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Three-dimensional motion capture protocol for seated operator in whole body vibration

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Abstract

A new methodology to measure the response of seated people to whole body vibration (WBV) is presented in this work. The proposed methodology is based on using motion capture systems with reflective markers to detect the position versus time motion of selective landmarks on the human body during vibration while taking into consideration the seatback. The methodology also circumvented the problem of tracking the motion of the physical markers on the lower thoracic and lumbar areas of the spine, which cannot be seen by the cameras due to the existence of the seatback, by introducing virtual (calculated) markers that substitute for the physical markers. Additional (redundant) markers were attached to the segments of interest to generate local coordinate systems that can be used to obtain the trajectories of the virtual markers. Simulated ride files containing both complex vibration and mild impact signals were played back through a man-rated 6 d.f. motion platform. The methodology was tested on three seated subjects; there was considerable agreement between the trajectories of the physical and virtual markers. Error assessments also showed insignificant discrepancy between the physical and virtual markers. The proposed methodology showed encouraging results in WBV testing and may be useful for other applications where people perform tasks in a seated position.

Relevance to industry

People who operate heavy construction machinery can be at increased risk for low back pain and other musculoskeletal problems. WBV in combination with postural constraints is one potential underlying cause for these complaints. However, WBV is difficult to study without altering the typical operator environment as the seatback and armrests often limit the ability to monitor human motion, particularly the lumbar spine. The development of an efficient and effective technique for measuring three-dimensional (3D) displacement data of the lower back region of seated operators in realistic environments exposed to WBV, could advance the development and validation process of computer human modeling in this field. Preventing these problems can save people significant suffering and industry significant cost due to compensation, medical care, lost productivity, and retraining.

Keywords: Whole body vibration; Marker protocol; Seated positions

1. Introduction

Due to advances in technology, people regularly conduct most of their tasks in seated positions. Examples include people sitting at their desks and working on computers, operators working in industry, and drivers and occupants performing tasks inside vehicles and heavy equipment. These technologies have increased work productivity and performance to a certain extent. However, many occupational injuries have accompanied this development, and it is now well known that sitting posture is associated with a number of musculoskeletal disorders such as low back pain (Adams and Hutton, 1985; Beach et al., 2005; Porter and Gyi, 2002). In whole body vibration (WBV), such as that encountered in aircrafts, ships, automobiles, farming

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machinery, construction equipment, army vehicles, and other moving environments, the problem becomes more acute as operators are subjected to complex forms of vibration, which may include low-amplitude sudden impact signals. Those types of motion may generate extensive stresses in the lower back area of the spine and may represent a potential cause of injury (National Research Council and the Institute of Medicine, 2001; Wilder and Pope, 1996; Pelmear and Wasserman, 1998; Fritz et al., 2005).

Most of the current WBV studies are based on assumptions that may not reflect the actual situation in the field. For example, domestic and international standards dictate exposure limits based on measurement of vibration at the interface between the seat and the operator's buttocks using seat-pad accelerometry (ANSI S3.18 2002/ISO 2631-1, 1997; ISO 2631-1, 1997; ISO 2631-5, 2004; European Commission, 2002). This is based on the assumption that the only major vibration is transmitted through the seat pan. This represents a substantial restriction, as vibration may also be imparted to the head and neck via the steering wheel and/or armrest controls and a relatively rigid upper body (Wilder et al., 2006). Therefore, seat configurations and accessories, similar to those used in practice, should be considered in WBV testing. A second limitation in current WBV testing is that most studies consider testing seated subjects using generated ride files with vibration signals applied to the seat in a single direction (Mansfield, 2005; Wang et al., 2004). However, in real-world scenarios, vibration signals are normally complex, composed of signals in multiple directions, and may contain impact signals that may have tremendous effects on the health and injury risk. Another limitation is that most current experiments are conducted using rigid platforms with no means of back or arm support. While this arrangement may facilitate to a certain degree the measurement process inside the lab, it does not reflect what is happening in real life, where people are normally sitting on a seat with a seatback that normally has lumbar support and occasionally an armrest. Finally, studies in modeling the response of people to WBV may provide a chance to predict the forces on the subject's body, such as those acting on the spine disks and the endplates of vertebrae (Seidel and Griffin, 2001). The development of these models requires a full description of the motion of the lower areas of the spine. Thus, it is very important to introduce and design a methodology that is capable of capturing the three-dimensional (3D) motion of the various parts of the body and specifically of the lower thoracic and lumbar areas of seated operators in response to WBV in a manner that is as close as possible to real life.

