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Measurement of the transmission of vibration to the trunk and to the pelvis during locomotion

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Systematic Review

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Abstract

Lumped parameter mathematical models have been developed to represent body motions associated with resonances of the vertical apparent mass in different postures. This research determines primary and secondary resonances, first and second damping ratio of the human body, during walking, from measured frequency response functions at S_2 and T_2 levels of the human spine. [DOI:10.12866/J.PIVAA.2014.03.001] [1]

Keywords: Human body vibration, Human spine, Frequency response functions

1 Introduction

Studies of human walking generally concentrate on the most obvious aspect of gait, namely, movement of the lower extremities and connecting pelvis. Less attention is paid to motion of the pelvis and trunk. Walking is a natural daily behavior that induces trunk and pelvis perturbations.

The aim of this investigation is to assess the use of skin–mounted accelerometers in measuring the in vivo transmissibility of the spinal column in healthy subjects during normal walking. The hypothesis that the spine may be a shock absorbing is tested over a wide range of age groups. While the subject is walking at a speed of 12 km/h, the vibration can be acquired by measuring the accelerations at the base S_2 of the human spine and at the thoracic region T_2. The most important aspect of this research consists on detection of primary and secondary resonances, first and second damping ratio of the human body, during walking, from measured frequency response functions at S_2 and T_2 levels of the human spine.

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2 Synthesis of the published studies

Waters et al. proposed two separate experiments [Waters et al., 1973]. In the first, displacement was directly measured by transducers attached to subjects walking on a treadmill. In the second, acceleration was directly measured by accelerometers attached to subjects walking along a straight course. Five normal subjects in this part of the experiment were males between the ages of 23 and 32. Accelerometers measuring vertical and progression acceleration were attached to the posterior midline at S_2, T_{10}, and the head. Lateral accelerations were not measured due to artifact from transverse rotations of the head and trunk. Each subject walked along a straight 15 m linoleum path at 70 steps/min, 90 steps/min and 120 steps/min, representing slow, comfortable and fast walking speeds. These step frequencies were chosen in order to achieve walking speeds comparable to the treadmill speeds previously selected. Figure 1 and Figure 2 indicate max fore acceleration and max aft acceleration. The accelerations are greatest at the sacrum and progressively decreased at higher levels. At the sacrum, forward acceleration reaches 0.38 g's and backward acceleration reaches 0.35 g's. At faster walking speeds, greater accelerations occur at all levels. As a result of fore and aft acceleration, the head and trunk do not move forward at a constant speed. After push–off, the forward velocity increases 23 cm/sec and after heel strike, decreases 15 cm/sec at the sacrum. These velocity changes also progressively decrease at higher levels.

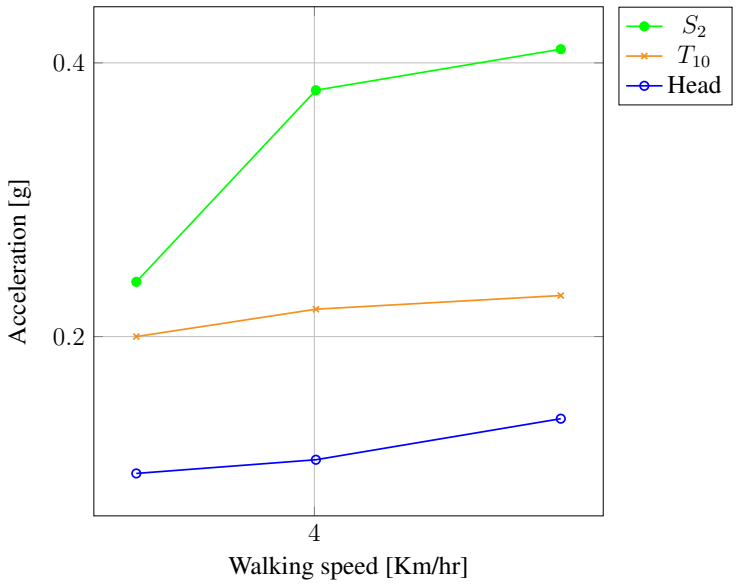

Figure 1: Max fore acceleration

Smeathers proposes a method for measuring the transmissibility of the human spinal column to vertical vibrations using light–weight, skin–mounted accelerometers [Smeathers, 1989]. The accelerometers are attached to the skin at the S_2 and T_2 levels of the spine using adhesive tape. In order to calculate the amplitude for each frequency component up to 40 Hz, the acceleration time records were analysed using a discrete Fourier transform. The ratio of the output over the input for each frequency component is the transmissibility. The analysis includes a compensation for both skin movement and differences in the inclination of the spine from the vertical at the accelerometer mounting sites. The healthy spine attenuates frequency components above 20 Hz, whereas in ankylosing spondylitis the spine seems a rigid structure.

