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CHARACTERISATION OF WALKING LOADS FROM INERTIAL MOTION TRACKING

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Abstract. *A 3D inertial motion tracking technique, originating from the movement science and entertainement industry, is applied for the analysis of the walking behaviour of pedestrians. The experiments in laboratory conditions simultaneously register the ground reaction forces and the motion of the test-subject. Based on this registered motion, the main step frequency and stride-to-stride variations are identified. The ground reaction forces are subsequently simulated using a step-by-step load model available in literature. It is shown that accounting for the identified imperfect walking behaviour of the test-subject leads to a significantly improved agreement between measured and simulated ground reaction forces.*

1 INTRODUCTION

Contemporary footbridges are often designed as slender structures and tend to be susceptible to human induced vibrations [1, 2]. The mathematical load models used in the vibration assessment of these structures, are based on the traditional direct force measurements utilising a force plate and instrumented treadmill. Since human-structure interaction and pedestrian-synchronisation modify the walking behaviour and hence the pedestrian-induced forces, they are assumed only to be justifiable in case of structures which do not vibrate perceptibly [3].

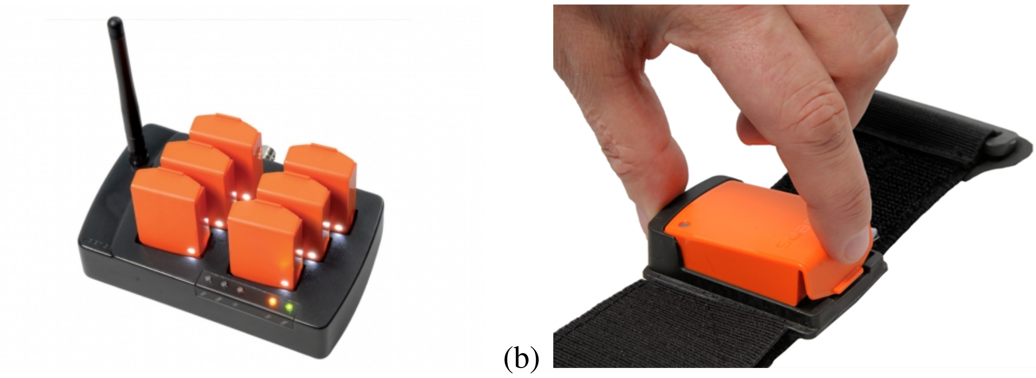
More recently, visual motion tracking systems are applied to help understanding the human motion and the resulting forces. Research in biomedical sciences uses technologically advanced tools, such as VICON [4] and CODA [5]. These techniques enable to study the human motion in laboratory conditions but a remaining challenge is the analysis of the walking behaviour of pedestrians and crowds *in situ*. In view of this challenge, the authors see great potential in a 3D motion tracking technique originating from the movement science and entertainment industry. The present contribution limits itself to the demonstration of the possibilities of the technique in laboratory conditions.

The experiments are performed in the MALL (Movement & posture Analysis Laboratory Leuven) at the Department of Biomedical Kinesiology and Rehabilitation Sciences of KU Leuven [6]. The motion of the test-subject and the measured ground reaction forces are registered simultaneously. The walking behaviour is analysed and the ground reaction forces are simulated using a step-by-step load model available in literature for which the characteristics are determined based on the registered movement of the body segments.

The outline of this paper is as follows. First, the 3D motion tracking technique is presented. Second, the experiments in laboratory conditions are discussed. Third, the walking behaviour of the test-subject is analysed considering both treadmill and overground walking. The final section presents the comparison between the simulated and measured ground reaction forces.

