

Comprehensive measurement in whole-body vibration

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Accurate measurements of human response to whole-body vibration are essential to any conclusions about the health risks, discomfort, and assessment of suspension systems in vibration environments. While accelerometers are traditionally considered the main measurement tools in whole-body vibration studies, their measurements become questionable when they are attached to inclined surfaces or when the motion has coupled components in multiple directions. Current measurement correction methodologies are subjective and limited to simple cases. A comprehensive correction methodology using inertial sensors was used in this work to quantify human response under single fore-aft, single-vertical, and multiple-axis whole-body vibration of twelve seated subjects with supported-backrest and unsupported-backrest upright posture. Vibration files of white noise random signals with frequency content of 0.5–12 Hz and vibration magnitude of 1.8 m/s² RMS were used in the testing. The results have shown considerable differences in the transmissibility measurements without proper correction. The work presented has the potential to standardize experimentation in whole-body vibration and make measurements more accurate and defined across labs.

Keywords: accelerometry, measurement, transmissibility, inertial sensors, posture

1. INTRODUCTION

Traditional measurements in whole-body vibration (WBV) studies using accelerometers present an effective way to quantify human response to WBV [1]. However, due to practical reasons, accelerometer readings are prone to misinterpretations, which may affect the quality of the resulting biodynamic response measurement and may result in inconsistency in the collected data across different labs. Many researchers in the field [2–5] have found that the misalignment of the accelerometer due to the curvature of the human body and postural changes during the experiment can greatly alter the magnitude and frequency content measured. Correction schemes are normally applied to the accelerometer reading when it is attached to inclined surfaces [2–5]; however, these corrections are limited and would not be accurate with large postural changes or multidirectional motion.

Accelerometers normally measure the local acceleration at a point in the direction of motion; therefore, an accelerometer should be attached to the surface such that its local axis is aligned with the direction of motion. This process could be suitable for uni-axial input motion where the output and input points move approximately in the same direction. However, the latter process will introduce errors if the input and output points have motion components in multiple directions [6,7].

Recently, inertial systems have shown encouraging performance and wide applications with more systems capable of recording tri-axial linear accelerations, tri-axial angular velocities, and orientation in the global space. These sensors could be very beneficial to any multiple-axis WBV study where the sensor local coordinate

system can be related to the global coordinate system, making it possible to remove the gravity effect (G component) in the sensor and to investigate the relationship between the motions of any segments of the body without concern regarding their location and orientation in the space. However, inertial systems could be sensitive to the electromagnetic fields and may drift like traditional accelerometers with time.

The objective of this work is to introduce a comprehensive measurement correction methodology in single- and multiple-axis WBV to minimize acceleration measurement errors when dealing with inclined surfaces, coupled motion, or multidirectional motion. The effectiveness of the proposed methodology was demonstrated in terms of the seat-to-head and seat-to-C7 transmissibility of twelve seated subjects maintaining supported-back and unsupported-back upright posture during single-fore-aft, single-vertical, and multiple-axis WBV.

2. METHODOLOGY

2.1. GRAVITY COMPONENTS IN DC ACCELEROMETER MEASUREMENTS

The gravity component (G) in the DC accelerometers can be used for calibration purposes and when measuring inclination angles; however, it creates difficulties when the sensor is installed on inclined surfaces for the dynamic measurement of motions. For situations when the accelerometer is attached to a flat, horizontal plane (Figure 1a), the G component can be compensated for because it has no effect on the acceleration in the X -direction and can be subtracted from the vertical component of the acceleration if the motion is in the vertical direction. However, when the accelerometer is attached to inclined surfaces, as is the case with many locations on the human body, the G term will have components in both the X_L and Y_L directions of the acceleration and will become more significant as the angle (q) increases (Figure 1b). The problem becomes more involved if the accelerometer has two planes of inclination; in this case, the acceleration from gravity will have components in the X_L , Y_L , and Z_L directions.