There are many techniques and devices on the market to collect 3D motion data. All existing sensors may suffer from a coupling effect between the sensors and the seatback, resulting in erroneously measuring the relative skin movement between the individual and the seatback rather than actual spine movement. This coupling process may become more problematic at the lumbar spine in WBV environments due to the complexity of the motion.

Historically, accelerometers have proven to be the most effective tool for collecting 3D motion data in WBV applications. However, to fully describe the 3D motion of each body segment, six accelerometers are needed. Furthermore, due to the nonlinear relationship between the linear and angular kinematics variables, and the influence of the gravity-related terms, multiple accelerometers (ISO 2631-1, 1997; ISO 2631-5, 2004; European Commission, 2002; Wilder et al., 2006) placed in a specific configuration are needed to resolve a segment's complete kinematics (Padgaonkar et al., 1975). This results in a very high number of sensors to monitor whole body motion and may adversely impact normal movements.

Passive optical motion capture systems are commonly used in biomechanical studies (Hagio et al., 2004; Rahmatalla et al., 2006a, b, 2007; Robert et al., 2005; Manal et al., 2003; Reft and Hasan, 2002; Zhang et al., 2003; Rachel et al., 2000; Andreoni et al., 2002; Chaffin, 2002; Maiteh, 2003) and have been shown to be accurate, reproducible, and consistent (Miller et al., 2002). While their use in WBV environments is not yet common, they provide advantages for several reasons. First, passive markers, reflective surfaces attached easily to the body, do not add any wires that could potentially limit motion. Second, only three to four markers are required to define the 3D velocity and acceleration of a body segment (Verstraete and Soutas-Little, 1990).

1.1. Aim

The primary aim of this study was to introduce a methodology that estimates the 3D motion of the various parts of a seated subject's body, specifically the lower thoracic and lumbar areas of the spine, while they are conducting tasks in a WBV environment. The proposed methodology is based on the implementation of motion capture systems with reflective markers to measure the 3D trajectories of selective points. The hypothesis is that the trajectories of the physical markers that cannot be seen by the cameras due to the existence of the seatback can be retrieved using virtual (calculated) markers. The virtual markers can be derived from the surrounding physical markers and additional (redundant) markers that are positioned on the segments of interest.

2. Materials and methods

2.1. Participants

Three healthy subjects with a mean age of 39.7 years, ranging from 25 to 57 years, were recruited for this study. The mean stature was 178.7 cm (70.34 in), and the mean body mass was 88.5 kg. Two of the subjects were professional operators with a minimum of 2 years of experience with large construction equipment. Written informed consent, as approved by the University of Iowa Institutional Review Board, was obtained prior to testing.

2.2. Occupational task

Subjects were seated in heavy machinery seats rigidly mounted to a vibration platform (Fig. 1). The motion platform was used to play back and reproduce ride files obtained from large construction equipment in the field, with a high degree of accuracy. Normally, ride files are complex and may include signals that contain impact. Therefore, in order to reproduce these signals with a high degree of fidelity, a 6 d.f. man-rated shaker table (Mannesmann/Rexroth/Hydraudyne 6 d.f. micromotion system, model HSE-6-MS-8-L-2D, Boxtel, The Netherlands) was used. Six different ride files were tested, with durations of 30 s each.