2 3D Motion Tracking

The Xsens - MTw Development Kit measurement system consists of multiple wireless inertial units (MTw's - figure 1), incorporating 3D accelerometers, gyroscopes, magnetometers (3D compass) and a barometer (pressure sensor). The accompanied ©Awinda radio protocol ensures time synchronization among the MTw's across the wireless network. The sensors are securely fixed onto the test-subject with specially designed click-in full body straps (figure 1b). The objective is to identify the main characteristics of the walking behaviour from the motion of the pedestrian tracked by the MTw's, enabling to accurately simulate the human induced forces.



(a) (b)

Figure 1: ©Xsens - MTw Development Kit consisting of multiple wireless inertial units (MTw's) and specially designed click-in full body straps.

3 Experiments in laboratory conditions

The experiments in laboratory conditions are considered to study the relation between the accelerations of the body segments and the measured ground reaction forces. The experiments are performed in the MALL (Movement & posture Analysis Laboratory Leuven) at the Department of Biomedical Kinesiology and Rehabilitation Sciences of the KU Leuven [6].

The positions of the MTw sensors are determined taking into account the recommendations of the manufacturer with the objective to limit the influence of skin motion artifacts which can occur with all forms of human movement measurement systems [7]. Using the click-in body straps, the Xsens MTw's are fastened tightly and robustly to the skin. Figure 2 illustrates the configuration setup applied in laboratory conditions. This setup consists of six sensors: on the lateral side of each leg, one sensor is placed close to the ankle and another on the thigh; the fifth sensor is placed as close as possible to the gravitational point of the test subject (at the small of the back) using the pelvis belt and the sixth sensor is placed at the upper back with the body strap fastened right under the armpits. The sampling frequency of the MTw's was set to 60 Hz, as recommended by the manufacturer for a configuration of 6 sensors.

The accelerations registered near the ankles of the test subject are assumed to be very strong due to the large movement of these body segments including both the impact and sway of one leg. The sensors at the lower and upper back on the other hand, will gather information about the global walking behaviour of the test subject. Analysis of the tracked motion and the corresponding registered ground reaction forces will reveal from which body segments the main characteristics of the walking behaviour can be identified.

3.1 Ground reaction forces

The experiments consider both treadmill and overground walking. The ground reaction forces are registered by an instrumented split-belt treadmill (*Forcelink*) and three *AMTI force plates* that are integrated in the walkway (Figure 3). The sampling frequency of both systems is 1 kHz.

The main advantage of the treadmill technology is that it allows identifying stride-to-stride variations [3]. The applied protocol considered a measurement time of 2 min for each walking speed which resulted in the registration of about 200 steps for each trial. The test-subject considered herself to be an experienced treadmill user and sufficient time was provided to get used to each treadmill speed. In total, 8 walking speeds were considered, varying from 2.5 up to 6.0

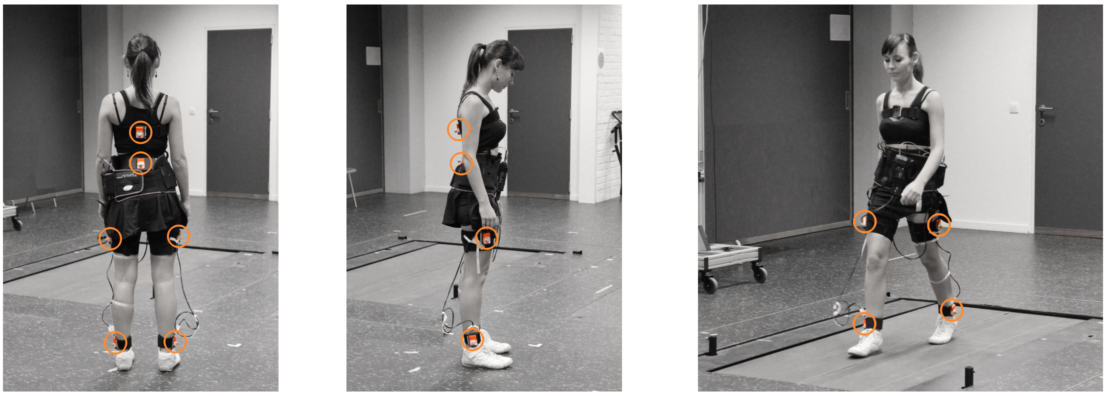


Figure 2: Configuration setup of the wireless inertial units (MTw's) in laboratory conditions.

km/h.