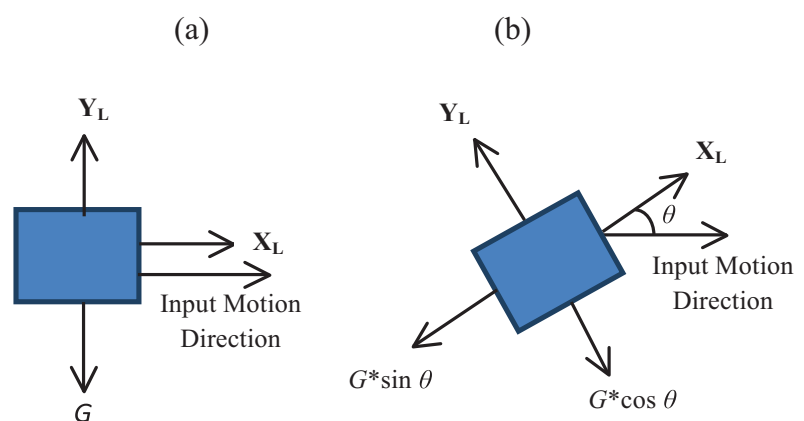


Figure 1. Orientation of accelerometer where X_L and Y_L are the local axes of the accelerometer where (a) the G component is easily known and (b) the G component depends on inclination angle θ .

The need for multiple accelerometers to resolve the complete kinematics of a body is a limitation that can be overcome once the local coordinate system of the accelerometer is known. Depending on the application, one may wish to know the acceleration measurement in either local or global space; however, the use of DC

accelerometers can present a problem if the measurement of gravity is not desired.

The inertial sensors have advantages over the traditional accelerometers due to their ability to provide additional information about the segment's kinematics. Each inertial sensor is comprised of 3D gyroscopes, 3D accelerometers, and 3D magnetometers, which give the sensor the ability to provide absolute orientation values, therefore making it possible to extract the real acceleration signal and isolate the gravity components. The inertial sensors used in this work, as one available inertial system, are MTx inertial trackers (Xsens Technologies, Enschede, Netherlands) in which the transformation matrix between the right-hand local coordinate system and a global system is defined as

$$\mathbf{R}_{L/G} = \begin{bmatrix} a^2 + b^2 - c^2 - d^2 & 2bc - 2ad & 2bd + 2ac \\ 2bc + 2ad & a^2 - b^2 + c^2 - d^2 & 2cd - 2ab \\ 2bd - 2ac & 2cd + 2ab & a^2 - b^2 - c^2 + d^2 \end{bmatrix} \quad (1)$$

where the unit quaternion $\mathbf{z} = a + b\mathbf{i} + c\mathbf{j} + d\mathbf{k}$ and $|\mathbf{z}| = 1$.

The contribution from gravity can be determined by multiplying the transformation matrix $\mathbf{R}_{L/G}$ with the magnitude of gravity (-9.81 in the global Z direction). The gravity contribution can then be removed from the inertial sensor's acceleration measurement in the local coordinate system, as shown in eqn 2.

$$\begin{bmatrix} \overline{A_{X_L}} \\ \overline{A_{Y_L}} \\ \overline{A_{Z_L}} \end{bmatrix} = \begin{bmatrix} A_{X_L} \\ A_{Y_L} \\ A_{Z_L} \end{bmatrix} + \mathbf{R}_{L/G} * \begin{bmatrix} 0 \\ 0 \\ G \end{bmatrix} \quad (2)$$

This calculation is performed at each time step of the sampling frequency, where A_{X_L} , A_{Y_L} , and A_{Z_L} are the local raw-acceleration components and $\overline{A_{X_L}}$, $\overline{A_{Y_L}}$, and $\overline{A_{Z_L}}$ are now the local accelerometer measurements where the gravity is removed.

Although the accelerometer measures are corrected without the gravity component present, its measurement is in its local coordinate system. If desired, the local coordinate system can be transformed to the global coordinate system as in eqn 3:

$$\begin{bmatrix} \overline{A_{X_G}} \\ \overline{A_{Y_G}} \\ \overline{A_{Z_G}} \end{bmatrix} = \mathbf{R}_{L/G}^{-1} * \begin{bmatrix} \overline{A_{X_L}} \\ \overline{A_{Y_L}} \\ \overline{A_{Z_L}} \end{bmatrix} \quad (3)$$

where $\overline{A_{X_G}}$, $\overline{A_{Y_G}}$, and $\overline{A_{Z_G}}$ make up the acceleration measurement in the global coordinate system with the gravity component removed.