2.3. Data collection

A 12-camera Vicon Motion Analysis System was used (infrared SVcam cameras with resolution of 0.3 megapixels per frame and a peak capture rate of 200 Hz) to collect the motion of 41 passive reflective markers (Fig. 2) during the WBV exposures. The data were collected at 200 Hz to maximize our ability to accurately capture the high frequency components of the motion signals, then low-pass filtered at 16 Hz. This cut-off frequency was based on power spectrum analyses of tri-axial accelerometers attached to the motion platform base, the head and the torso of the subject. Additional markers were also used to define the location of the platform and the seat.

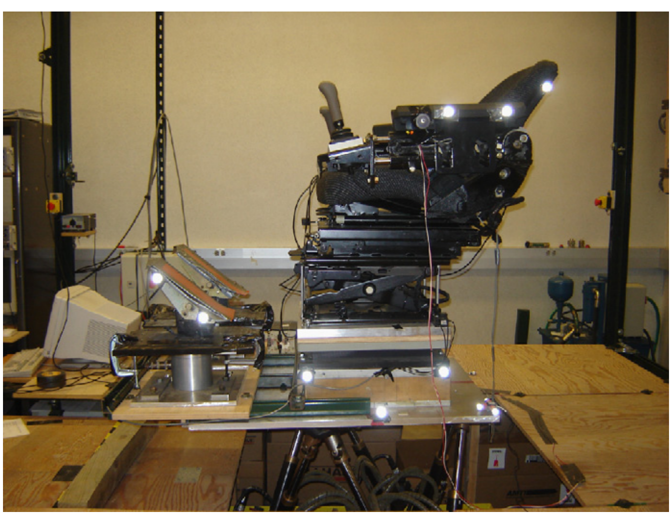

Fig. 1. The motion platform and seat assembly used in testing in the Jolt/Vibration/Seating Lab.

2.4. Marker placement protocol

Several marker placement protocols have been introduced in the literature to study various types of motion. Among them, the Helen Hayes marker set protocol is the basis for the plug-in gait protocol and has been adopted in a number of commercial software programs such as LifeMOD and Vicon. In the plug-in gait protocol, markers are attached to bony landmarks on the subject's body to establish local coordinate systems on various segments. While the protocol is very efficient for standing postures and motion, it is deficient if applied to seated positions where four markers typically cannot be seen by the cameras due to the seatback (Fig. 2). These four markers are: T10 (attached on the spine at the T10 vertebra), Sacrum (attached on the spine at the S1 vertebra), LPSI (attached to the iliac bone on the left posterior side of the back at the level of L5), and RPSI (attached to the iliac bone on the right posterior side of the back at the level of L5) (Fig. 3). This deficiency is considered significant in any ergonomic study for seated people where considerable motion and postural change can take place at the lower thoracic and lumbar areas of the spine. Therefore, it is very important to introduce or develop a new marker placement protocol that can handle this deficiency.

In this work, a new methodology is introduced to supplement the plug-in gait protocol and make it adequate for capturing the motion of seated people. The improvement process considers adding redundant markers (Fig. 3) to the segments of interest where markers are occluded from the camera's view and then uses these markers to create local coordinate systems that can be used in

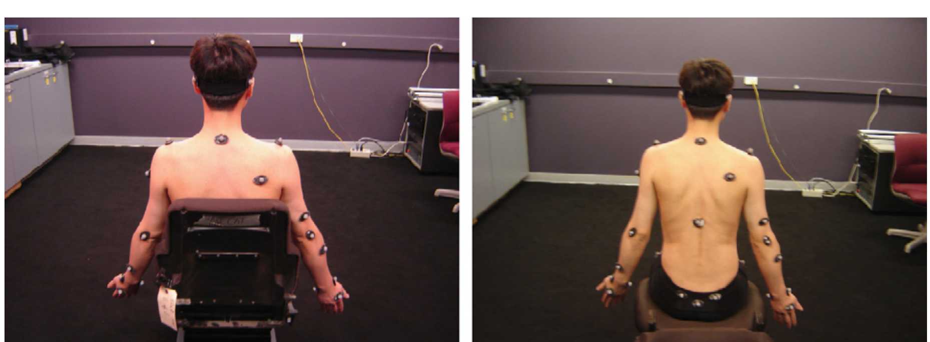

Fig. 2. Physical markers on the subject's back when the seatback is upright (left) and fully reclined (right).

subsequent operations to introduce virtual markers that can substitute for the occluded physical markers. In order to show the discrepancy between the trajectories of the physical markers and the virtual markers, the subjects were tested in a seated position with the seatback fully reclined (Fig. 3). With this setting, it is possible to define the trajectories of the physical markers and then use the proposed methodology in this work to define the trajectories of the virtual markers.