In case of overground walking, the different trials considered normal (self-selected), slow and fast walking. Since the laboratory floor has 3 force plates integrated in the walkway (figure 3), two successive steps could be registered for each path and at least 4 steps were taken before and after crossing the plates. In total, 24 successful steps were registered for each walking speed.

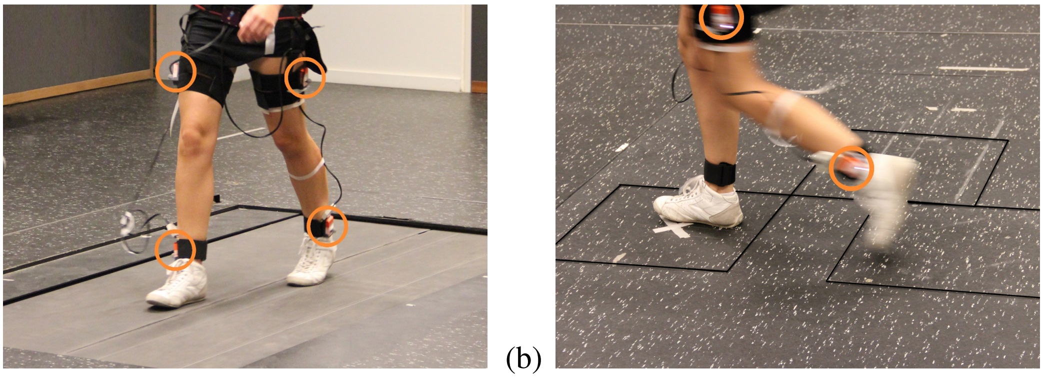
(a)  (b)

Figure 3: Measurement of ground reaction forces (GRF's): (a) instrumented split-belt treadmill (*Forcelink*) and (b) three *AMTI force plates* integrated in the walkway (the borders of the plates are artificially accentuated).

Figure 4 presents two successive steps registered by the force plates together with the single-sided amplitude spectrum of a single step. This figure illustrates that the main frequency content of the induced forces is found below 10 Hz. Figure 5 presents the ground reaction forces registered by the instrumented treadmill. To minimise the influence of instrumental noise and moving parts of the treadmill [8], a cutoff frequency of 12 Hz is applied (figure 5b).

4 Analysis of treadmill and overground walking

In this section, the registered accelerations of the selected body segments are studied in relation to the measured ground reaction forces.

Figure 6a and 6b show that the frequency content of the sum of the vertical forces and the ones of the measured acceleration levels of the lower back respectively, are highly similar. The

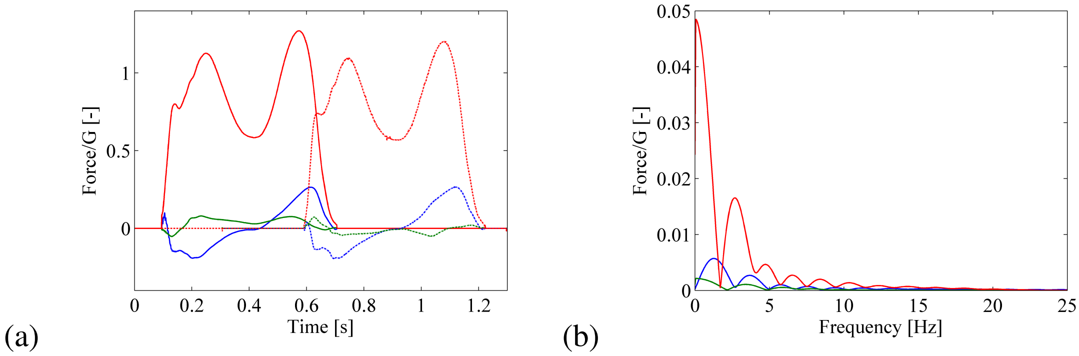


Figure 4: (a) ground reaction forces registered by the *AMTI force plates* with a sampling frequency of 1 kHz for a normal walking speed and (b) corresponding Fourier series coefficients of a single step: longitudinal (blue), lateral (green) and vertical (red) component.