2.2. PARTICIPANTS AND EXPERIMENTATION

Twelve male subjects participated in this study, with an average age of 23.1 ± 2.12 years, height of 184.15 ± 8.3 cm, and weight of 85 ± 14.58 kg. Subjects reported no

prior neck, shoulder, or head injuries nor any neurological conditions. Written informed consent, as approved by the University of Iowa Institutional Review Board, was obtained prior to testing. Subjects were asked to remain in an upright seated posture with and without backrest support for each 60-second vibration file. Files were run in the fore-aft direction (X) at 1.8 m/s² RMS, vertical direction (Z) at 1.8 m/s² RMS, and in multi-axis directions (3D) at 1.8 m/s² RMS resultant acceleration (1.04 m/s² in each single direction). Each subject was fitted with inertial sensors adhered to skin overlaying the C7 and to a head-worn halo, similar to a study by Wang and Rakheja [8]. An additional sensor was rigidly attached to the seat frame. Each inertial sensor had a mass of 30g and a contact surface area of 20 cm². Initial experimentations showed that the inertial sensor has a natural frequency around 25 Hz, which is outside the range of the frequency under consideration. Subjects were asked to maintain a normal sitting posture with and without the use of a backrest. The footrest was adjusted so that each subject's thighs were horizontal. Subjects were asked to avoid any involuntary movements.

3. RESULTS

3.1. VALIDATION OF INERTIAL SENSORS IN SIMULATED VIBRATION ENVIRONMENT

A test was performed in 3D vibration to show the validity of using the current inertial sensors (Figure 2) in WBV studies. The sensor was first tested using an off-axes testing apparatus in a multiple vibration environment. This arrangement allowed all three accelerometer axes to be off-alignment with respect to the global coordinate system (fore-aft, lateral, and vertical). The apparatus was attached rigidly to the shaking platform. A six-degree-of-freedom man-rated motion platform (the Moog-FCS 628 electrical system) was used for the test. For this dynamic vibration test, the shaker platform produced 3D random vibration for 15 seconds, and the data were recorded at 120 Hz. To verify the results, an additional traditional tri-axial DC accelerometer, Dytran 7523A1, Chatsworth, CA) was rigidly fixed to the shaking platform, aligned with the global coordinate system, and used as a baseline between the two systems.

The resulting acceleration components from the inertial sensor and traditional accelerometer test are depicted in Figure 3. It should be noted that the offset value of 9.81 was subtracted from the hard-mounted traditional accelerometer only in the Z direction. The output acceleration from the inertial sensor was transformed using the described methodology by first removing gravity (eqn 2) and then rotating to the global coordinate system (eqn 3). It can be seen that the inertial sensor signal follows very closely with the hard-mounted traditional accelerometer.



Figure 2. Testing block for dynamic vibration tests where all three sensor axes were rotated off-alignment from the global coordinate system. The testing block was rigidly attached to the motion shaker platform.