The purpose of the study of Hirasaki et al. was to obtain quantitative information about the relationship between stride length, stepping frequency, and head and trunk coordination during

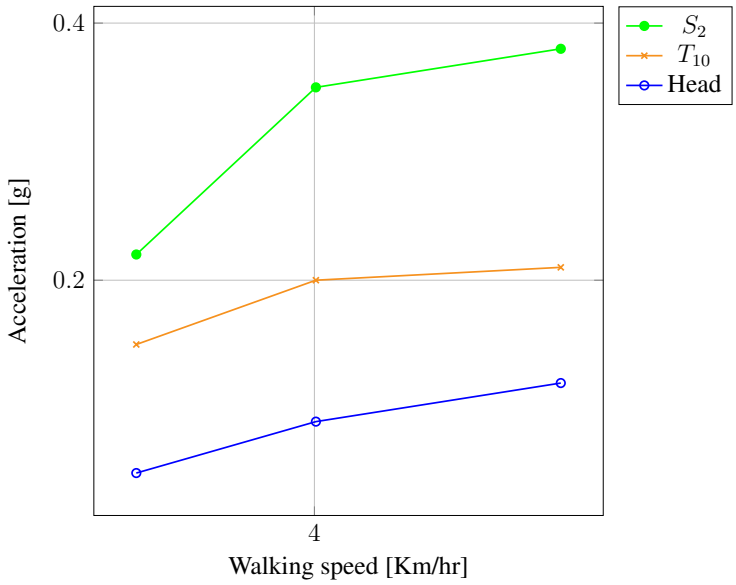

Figure 2: Max aft acceleration

walking over a wide range of walking velocities with a fixed target distance [Hirasaki et al., 1999]. Changing walking velocities could also give a clearer picture of the motor mechanisms for head movements and their relationship to trunk motion during natural locomotion. The results of this study indicate that the predominant frequency of trunk translation increased with walking velocity and ranged from 1.4 to 2.5 Hz (Fig. 3).

A three dimensional model of the human body is used to simulate a maximal vertical jump [Anderson and Pandy, 1999]. The human body is modeled as a 10–segment, 23 degree–of–freedom, actuated by 54 muscles. The study analyses muscle coordination during whole–body movement.

It is commonly accepted that an elevated risk of health impairment is given by long–lasting exposure to whole body vibration of high intensity. Mainly, the lumbar spine and the connected nervous system are affected. This risk is demonstrated for vertical vibrations of sitting operators, a lower health risk is assumed for the standing operator. This minor risk seems to be due to the damping properties of the legs which reduce reaction forces to the ground during walking or running. The fundamental frequencies of the forced oscillations are low at these movements. The aim of the study of Fritz is to develop a biomechanical model which includes especially the legs as active elements so that the imitated, vibration–stressed operator can stand on the feet. [Fritz, 2000].

The model of Menz is a useful approach for the analysis of walking stability in clinically relevant populations such as older people, people with diabetic peripheral neuropathy and people with vestibular impairment. Analyzing acceleration patterns of the head and pelvis during normal level walking in healthy adults, the study evaluates the effect of an irregular surface on basic gait parameters and head and pelvis accelerations when walking. By reducing their walking speed, young healthy adults are able to successfully maintain head and pelvis stability when walking on an irregular surface. The consistency of head accelerations between the level and irregular surface conditions suggests that the control of head motion may be a fundamental goal of the postural control system. [Menz et al., 2003]

Resonances in the apparent mass and transmissibility to the spine and pelvis in the fore–and–aft and vertical directions are analyzed in the research of Nawayseh and Griffin[Nawayseh and Griffin, 2003]. Their results show that the vertical apparent mass of the human body exhibits a primary

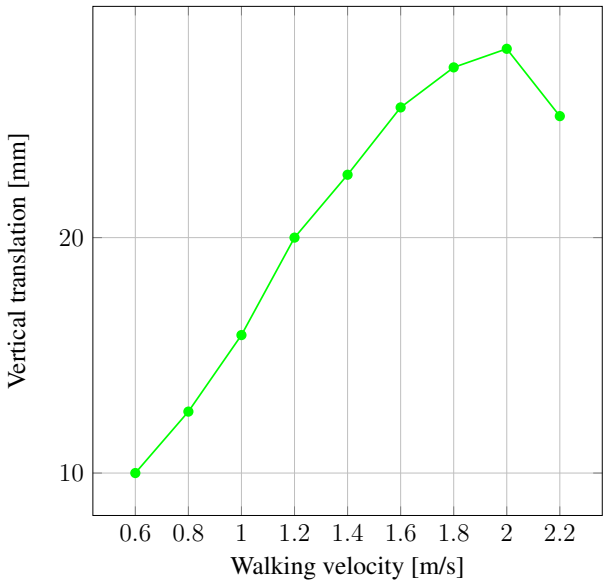

Figure 3: Amplitude of vertical translation of trunk

resonance at about 5 Hz.

For most subjects (both male and female) the lumbar region of the spine exhibited a significantly higher dynamic impedance and stiffness when compared with the thoracic region [Keller et al., 2000].

Estimating biomechanical parameters, related to the cinematic chains of the lower limbs during training, is based on evaluation of the vertical component of an athlete's acceleration in a squat jump [Innocenti et al., 2006].

The purpose of Levine and other Authors is to measure lumbar spine position in the sagittal plane during standing, walking, and running on level, uphill, and downhill surfaces. Understanding the amount of motion through which the spine moves will help us to develop return–to–activity protocols and prevent injury based on how much motion is desirable and which lumbar position(s) the athlete should avoid [Levine et al., 2007].