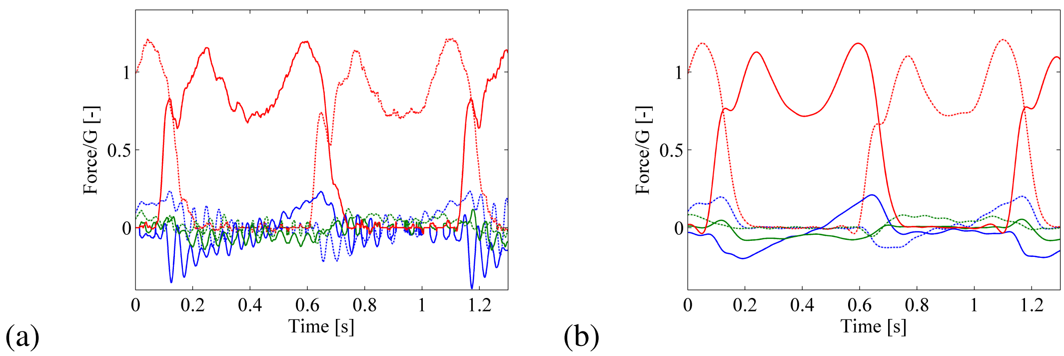


Figure 5: Ground reaction forces for a normal walking speed of 5 km/h, registered by the instrumented split-belt treadmill: (a) original signal with a sampling frequency of 1 kHz and (b) low-pass filtered using an eighth order Chebyshev type I filter with a cutoff frequency of 12 Hz: longitudinal (blue), lateral (green) and vertical (red) component.

fundamental frequency of these spectra represents the main step frequency of the test-subject during the treadmill trial. Analysis of the measured ground reaction forces and the registered lower back accelerations of all trials, covering different walking speeds, shows that the same step frequency is in this way identified up to $\pm 0.1\%$.

The accelerations measured near the ankles are very strong due to the large movement of these body segments that include both the impact and sway of one leg. Analysis showed that the magnitude of the total acceleration vector enables in this case a clear interpretation. Figures 7 and 8 present the ground reaction forces, the acceleration levels registered at the lower back and the magnitude of the total acceleration vector measured near the ankles. The signals are normalised respectively to the weight of the test-subject, the gravitational constant and the mean peak value. These figures illustrate that both the acceleration levels at the lower back and at the ankles, enable to identify the time in between two successive steps, and therefore, the pacing rate of the test-subject.

