Medical Engineering & Physics 35 (2013) 690–695

Contents lists available at SciVerse ScienceDirect

Medical Engineering & Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

Measurement of transmission of vibration through the human spine using skin-mounted inertial sensors

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ARTICLE INFO

Article history:
Received 10 May 2012
Received in revised form
12 December 2012
Accepted 27 December 2012

Keywords:
Spine
Physical activity
Inertial sensor
Skin
Vibration transmission

ABSTRACT

The purpose of this study was to examine the feasibility of measuring the transmission of vibration using skin mounted inertial sensors and to assess the dynamic properties of the human spine during activities of daily living. Two inertial sensors were attached to skin overlying the first thoracic vertebra (T1) and another one over the first sacral vertebra (S1) with double sided adhesive tape. Subjects walked along a straight line, and up and down stairs at a self selected, comfortable speed. Transmissibility of vertical vibration was calculated as the ratio of the power spectral density of the acceleration signal at T1 over that at S1, over the frequency range of 0.5–12 Hz. Cross correlation and coherence of the acceleration signals between the two T1 sensors were performed to evaluate the similarity of the data after correction. Cross correlation of signals between trials was also performed to examine the repeatability of the signals. Cross correlation coefficients were found to be very high (>0.9). Inter-trial consistency of the signals of all sensors was also high (>0.9). It is concluded that skin measurement of transmission of vertical vibration is feasible with the inertial sensors and correction method presented. Different physical activities seem to elicit different frequency characteristics of vibration.

1. Introduction

Vibration is an oscillatory motion with magnitude and repetition rate. The magnitude of vibration can be measured in terms of acceleration and frequency content through spectral analysis. The simplest type of vibration wave is a sine wave [1], but due to the characteristics of human gait, the human body is exposed to complex waves rather than simple sine waves. During gait, each impact of the heel with the ground produces transient waves that propagate up throughout the body [2,3]. Transmitted waves or vibration may be attenuated and amplified due to muscular contraction [4] and due to the intrinsic mechanical properties of the tissue through which this vibration is transferred. Accordingly, the shape of these stress waves is expected to change in the time spectrum as they are transmitted [2]. Transmitted waves up the lower limb during heel strike have not only vertical but also transverse components [2]. Through the movement of joints during gait, the vertical and transverse vibration travelling through the lower limbs is stored (resembling a spring) and dissipated (resembling a dashpot) [2]. The attenuation capacity of lower limbs has been investigated previously [5,6]. The human spine has multiple elements (bone, muscle, ligaments, tendons, cartilage) which may store, generate and dissipate energy [7]. It has been suggested that the spinal column has shock absorbing properties when subjected to mechanical shocks [8], whole body vibration devices [8] and while walking and running [9]. However, it may have different responses at different frequencies when exposed to random and complex waves produced during daily life activities. Assessment of the mechanical stimuli associated with daily life activities will allow us to develop an understanding of the effects of these activities on the musculoskeletal system.

The dynamic properties of the spine can be expressed in the frequency domain as the transmissibility of vibration from the sacrum to the upper end of the thoracic spine [10]. This vibration can be measured with accelerometers attached to the skin over bony prominences after performing corrections for the skin–sensor interface movement [11] and for the inclination of the sensor in relation to the vertical [9]. This method has been previously validated against pins inserted directly to bone [11–13]. Currently there is no strict guideline for the use of specific brands and models of accelerometers for the measurement of vertical human vibration transmissibility. Therefore the feasibility of performing this measurement has to be carefully tested with customized correction procedures (skin–sensor interface movement and sensor inclination).

The transmissibility capacity of the human spine has also been studied previously but not extensively during stair negotiation. The transmissibility of the human spine has been investigated during walking [9], running [9] and heel strike [14]. Smeathers

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http://dx.doi.org/10.1016/j.medengphy.2012.12.013

[9,14] attached one accelerometer over the second sacral vertebra and another over the second thoracic vertebra with adhesive tape. He calculated vibration transmitted through the spine by correcting for skin movement and sensor inclination in the sagittal plane using the accelerometers as inclinometers before subjects performed walking and running. The main limitation of this study was that a constant inclination angle of the trunk was assumed in determining transmissibility, although the spine orientation may change significantly during these activities [15]. Moreover, the description of vibration transmissibility measurements during daily life physical activities has not been performed rigorously but only through visual analysis of vibration transmissibility curves.

The present study will address the limitations of previous work and extend the transmissibility analysis to a wider range of daily activities. The purpose of this study was (1) to examine the feasibility of measuring the transmission of vibration through the human spine using skin mounted inertial sensors and (2) to assess the dynamic properties of the spine during activities of daily living. The effect of corrections will be objectively established. The measurement method will be employed to determine transmissibility through the spine during level ground walking along a straight line and during stairs ascent and descent.