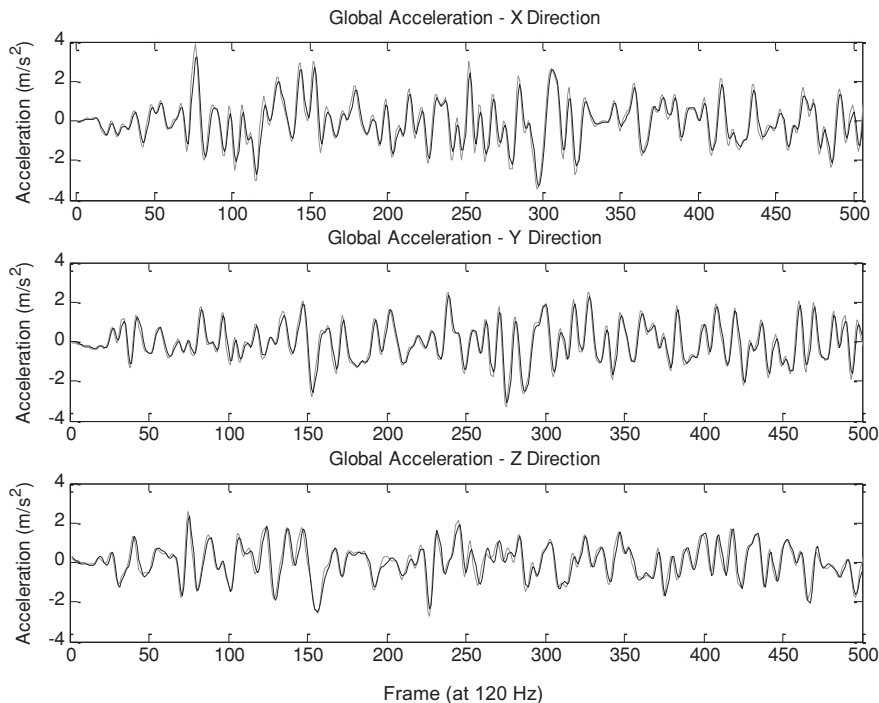


Figure 3. Comparison of inertial sensor accelerations (m/s^2) in 3D vibration on an off-axes testing block. The bold black line represents the acceleration signal of the accelerometer fixed to the shaking platform and aligned with the global coordinate system. The gray line represents the acceleration signal of the inertial sensor with the gravity component removed and the accelerations rotated to the global coordinate system.

3.2. WBV APPLICATION

After the initial validation step, the proposed system is tested in a real WBV testing environment. In this work, the transmissibility was calculated by taking the cross-spectral density of the output acceleration at a point on the subject's body and the input acceleration at the rigid seat, divided by the auto-spectral density of the input acceleration. The input motion directions are denoted as uppercase letters, while the output motion directions are denoted by lowercase letters. For example, the transmissibility for fore-aft input vibration and output vertical vibration would be denoted as X_z .

3.2.1. Single Fore-Aft WBV

Inertial sensors were adhered to each subject's skin at the C7 level and to the front of a head-worn halo, as shown in Figure 4. The sensor on the head remained at relatively the same orientation as the global coordinate system; however, the sensor placed at the C7 location resulted in a moderate angle with respect to the vertical direction (Figure 4c). Madaksahira [2] found this angle in a similar study to be greater than 30 degrees, regardless of the sitting posture. Matsumoto and Griffin [4] found an inclination angle of 20 to 35 degrees for the T1 vertebrae for a similar seated posture.

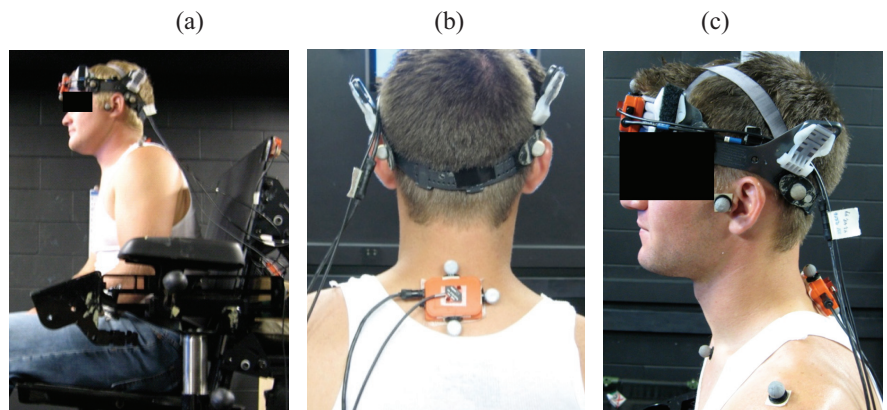


Figure 4. Seated posture and sensor setup for fore-aft and vertical WBV vibration test: (a) unsupported backrest posture; (b) posterior view of C7 inertial sensor; (c) side view showing the angle of tilt of the head and C7 inertial sensor.

Figure 5 compares the uncorrected (local) seat-to-head transmissibility to the corrected (global) seat-to-head transmissibility between the individual motion components for random fore-aft vibration during both backrest-supported (Figures 5a, 5b) and unsupported (Figures 5c, 5d) upright conditions. Because the orientation of the sensor is on the forehead and aligned very closely to the global coordinate system, only small differences can be seen between the corrected and uncorrected data.