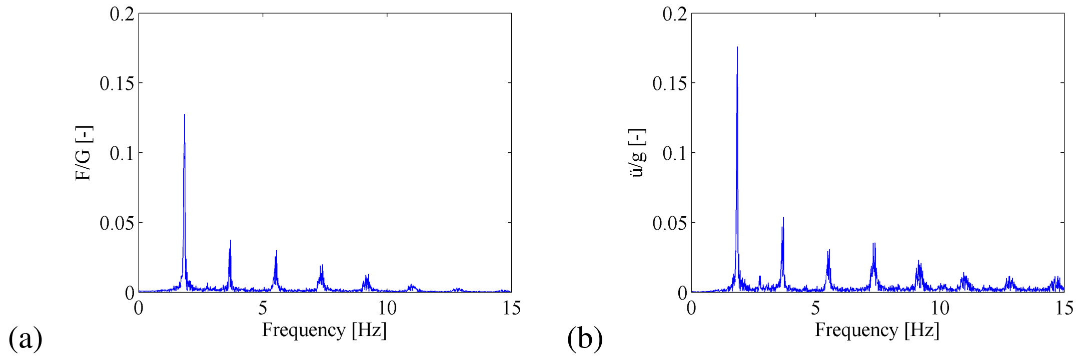


Figure 6: Fourier series coefficients up to 15 Hz of (a) the sum of the vertical ground reaction forces registered by the instrumented split-belt treadmill (*Forcelink*) for a normal walking speed of 5 km/h and (b) the corresponding measured vertical acceleration levels at the lower back.

5 Simulation of the ground reaction forces

In this section, the measured vertical ground reaction forces (GRF) are simulated using a step-by-step load model available in literature for which the characteristics are determined based on the registered movement of the body segments. To include the stride-to-stride variations of the human-induced forces, the results of the treadmill experiments are applied.

First, the mean step frequency of the test-subject is determined for the considered treadmill trial based on the analysis in the frequency domain of the accelerations measured on the lower back. This step frequency along with the static weight of the test-subject, determines the vertical single foot force F_1 [N] as defined by Li *et al.* [9]:

$$F_1(t) = G \sum_{n=1}^{5} A_n\left(f_s\right) \sin\left(\frac{\pi n}{T_c\left(f_s\right)} t\right), \qquad 0 \leq t \leq T_c\left(f_s\right) \tag{1}$$

with G [N] the static weight of the test-subject, f_s [Hz] the step frequency, $A_n\left(f_s\right)$ [-] the Fourier coefficient of the n^{th} harmonic, and $T_c\left(f_s\right)$ [s] the time duration of contact between the foot and the ground. The ratio of the cycle of the single foot force to the period during which the foot has contact with the ground is basically unchanged [10]:

$$T_c = \frac{1}{0.76 f_s} \tag{2}$$

Secondly, the accelerations measured near the ankles (or at the lower back) are applied to determine the beginning of each step in time (t_i). Subsequently, the corresponding force due to step i in time is found as:

$$F_i(t) = \kappa\left(t - t_i\right) F_1\left(t - t_i\right), \qquad \text{with} \quad \kappa\left(t\right) = \begin{cases} 1 & 0 \leq t \leq T_c \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

with t [s] the general time of the considered treadmill trial. Together, this collected time information and mean step frequency, provide the necessary input to simulate the measured ground reaction forces based on the generalised vertical single foot force of Li *et al.* [9].