Accelerometry is a technique for quantifying movement patterns during walking [Kavanagh and Menz, 2008]. Accelerometry can provide accurate and reliable measures of basic temporospatial gait parameters, shock attenuation, and segmental accelerations of the body when walking, thereby providing useful insights into the motor control of normal walking, age–related differences in dynamic postural control, and gait patterns in people with movement disorders.

It is demonstrated that uphill walking and running produced an overall decrease in lumbar spine position and that downhill walking and running produced an overall increase. Alterations in the lumbar spine occur depending on the gradient of the running surface [Ramirez et al., 2013].

With reference to impact–related shock during walking, the results of an important research indicate that the amplitude of the low–frequency component of an acceleration signal during gait is dependent on knee and ankle joint coordination behaviour [James et al., 2014].

3 Method

With reference to Fig. 4, the approach consists on the following phases:

- Experimental investigation

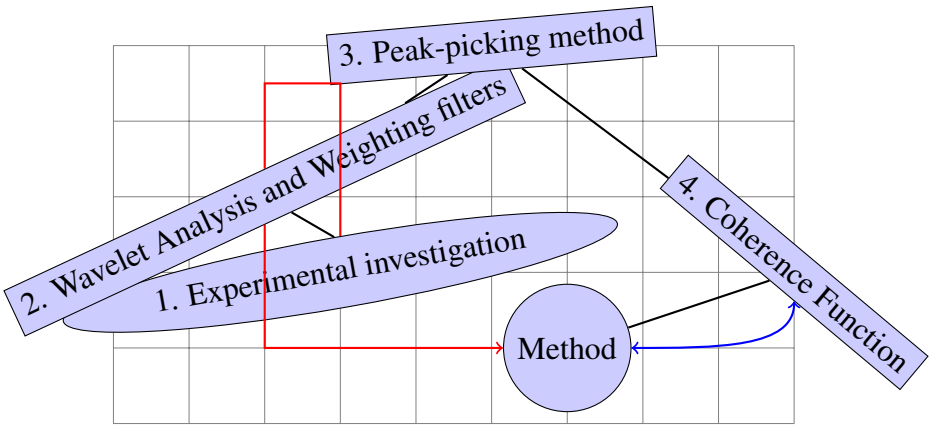

Figure 4: Phases of Method

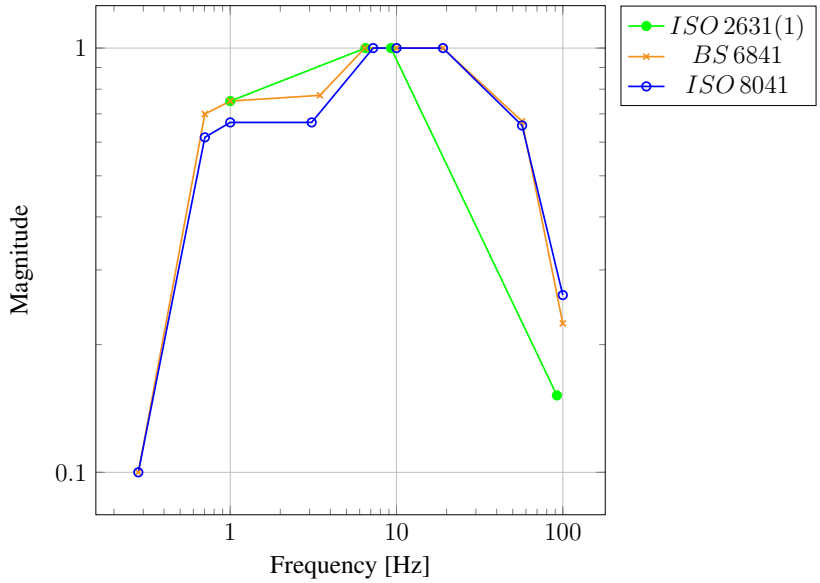

Figure 5: Comparison of gain response of the weighting filters for vertical Z–axis seat acceleration

- Wavelet Analysis and Weighting filters
- Peak–picking method
- Coherence function

3.1 Experimental investigation

The aim of this investigation is to determine the transmissibility of the spinal column to the self–generated impulses of heel strike during walking. The magnitude of the impulse is acquired at the base S_2 of the spine. The impulse is transmitted from the base of the spine to the thoracic region T_2. The impulse can be acquired by measuring the accelerations at the base S_2 of the spine and at the thoracic region T_2.

Accelerometers are put on the skin at the T_2 and S_2 spinal levels. The accelerometers are aligned with the long axis of the spine and with the most sensitive axis as near vertical as possible

and in the sagittal plane.

At S_2 and T_2 spinal levels small piezo–electric triaxial accelerometers are used (type BOSCH BMA 220) bwith acceleration range 16 g.