When the orientation of the sensor is greatly misaligned with the global coordinate system, considerable errors are present (as in measurement at the C7 location). Figure 6a shows the uncorrected (local) seat-to-C7 transmissibility components for random fore-aft vibration in an unsupported-upright posture. Here major motion components are seen in both the X_x and X_z transmissibilities. Figure 6b shows the corrected (global) seat-to-C7 transmissibility and demonstrates the considerable errors with the uncorrected (local) measurement. In the global system, the main transmissibility component lies almost solely in the X_x directions. Similar

behaviors exist for the supported-back condition as shown in Figure 6c and 6d. However, as expected, the transmissibility based on the global system has shown observable contribution in the Xz component (Figure 6d) due to the pitching motion of the head and neck.

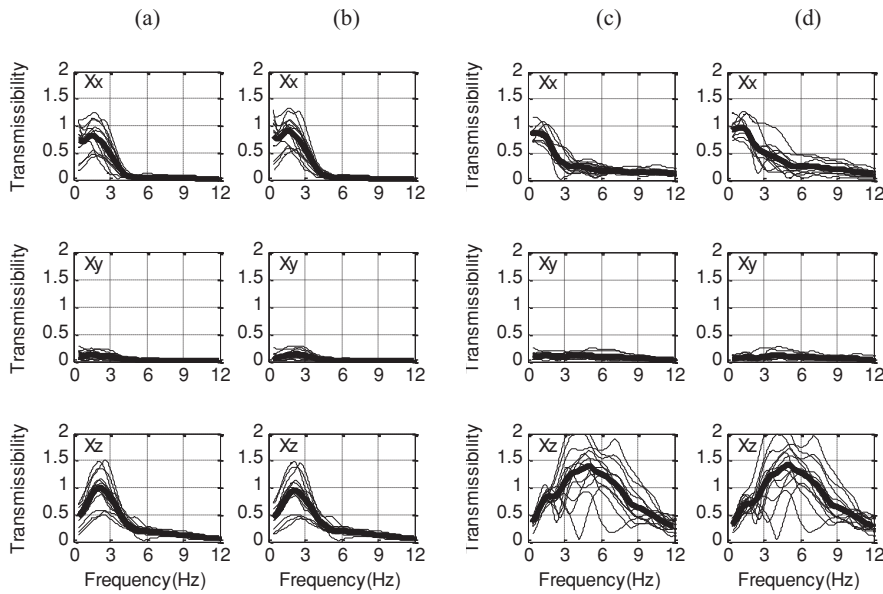


Figure 5. *Seat-to-head transmissibility during fore-aft vibration: (a) uncorrected (local) data during unsupported upright seated posture; (b) corrected (global) data during unsupported-upright seated posture; (c) uncorrected (local) data during backrest-supported seated posture; (d) corrected (global) data during backrest-supported seated posture. Bold lines represent the mean data.*

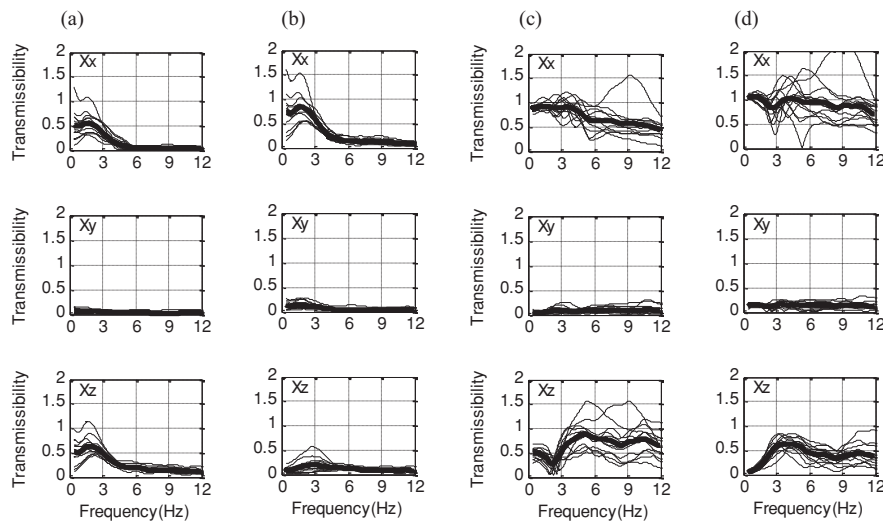


Figure 6. *Seat-to-C7 transmissibility during fore-aft vibration: (a) uncorrected (local) data during unsupported-upright seated posture; (b) corrected (global) data during unsupported-upright seated posture; (c) uncorrected (local) data during backrest-supported seated posture; (d) corrected (global) data during backrest-supported seated posture. Bold lines represent the mean data.*