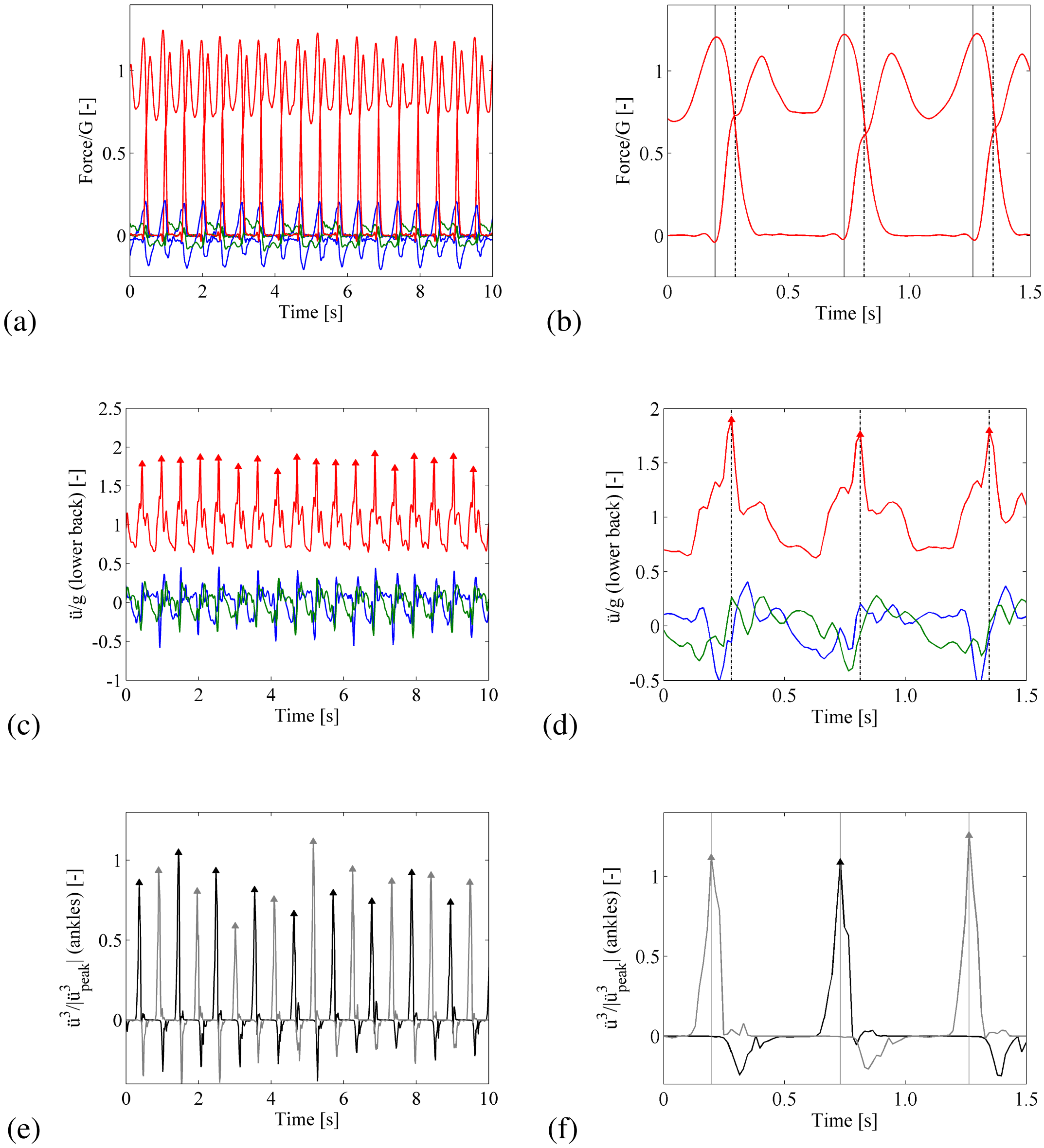


Figure 7: For a normal walking of speed of 5 km/h: (a-b) normalised ground reaction forces registered by the instrumented split-belt treadmill and (c-d) normalised measured accelerations at the lower back for the longitudinal (blue), lateral (green) and vertical (red) component. (e-f) normalised magnitude of the total acceleration vector measured near the left (black) and right (gray) ankle.