During the experiments, and while the seatback is fully reclined, the physical markers on the back of the person can be seen by the cameras. Therefore, for a marker like P in Fig. 4:

$$X_p = R + {}^{l}_{G}A x_p, \tag{1}$$

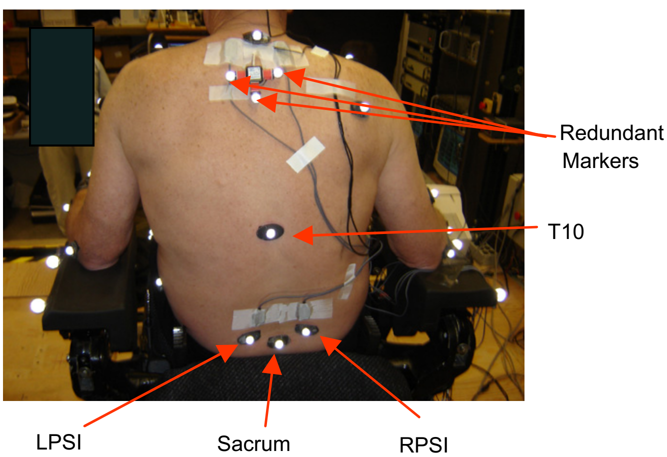

Fig. 3. Position of the physical markers (T10, Sacrum, LPSI, and RPSI) and redundant markers on the subject's back when the seatback is fully reclined.

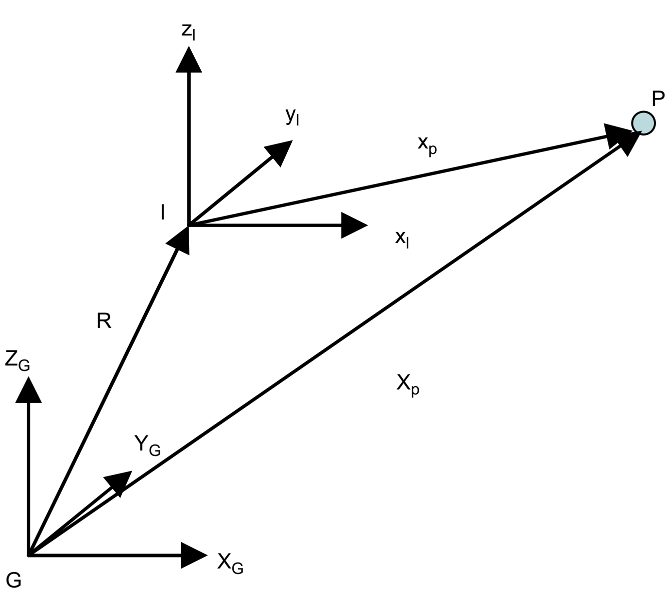

Fig. 4. The position of a generic marker P, defined using the global coordinate system (G) and a local coordinate system (l).

where $\boldsymbol{X_p}$ represents the global position of marker P with respect to the global coordinate system G. $\boldsymbol{R}$ is the location of the local coordinate system, established by any three combinations of the redundant markers, with respect to the global coordinate system G. ${}^{l}_{G}A$ is a transformation matrix, normally orthogonal, between the local coordinate system (l) and the global coordinate system (G):

$${}^{l}_{G}A = \begin{pmatrix} x_l X_G & y_l X_G & z_l X_G \\ x_l Y_G & y_l Y_G & z_l Y_G \\ x_l Z_G & y_l Z_G & z_l Z_G \end{pmatrix}. \tag{2}$$

Finally, $\boldsymbol{x_p}$ is the coordinate of the marker P with respect to the local coordinate system (l).