While the subject is walking at a speed of 1.8 ± 0.4 Hz, the slope of the body contours to the vertical is controlled at the S_2 and T_2 mounting sites. The angle from the vertical is used to adjust for differences in the slopes between the two sites S_2 and T_2 . Differences of these angles, during locomotion, can not be accounted for by this technique. The accelerometers are connected via short screened cables to battery–operated pre–amplifiers. The signals were then carried to the data collection system via a trailing screened cable.

Transmissibility was calculated over the frequency range of 0–20 Hz. Then the justments for skin resonance and slope are applied to calculate the transmissibility function, damping ratio and damped frequencies of the human spine. The subjects invited in this pilot study are in the age range 17–56 years. They are of lean build to minimize the effects of skin movements. The subjects were asked to walk in bare feet to maximize the impulse and avoid anomalies due to different footwear.

3.2 Wavelet Analysis and Weighting filters

Wavelets analysis offers a powerful tool for the task of signal denoising. The ability to decompose a signal into different scales is very important for denoising, and it improves the analysis of the signal significantly. For ISO 2631–1 alternative weightings are implemented by fast convolution, with the same magnitude response as the standard filters but with a flat phase response over all frequencies.

For BS 6841 and ISO 2631–1 alternative weightings were implemented by fast convolution, with the same magnitude response as the standard filters but with a flat phase response over all frequencies. The gain and phase responses of the weighting filters for vertical z–axis seat acceleration are compared in Figure 5.

3.3 Peak–picking method

The procedure of the pick–picking method is:

1. *Estimating the natural frequency*. The natural frequency of the *r*th mode selected for analysis is identified from the peak value of the FRF

$$|\alpha_r(\omega)|_{max} \Rightarrow \omega_r = \omega_{peak} \ . \tag{1}$$

2. *Estimating damping*. The half power points at ω_a and ω_b are located first from each side of the identified peak with amplitude $\alpha_{max}/\sqrt{2}$. The damping ratio can be estimated from the width of the resonance peak as

$$\zeta_r = \frac{\omega_b - \omega_a}{\omega_r} \ . \tag{2}$$

3.4 Coherence function

The study of two signals, recorded simultaneously at S_2 and T_2 levels of the human spine, is a very interesting task. When the system under consideration is a part of human body and we record signals related to the activity of some organ, it can also provide a diagnostic value.

Coherence function is based on Fourier transform. Word *coherence* is from the Latin word *cohaerentia*. It means natural or logical connection or consistency. The coherence function allows

us to find common frequencies and to evaluate the similarity of signals. However, it does not give any information about time domain.

Since coherence function is a frequency domain measure, it allows to find common frequencies in two signals and to evaluate the similarity of signals. Thus it can be useful in analyzing two simultaneously recorded biomedical signals and it can provide some diagnostic value.

The coherence function $\gamma_{XY}^2(\omega)$ is defined as the ratio of the squared modulus of the cross–spectral density function, $|S_{XY}(\omega)|^2$, to the auto–spectral density functions $S_X(\omega)$ and $S_Y(\omega)$

$$\gamma_{XY}^2(\omega) = \frac{|S_{XY}(\omega)|^2}{S_X(\omega)\, S_Y(\omega)} \,. \tag{3}$$

The coherence function provides a nondimensional measure of the linear dependence between $X(t)$ and $Y(t)$ at each frequency, similar to the correlation coefficient.It can be shown that the coherence function has values between 0 and 1:

$$0 \leq \gamma_{XY}^2(\omega) \leq 1 \,. \tag{4}$$

Values near 1 imply a linear relationship between $X(t)$ and $Y(t)$ at frequency ω. If $X(t)$ and $Y(t)$ are uncorrelated, their cross–correlation, cross–spectral density and coherence function are equal to zero.

4 Discussion

The human body is designed to move. It can move around in lots of different ways because human subjects have a certain amount of accessory motion or soft tissue mobility in every joint. If human subjects didn't have soft tissue mobility then human subjects could only move in one way.

Fourier analysis of the acceleration time traces for both walking demonstrates that the main frequency components for impulses passing along the spine are lower than 40 Hz. Over this frequency range, the normal spine seems to be able to attenuate frequencies above 20 Hz.

These results show that a healthy spine is able to attenuate frequencies as low as 20 Hz. The mobility of the normal spine in bending provides an optimal mechanism for absorbing shock loads.

This technique was primarily developed to assess the shock absorbing properties of the spinal column, but it also has potential as a diagnostic tool for assessing patients with low back pain caused by degenerative changes to the spine. However, in its present form the whole procedure takes about 15 minutes per subject, and so would not be appropriate for routine use. The transducers are easily fixed to the skin.

As a research technique it has proved to be flexible and informative, providing data on the transmission of physiological levels of vibrations through the human body. It has applications for assessing the transfer function across other joints, for example the attenuation of heel strike transients between the ankle and pelvis. This method would also be amenable for investigating the effect of corsets, physiotherapy or training exercises on the stiffness of the spine. Another potential use for this technique would be to study the effect of externally applied loads on the transmissibility of the spine, such as when carrying a rucksack, or lifting heavy items, particularly in an industrial environment where there may be exposure to severe vibrations.

Physical characteristics of subjects taking part in the experiments are summarized in Table 1. Body mass index (BMI) is a measure of body fat based on height and weight that applies to adult men and women.