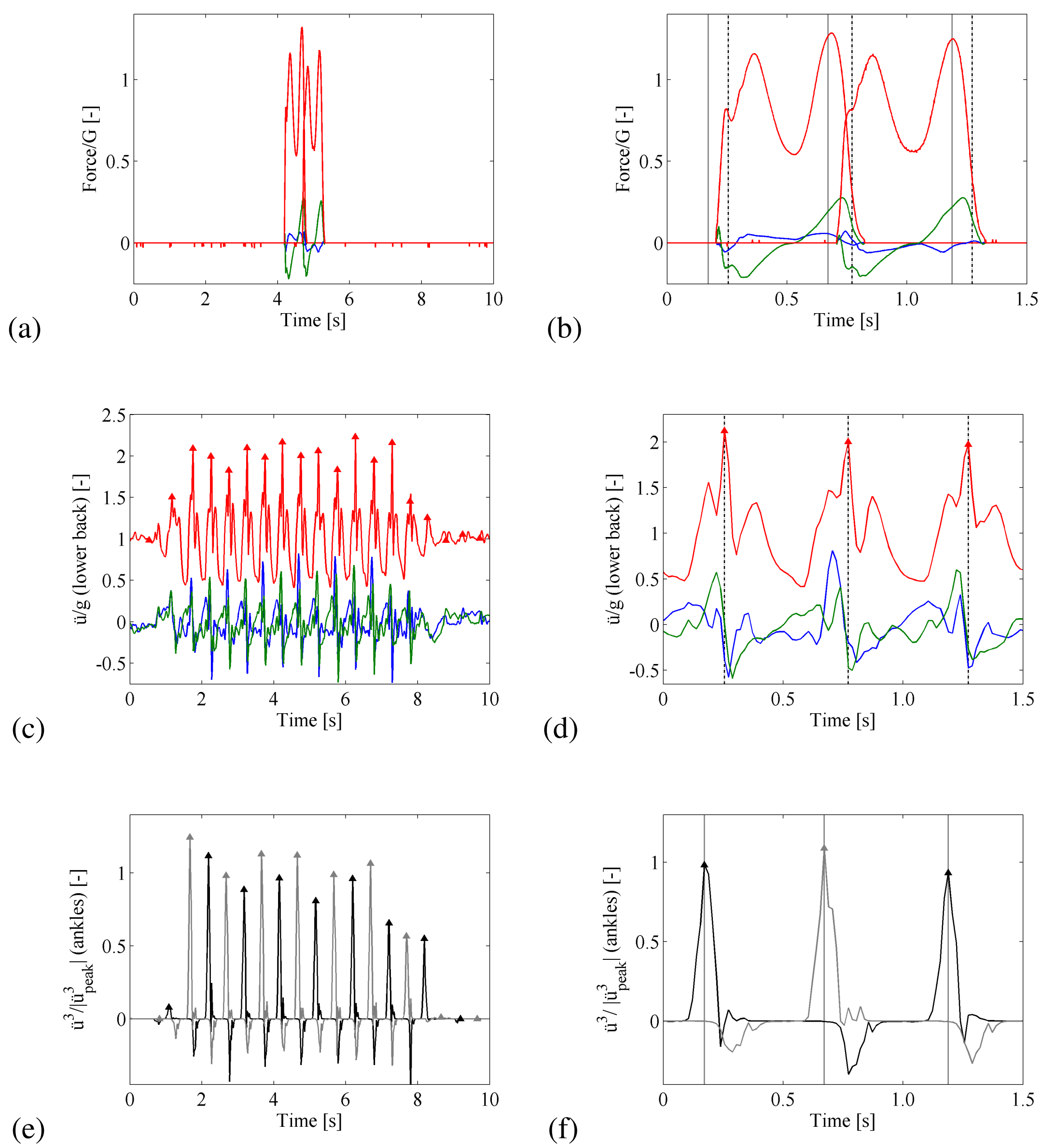


Figure 8: For a normal walking of speed: (a-b) normalised ground reaction forces registered by the *AMTI force plates* and (c-d) normalised measured accelerations at the lower back for the longitudinal (blue), lateral (green) and vertical (red) component. (e-f) normalised magnitude of the total acceleration vector measured near the left (black) and right (gray) ankle.

Figure 9 shows that there is a difference between the simulated vertical single foot force of Li *et al.* [9] and the measured forces. This difference could be minimized using the averaged vertical single foot force of the test-subject for the corresponding walking speed, however, it is expected that the simulated vibration response is more sensitive to the variations of the pacing rate for successive footfalls, than to the small variations in force amplitude or contact time, which was also observed by Middleton [11]. Figure 9 illustrates that the beginning of each step, and therefore also the pacing rate, can be accurately estimated from the measured accelerations of the ankles. The same results (with a certain time-shift) are found for the analysis based on the measured accelerations at the lower back.

