.60	0.58/0.48/0.58	0.62/0.53/0.63	0.52/0.39/0.50

single footfall trace, from parameters such as step frequency, stride time, double support proportion and double support time respectively, into a continuous force curve that can be used as load for floor vibration serviceability analysis. Because the duration of a single footfall trace is very short, the extension result is very sensitive to the method and its corresponding parameter. The following conclusions are drawn based on the observations in this study.

(1) The double support duration in a stride is the key factor for the extension of a single footfall trace. The more accurate the double support duration is, the better the extension result will be.

(2) Among all the four extension methods, Method I and Method II perform better than Method III and Method IV for all the cases considered. However, the sub-harmonic feature in the footfall traces cannot be reproduced by any of the four methods due to the assumption of perfect bilateral symmetry and repeatable walking process.

(3) When temporal-spatial gait parameters such as step frequency or stride time are known with high accuracy, Method I or Method II is recommended. In practical application, the two parameters can also be indirectly acquired from other gait parameters such as stride length, walking speed, etc.

(4) When kinematic data is absent in the experiment, Method III is recommended, and the double support proportion is suggested to be 22.76%, based on the experimental data in this study.

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