While the subject is walking at a speed of 1.8 ± 0.4 Hz, the accelerations are acquired with sampling time $T = 0.02$ s. Wavelets analysis offers a powerful tool for the task of signal denoising.

Subject	Age [yr]	Weight [kg]	Stature [m]	BMI
Subject 1	56	68	1.70	24.1
Subject 2	46	54	1.75	18.7
Subject 3	20	78	1.80	24.1
Subject 4	17	68	1.70	23.5

Table 1: Physical characteristics of subjects

The vertical transfer response functions (FRFs), at S_2 and T_2 levels of the human spine, show a peak in the region of 4–5 Hz which corresponds to a sudden change in the phase function (Figures 6-11). This peak might correspond to the principal resonance of human body. This remark is in good agreement with the results obtained in the research of Nawayseh and Griffin [Nawayseh and Griffin, 2003].

The vibration mode at around 7–8 Hz may correspond to the second resonance of the FRFs (Figures 6-11). Also this remark could be in good agreement with as stated in the research of Subashi, Matsumoto and Griffin [Subashi et al., 2008]: *It was found that the principal resonance observed at* 4–5 *Hz was associated with motion of the entire body and that a second resonance at* 7–10 *Hz was associated with motion of the spinal column.* (Table 2)

The coherence function has been used to examine the relation between two signals, acquired at the S_2 and T_2 mounting sites. The coherence function is used to estimate the power transfer between at the S_2 and T_2 mounting sites.

It can be shown that the coherence must lie in the interval $[0, 1]$. When the random processes $X(t)$, acquired at S_2 level, and $Y(t)$, recorded at T_2 level, are completely uncorrelated at frequency ω (in a linear sense): $\gamma^2_{XY}(\omega) = 0$. When they are linearly related to one another, $\gamma^2_{XY}(\omega) = 1$.

By analyzing the coherence functions between the signals $X(t)$ and $Y(t)$, acquired at S_2 and T_2 levels of the human spine, the maximum energy transfer is recorded in the range 5–10 Hz in all subjects (Fig.14).

High values of the coherence functions are recorded in subjects 1 (Fig.14(a)), 2 (Fig.14(b)) and 4 (Fig.14(d)). For against in subject 3 coherence function assumes low values (Fig.14(c)).

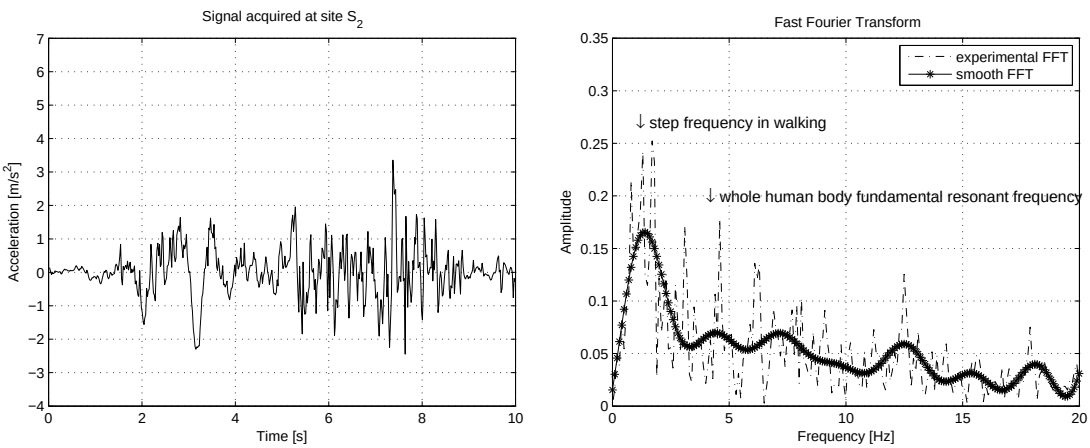

Figure 6: Time history and frequency response function at S_2 level of human spine of subject 1

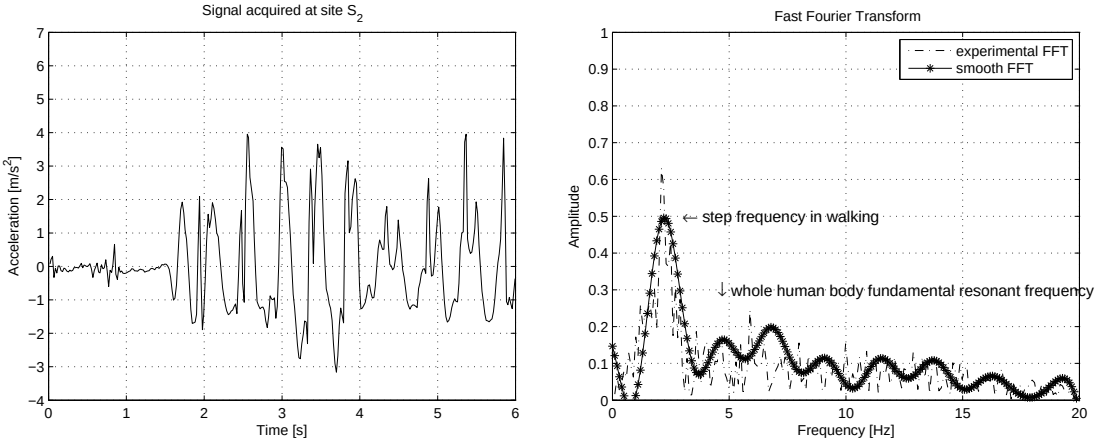

Figure 7: Time history and frequency response function at S_2 level of human spine of subject 2