2. Methods

Ten young and healthy subjects were recruited; individual details can be seen in Table 1. Subjects were excluded if they had experienced back or leg pain in the last 12 months that required medical treatment, rheumatological disorders, dislocation, fracture or surgery of the spine or lower limbs, neurological disorders which affected their gait and if they were obese (with a body mass index greater than 29 kg/m^2). All subjects underwent a Broad Ultrasound Attenuation test to determine their bone mineral density. This test was performed using a Quantitative Ultrasound Scanning (QUS) system (CUBAClinical, McCue Plc.) with dedicated software (CUBA Plus, McCue Plc.). Left and right heel bones (calcaneus) were tested in order to identify the heel with the lowest *T*-score. QUS results expressed in terms of the *T*-score and World Health Organization guidelines [16] were used to select only those subjects with normal density (*T*-score > −1). Subjects were excluded if they had osteopenia or osteoporosis (*T*-score < −1). Selection of healthy subjects was necessary in order to reduce biased results since the vibration transmissibility measurement is dependent on geometry (vertebrae) and material properties (soft tissue and bone). Ethical approval was given by University of Roehampton ethics committee (reference number: SS10/021). All volunteers gave informed consent by signing the approved consent form. No funding external to University of Roehampton was received to conduct this research.

Three inertial sensors (Wireless InertiaCube3^{TM}, InterSens Inc.) were put over three locations of the spine. Each inertial sensor had a weight of 20 g, an operating range of ±2 g and comprised of three dimensional accelerometers and gyroscopes, which were used to measure vertical acceleration and angular rotation of the sensor respectively. To evaluate the suitability of the inertial sensors for vibration transmissibility measurement, two inertial sensors were put side by side over the first thoracic spinous process (T1) allowing for each to move in their vertical direction without touching each other. These sensors recorded the output signals on two sides of the T1 vertebra. Each sensor being in a different location had a different source of error since the skin properties are diverse in different parts of the spine [14,17]. Thus the assessment of the similarity of these two output signals after signal correction helped to establish the effectiveness of the correction procedure. Another accelerometer was put over the first sacral vertebra (S1) to measure the input signals. All sensors were aligned with the sagittal plane of the spine (to be able to measure vertical acceleration) and attached to the subject's skin with double sided adhesive tape.

To correct for skin movement, all skin–sensor interfaces were subjected to "nudge" tests. This test assumes that the skin has a linear response thus it is represented by a single degree of freedom system [11]. The nudge test was repeated four times on each sensor to provide the best estimates of the correction parameters. During these tests subjects were asked to stand still and to look forward with arms by their sides in a relaxed and comfortable way. The test involved manual displacement of the skin above the sensor by approximately one centimetre in the vertical direction, followed by a quick perpendicular release of the finger performing the test [11]. All nudge tests were performed with the same finger and by the same investigator. Acceleration measured during this test leads to a free vibration response of the skin–sensor system, which allows the calculation of a damping factor (ζ) and natural frequency (f_n) [11]. These values are employed in the skin–sensor interface movement correction method which has been validated elsewhere [12,18]. Subjects were then asked to perform three activities three times at a self selected, comfortable speed: walk in a straight line (33 m in length and 2 m wide), ascend and descend standard stairs consisting of 15 steps of normal height and 1.19 m wide with a continuous hand rail on both sides. Vertical acceleration and dynamic sensor inclination were wirelessly stored in a laptop computer for each inertial sensor. Wireless timing gates (Smartspeed^{TM}, Fusion Sport Pty Ltd.) were used to measure the time that each subject took to complete each walking trial. These times were used to calculate average walking speed. A rest was given between trials to prevent fatigue.

Data was analysed using custom made scripts in Matlab (R2010b, Mathworks Inc.) and with SPSS statistical software (PASW Statistics 17.0, IBM Corp.). Raw sensor acceleration and angular rate signals were unevenly sampled by the software that the manufacturer provides for the inertial sensors (IsPlot 1.006, InterSens Inc.). Thus these signals were resampled at 110 Hz as well as low pass filtered at 20 Hz with a zero phase 5th order Butterworth

Table 1
Subjects details, individual and mean (SD).

Subject	Gender	Height (m)	Mass (kg)	BMI (kg/m^2)	*T*-score	Age
1	M	1.71	64.8	22.16	1.543	28
2	M	1.7	65	22.49	−0.237	27
3	M	1.64	54.95	20.43	−0.343	25
4	M	1.86	71.8	20.71	−0.807	32
5	M	1.74	66.75	21.92	−0.873	25
6	M	1.85	76	22.21	−0.227	25
7	F	1.55	53.3	21.96	−0.407	36
8	M	1.77	76.4	24.25	1.797	33
9	F	1.67	62.1	22.27	0.220	25
10	F	1.63	58.5	22.02	0.373	27
Mean (SD)		1.71 (0.09)	64.96 (8.08)	22.04 (1.03)	0.104 (0.91)	28.3 (3.97)