In situations where marker P can be seen by the cameras, Eq. (1) can be used to find the distance $\boldsymbol{x_p}$:

$$x_p = {}^{l}_{G}A^T (X_p - R). \tag{3}$$

Generally, there is uncertainty of the rigid-body assumption between the markers on each rigid segment due to the skin movement; therefore, the calculated distance $\boldsymbol{x_p}$ is considered approximately constant throughout the experiments in this work.

Now, if marker P is considered as one of the markers on the person's back that will be occluded from the camera's view due to the existence of the seatback, local coordinate systems like l in Fig. 4 can be established from any three markers that can be seen by the cameras (as is the case for T10 in Fig. 5) and are attached to the same segment where marker P is attached. For such cases, Eq. (1) can be used to obtain the global position ($\boldsymbol{X_p}$) of the missing marker P. Due to skin movement; however, the rigid-body assumption by considering $\boldsymbol{x_p}$ = const may not be achieved in most cases. Therefore, more accurate results can be obtained by generating more than one local coordinate system from the redundant markers. For each local coordinate system, the magnitude of $\boldsymbol{X_p}$ can be found

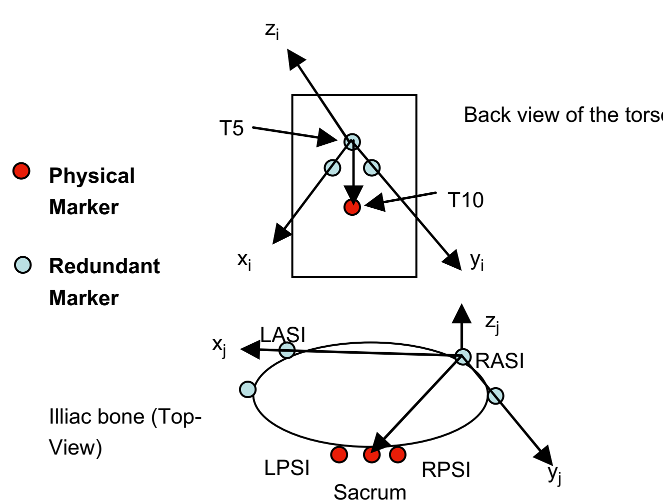

Fig. 5. Physical (red) and redundant (blue).

using Eq. (1), and the final value of $\boldsymbol{X}_p$ is obtained as the average value over those local coordinate systems.

Fig. 5 shows a schematic drawing of the proposed methodology. In Fig. 5, the red markers represent physical markers that would be occluded from the camera's view when the seatback is in the upright position. The blue markers are additional markers (redundant markers) that need to be attached to the subject so they can be seen by the cameras when the seatback is present. Using any three combinations of the redundant markers will result in a local coordinate system that can be used to create a virtual marker (virtual marker) to substitute for the missing physical (red) marker.

Before the real experiment is started, it is important to obtain a relationship between the red and blue markers; i.e., to obtain vector $\boldsymbol{x}_p$ using Eq. (3). This can be achieved using a static test. In the static test, the seatback will be fully reclined so the cameras can see the physical markers on the person's back. During the static test, it is possible to define the local position of the red physical markers with respect to the corresponding local coordinate systems using Eq. (3). Later, in the real experiment, the seatback will be returned to the upright position, and the camera will see the blue redundant markers but not the red markers. The global position of the red markers $\boldsymbol{X}_p$ can be retrieved using Eq. (1).

3. Results

The physical and virtual marker trajectories in the x, y, and z directions for markers T10, Sacrum, LPSI, and RPSI were similar across the three subjects. A single subject representation is represented in Fig. 6 for the sake of clarity; Fig. 7 depicts the trajectories of the second subject for the Sacrum marker in the individual directions x, y, and z for the whole trial (7000 frames, right column) and a more detailed representation (only 2000 frames) in the left column.