It should be mentioned here that there are some discrepancies between the shapes of the seat-to-head transmissibility across different labs, especially in fore-aft WBV of seated subjects [6-7, 9-10]. One explanation for this difference is the inclusion of the three-directional combined RMS acceleration of the output point instead of solely using the Xx component. For the unsupported backrest posture, Figure 7a shows considerable differences in the magnitude of the fore-aft seat-to-head transmissibility of the three-directional combined RMS acceleration from that of Figure 5b. The three-directional combined RMS acceleration for the backrest-supported posture (Figure 7b) demonstrates two peaks around 2 Hz and 5 Hz. The peak at 2 Hz is a result of the Xx component, while the peak at 5 Hz reflects the vertical resonance in the Xz component (Figure 5d).

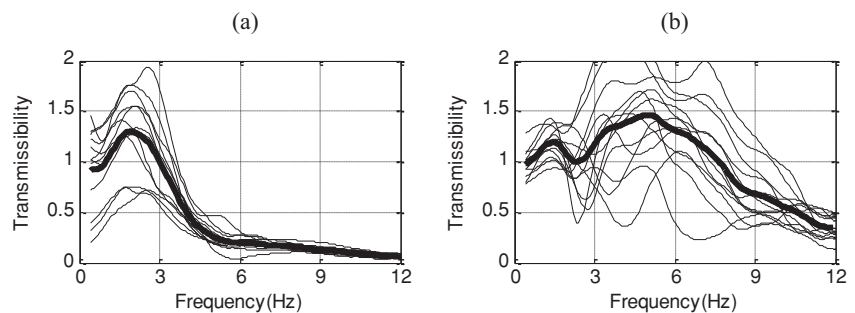


Figure 7. Combined (all output motions) seat-to-head transmissibility during fore-aft vibration for (a) unsupported-upright seated posture; (b) backrest seated posture. Bold lines represent the mean data.

3.2.2. Single Vertical WBV

The results for seat-to-C7 transmissibility for vertical vibration are presented in Figure 8, where major differences between the uncorrected (local) data (Figure 8a) and the corrected (global) data (Figure 8b) are present. Transmissibilities with input/output motions of the same direction (Zz) should come close to 1.0 at frequencies near zero, whereas cross-coupled motions (Zx, Zy) should have transmissibilities close to zero at frequencies near zero.

3.3. MULTIPLE-AXIS WBV

While the conventional 2D correction method [2-5] may work for simple postures and motions, the method has difficulties correcting data in a realistic 3D WBV environment. Problems such as curvature of the human body and involuntary postural changes only increase the difficulty of acceleration measurements. Such difficulties can be overcome, however, by use of the proposed method.

Figure 9 shows the uncorrected (local) transmissibility for the transmission of vibration from the seat to the C7 location for the backrest seated posture. As previously stated, uppercase letters indicate the vibration input direction, and lowercase letters indicate the vibration output.

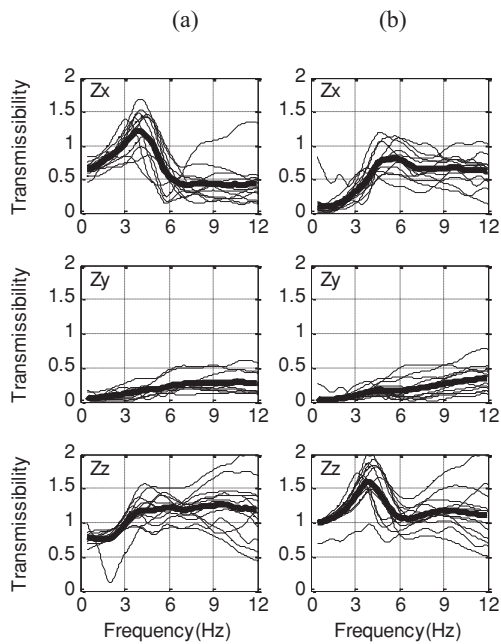


Figure 8. Seat-to-C7 transmissibility in vertical vibration for an unsupported upright posture: (a) uncorrected (local) data; (b) corrected (global) data. Bold lines represent the mean data.