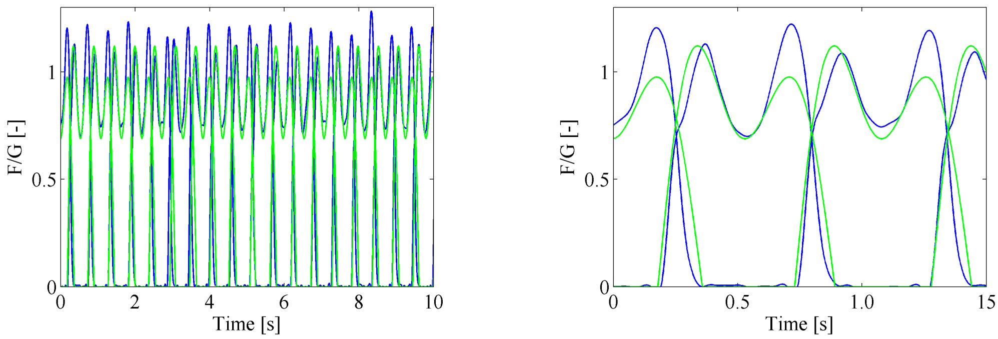


Figure 9: The measured vertical ground reaction forces for a normal walking speed of 5 km/h (blue) and the corresponding simulated vertical walking forces according to Li *et al.* [9] with step frequency and time in between two successive steps identified based on the tracked motion of the body segments of the test-subject (green).

Figure 10 presents the single-sided amplitude spectrum of the simulated and measured ground reaction forces. For the simulated forces, two cases were considered. In case 1, perfectly periodic forces are generated simply based on the identified mean step frequency. In case 2, the simulations account for the identified pacing rate. Figure 10 illustrates that the perfectly periodic forces only succeed in identifying the dominant harmonics of the walking forces. Imperfect real walking forces are however near-periodic by nature [12] and result into a distribution of forces around the dominant harmonics [13, 14]. These narrow band forces are clearly present in the measured forces but also in the simulated forces that account for the identified pacing rate. This comparison shows that simulations based on the generalised single foot force model and the in situ identified pacing rate, allow for a good approximation of the GRF in case of imperfect real walking.

6 Conclusions

A 3D motion tracking technique is presented for the analysis of the walking behaviour of pedestrians. The technique is applied in laboratory conditions and it is shown that it enables to identify the main step frequency and pacing rate of the test-subject. Applying a generalised model for the ground reaction forces available in literature, together with the weight of the test-subject and the identified pacing rate, provides a good approximation of the imperfect real walking forces.

The major advantage of the presented technique is its applicability for the in situ analysis of the walking behaviour of (groups of) pedestrians and crowd. The time synchronisation

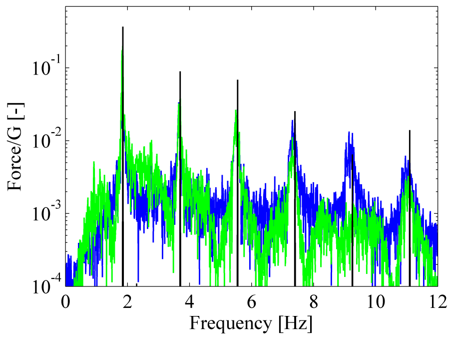


Figure 10: The Fourier series coefficients of the measured vertical ground reaction forces for a normal walking speed of 5 km/h (blue) and the corresponding simulated vertical walking forces according to Li *et al.* [9] with main step frequency f_s and pacing rated identified based on the tracked motion of the body segments of the test-subject (green) and the perfectly periodic forces with the identified main step frequency and the time in between two successive steps equal to $1/f_s$ (black).

among the inertial sensors will also enable to study the synchronisation rate among the different test-subjects. The application in situ and the simultaneous registration of the movement of pedestrians and the structure, will contribute to a better understanding of the normal walking behaviour, the resulting forces and the observed crowd-structure interaction phenomena.

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