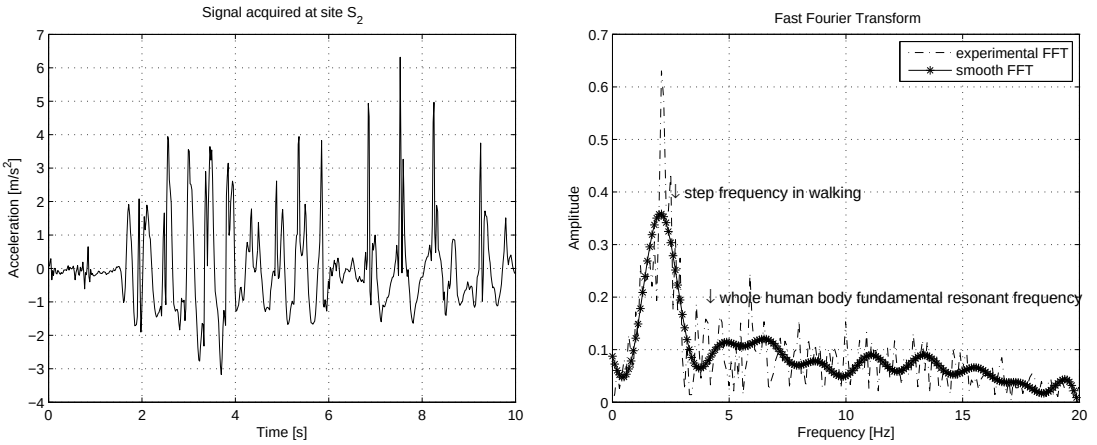

Figure 8: Time history and frequency response function at S_2 level of human spine of subject 3

5 Conclusion

The motion of the body associated with the resonances of the vertical frequency response functions of the standing human body is investigated by developing a model representing the standing body during walking. The distinctive feature of this process is to extract modal parameters (damped frequencies, damping loss factors) from measured vibration data. In the absence of significant external factors, humans tend to walk at about 1.8 ± 0.4 Hz. The peaks of damped resonances of the FRFs occur at 4–5 Hz for the principal resonant frequency and 6.5–7.5 for the secondary resonant frequency.

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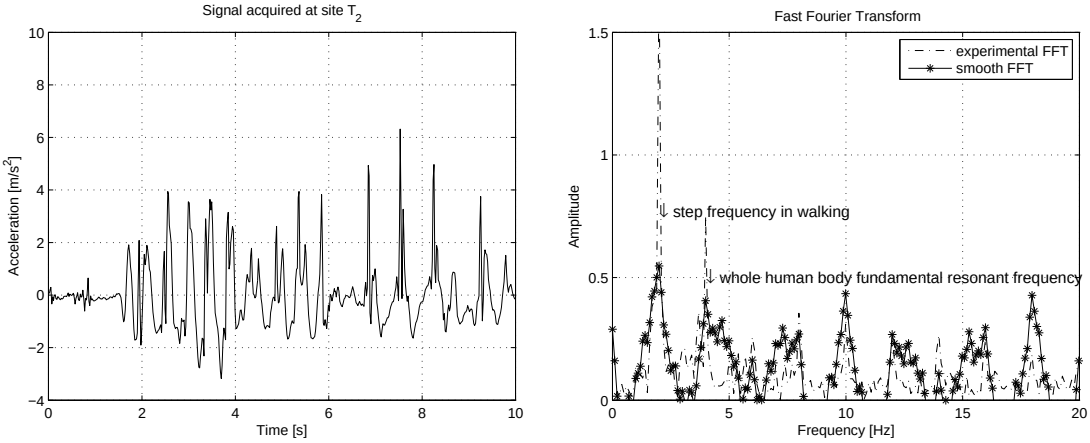

Figure 9: Time history and frequency response function at S_2 level of human spine of subject 4

		1st mode		2nd mode	
Subject	Step frequency in walking [Hz]	Fundamental resonant frequency [Hz]	Damping ratio	Secondary resonant frequency [Hz]	Damping ratio
1	1.4	4.5	0.24	7.2	0.19
2	2.2	4.8	0.17	6.8	0.12
3	2.1	4.9	0.21	6.5	0.21
4	2.0	4.0	0.27	7.3	0.17