4. Discussion

As can be seen from Fig. 6, and in spite of the complexity of the motion, the trajectories of the virtual markers are considerably close to the physical markers in general terms. However, more insight details can be depicted when considering individual directions (x, y, and z) and considering error assessment analysis.

Fig. 8 demonstrates the absolute error (mm) between the trajectories of the physical and the virtual markers (ε_{Abs}) for the third subject at the four markers of interest:

$$\varepsilon_{Abs} = (X_{physical} - \bar{X}_{physical}) - (X_{calculated} - \bar{X}_{calculated}), \quad (4)$$

where $X_{physical}$ and $X_{calculated}$ are the trajectories of the physical and virtual markers in a certain direction, $\bar{X}_{physical}$

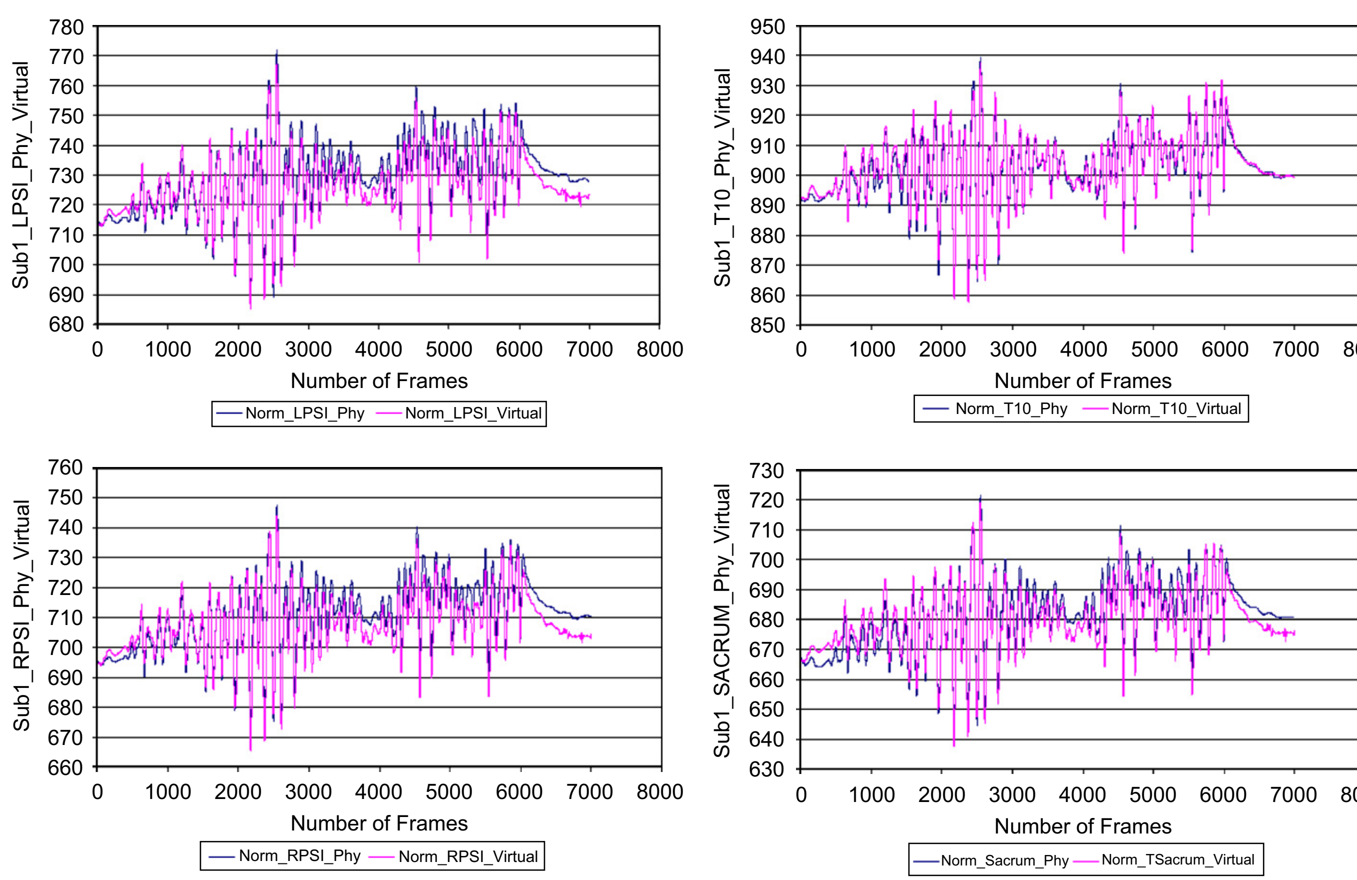

Fig. 6. Norm of the physical and virtual markers of subject 1 at T10, Sacrum, LPSI, and RPSI locations.