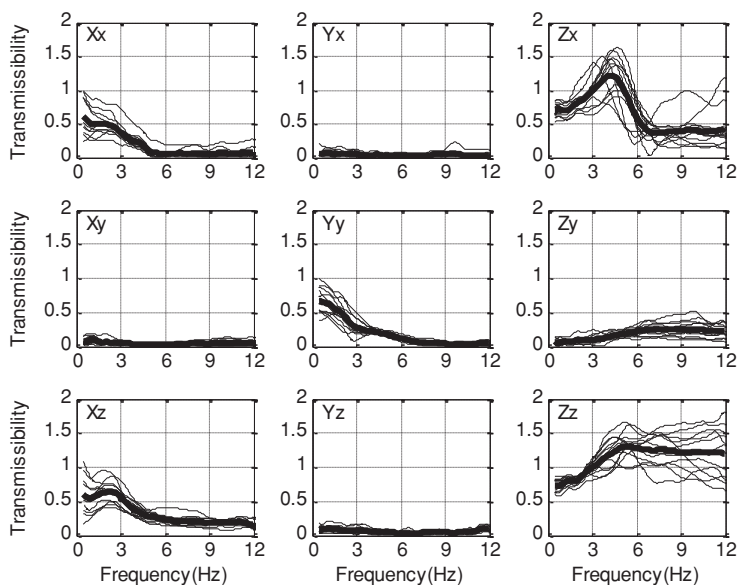


Figure 9. Seat-to-C7 transmissibility in 3D vibration for uncorrected (local) measurement. Bold lines represent the mean data.

Figure 10 shows the corrected (global) transmissibility for the transmission of vibration from the seat to the C7 location for the backrest seated posture. Major differences are seen between the two figures. As with vertical single-axis vibration, it can be seen that the data in Figure 9 are not correct because all input/output motions (Xx, Yy, Zz) with the same directions should come close to 1.0 at frequencies near zero. Additionally, all cross-coupled motions should be near zero at frequencies close to zero.

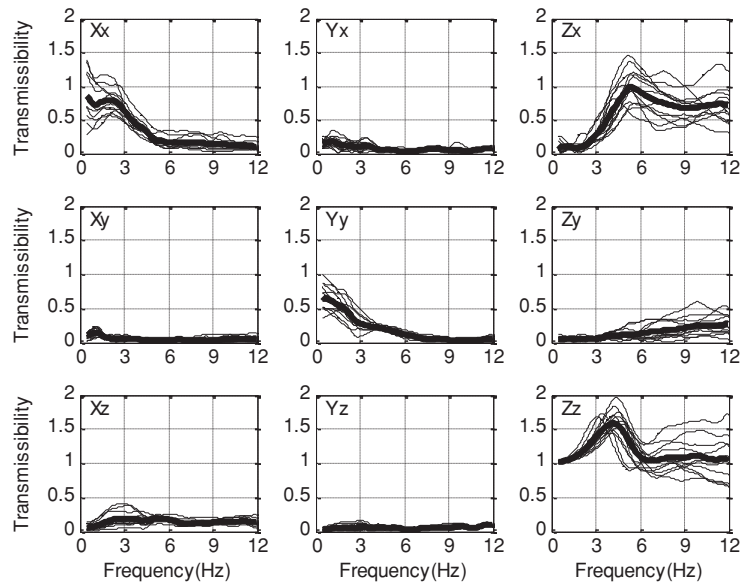


Figure 10. Seat-to-C7 transmissibility in 3D vibration for corrected (global) measurement. Bold lines represent the mean data.