Table 2: Modal parameters of whole human-body estimated at site pelvis level

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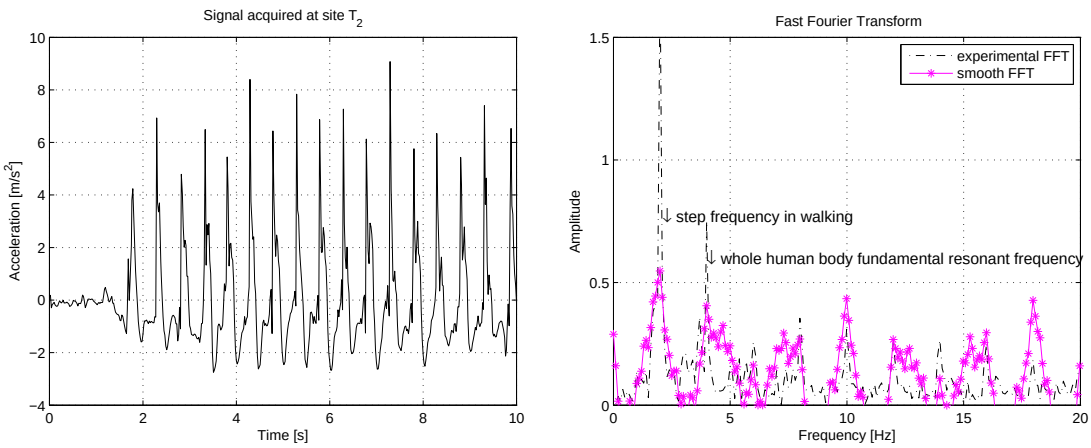

Figure 10: Time history and frequency response function at T_2 level of human spine of subject 1

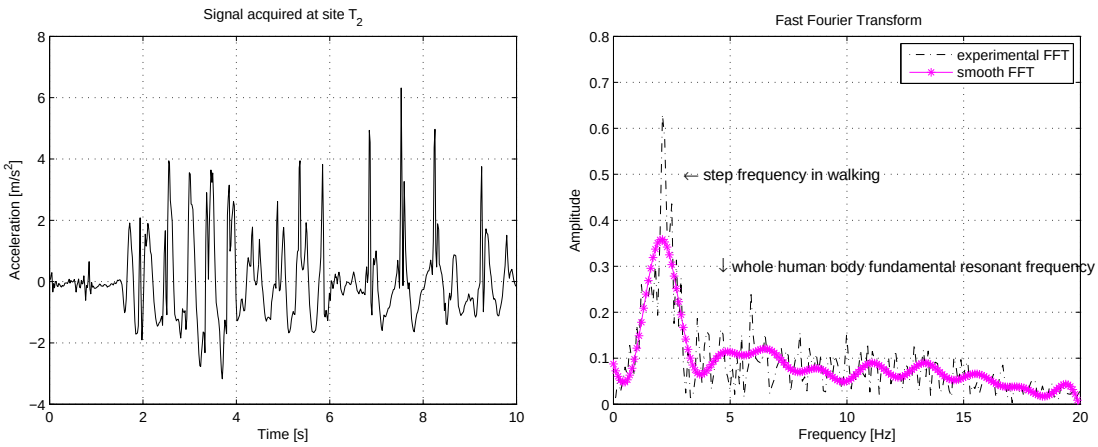

Figure 11: Time history and frequency response function at T_2 level of human spine of subject 2

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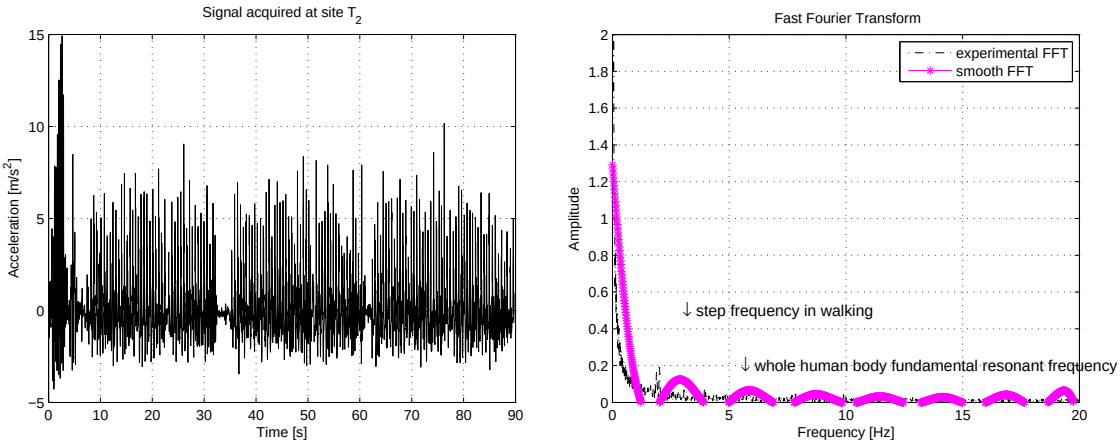


Figure 12: Time history and frequency response function at T_2 level of human spine of subject 4