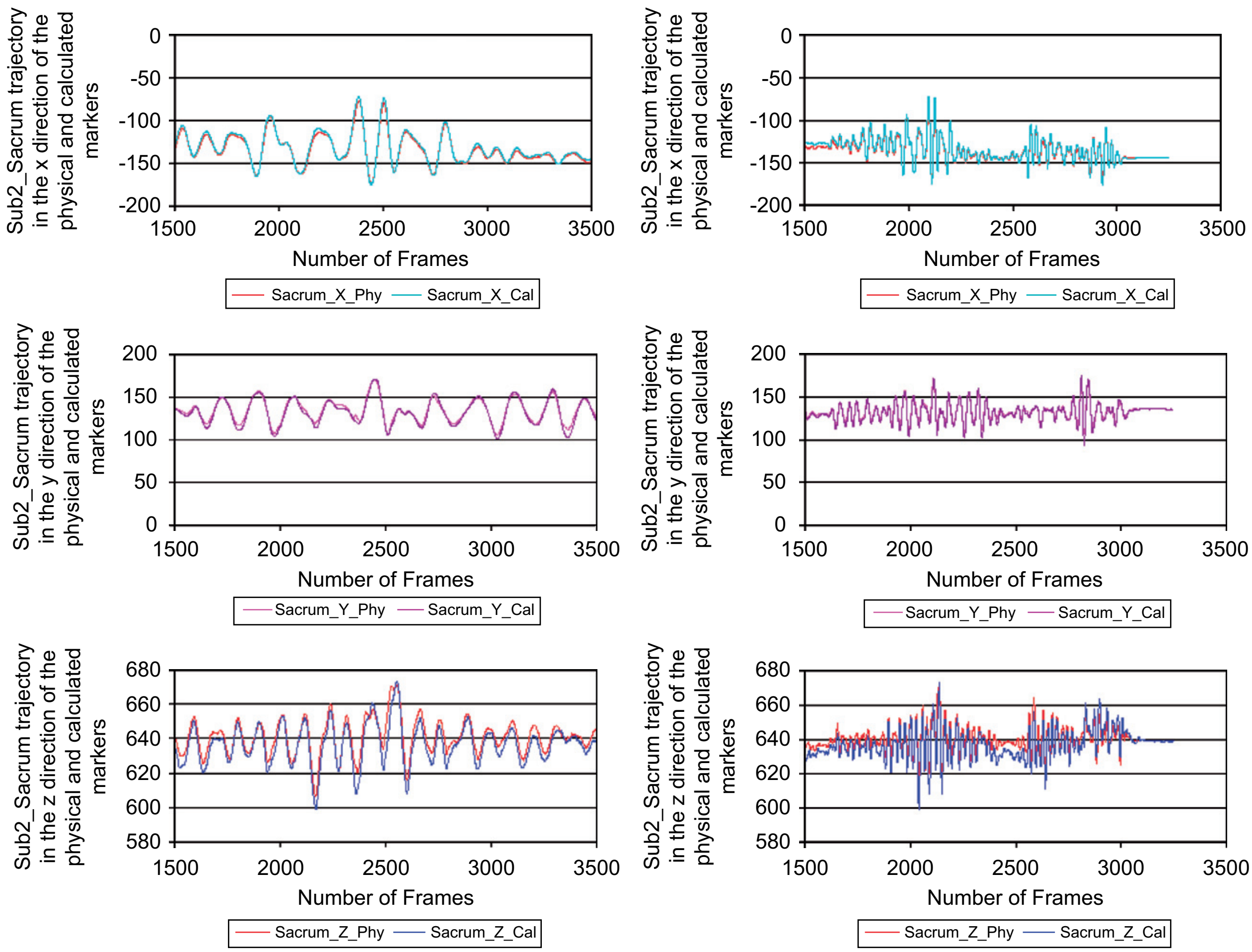

Fig. 7. The trajectory of the Sacrum marker for the second subject using physical (Phy) and virtual (calculated, Cal) markers in the x, y, and z directions for the whole trial of 7000 frames (35 s) and trajectories for only 2000 