4. DISCUSSION

The ability of monitoring the kinematics of the segment's 3D orientation objectively makes the method presented in this work extremely useful, especially for standardization purposes and when sharing data across different labs. With this proposed methodology, it becomes possible to investigate various biodynamic measures in any direction with a clear picture of the relationship between the direct and cross-components of the motion.

When the inclination angle θ changes during an experiment, the acceleration components change and no longer become valid. This can be seen when transmissibility values of cross-coupled motions are not near zero at frequencies close to zero. Additionally, transmissibility values between input/output motions (Xx, Yy, Zz) should be close to 1.0 as frequency nears zero. This trend seems to be extremely close for vertical input/output transmissibilities (Zz) but seems to be much more variable in the fore-aft (Xx) and lateral transmissibilities (Yy) [6,7,9,10]. This could be due to the posture conditions, the involuntary low-frequency motions of the head, and because the resonance transmissibility in these directions tends to be at low frequencies (below 2.0 Hz).

Researchers have also tried to correct the acceleration data due to problems with skin motion [5, 11-13]. During the setup of the current study, a large surface area (20 cm²) was used at the C7 testing area in an attempt to minimize skin motion. Additional correction for skin motion was not needed due to the natural frequency of the inertial sensor-skin system being higher than the frequency range being studied. This is similar to the findings of Kitazaki and Griffin for an accelerometer of approximately the same mass [11] measured on the skin over the L3.

The inertial sensors have the benefits of less processing time and an all-in-one accelerometer, gyroscope, and magnetometer package for greater capability of collecting six-degree-of-freedom motion data. The current inertial sensors have the disadvantages, however, of being able to capture only up to 120 Hz, sensitivity to electromagnetic fields, and being of slightly larger size and mass than current accelerometers.

5. CONCLUSION

This work presents a methodology for the correction of acceleration measurements in WBV when dealing with inclined surfaces or when the motion has multiple directions. The method presented an objective measurement that can be used across labs and for standardization purposes. Current correction methodologies may work well with uni-axial direction WBV testing, with some precautions; however, they will encounter considerable errors under multiple-axis WBV.

6. ACKNOWLEDGEMENTS

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WALSALL COMPLAINTS ON NOISE TOP 3,000

More than 3,000 noise complaints were made in Walsall in a single year – with nuisance animals among the top offenders, new figures have revealed. Almost 80 written warning notices were issued to noisy neighbours and businesses. There were 1,846 complaints made about domestic noise, 982 relating to animals, 153 because of commercial noise and there were 67 about alarms in the 12 months up to April, figures show. As a result some of the alarms were disconnected. There were 11 complaints about sport and leisure premises, 20 about loud speakers and four on construction noise. In total there were 3,083 complaints across the borough from April 2011-12. There were 77 abatement notices issued by environmental health officers for ongoing problems while there were two prosecutions for a breach of the warning.

WHAT'S NOISE-INDUCED HEARING LOSS WORTH?

Attwood Solicitors, of Burslem, UK, has settled hundreds of cases of noise induced hearing loss since 2008. According to the firm, compensation ranges from £1500 – £12,000, with the average compensation being around £5,000.

£4000 FINE FOR NOISY PUB

A public house in Mitcham, South London, has been prosecuted for making too much noise and causing a nuisance to local residents. The Burn Bullock Public House, Mitcham, was ordered to pay over £4000 by Wimbledon Magistrates Court after being found guilty of breaching a noise abatement notice from the council's environmental health service last year. Over 20 complaints were received about the premises.

OSHA SEEKS \$49,000 FINE ON TIMBER FIRM

The U.S. Department of Labor's Occupational Safety and Health Administration has cited lumber manufacturer Shingleton Timber & Trucking Inc. for noise and safety hazards at its Augusta facility. OSHA initiated an inspection in January as part of the agency's National Emphasis Program on Amputations and found four repeat, three serious and one other-than-serious violation. Proposed penalties total \$49,500. The repeat violations include failing to establish a valid baseline audiogram, institute a noise training program, conduct annual noise training and obtain an annual audiogram. The citations carry \$36,960 in penalties. A repeat violation exists when an employer previously has been cited for the same or a similar violation of a standard, regulation, rule or order at any other facility in federal enforcement states within the last five years. Similar violations were cited in 2009.