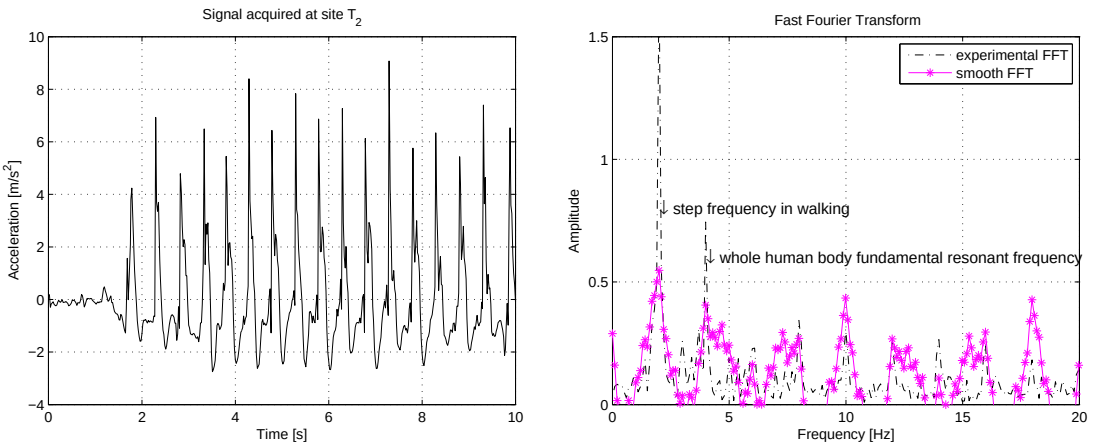
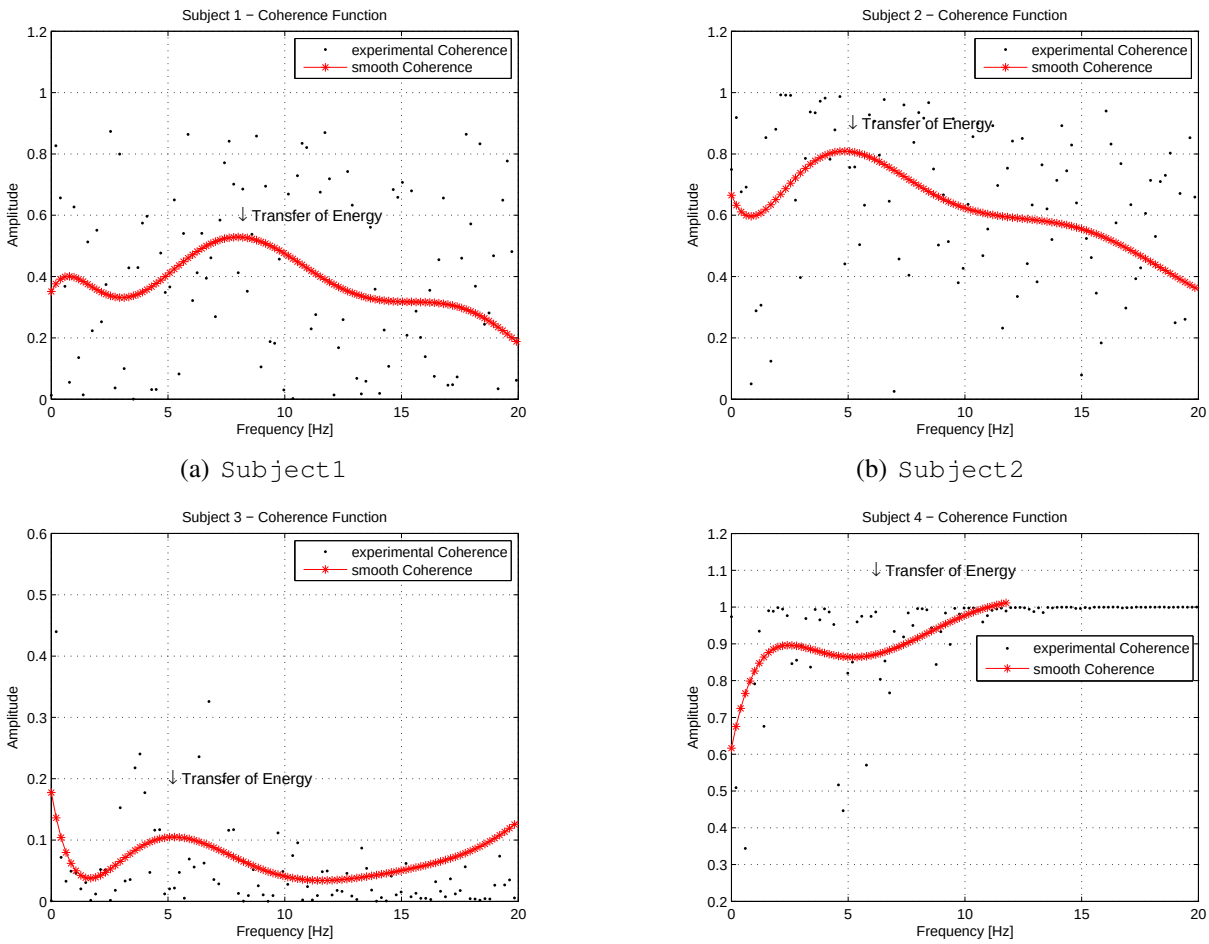


Figure 13: Time history and frequency response function at T_2 level of human spine of subject 4



(a) `Subject1` (b) `Subject2`

(c) `Subject3` (d) `Subject4`

Figure 14: Coherence Functions