frames (10 s) in the area where are there are significant activity.

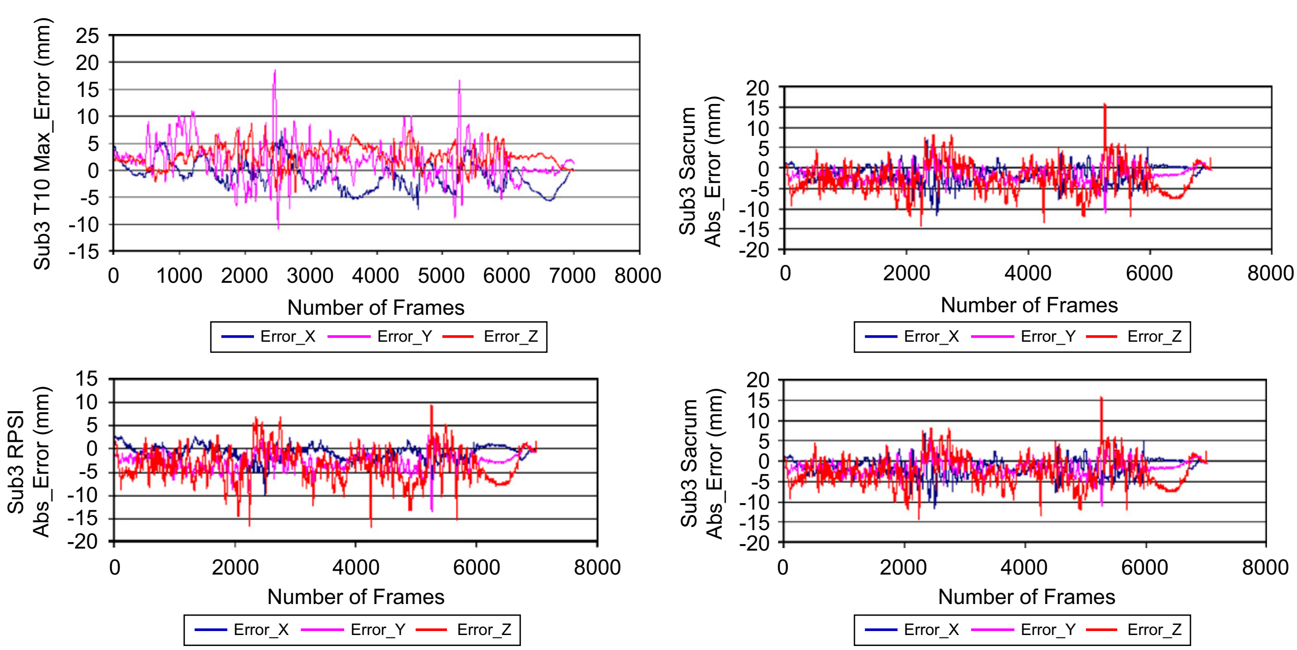

Fig. 8. Absolute error (mm) between the physical and virtual markers at T10, Sacrum, LPSI, and RPSI for the third subject during the trials (7000 frames (35 s)).

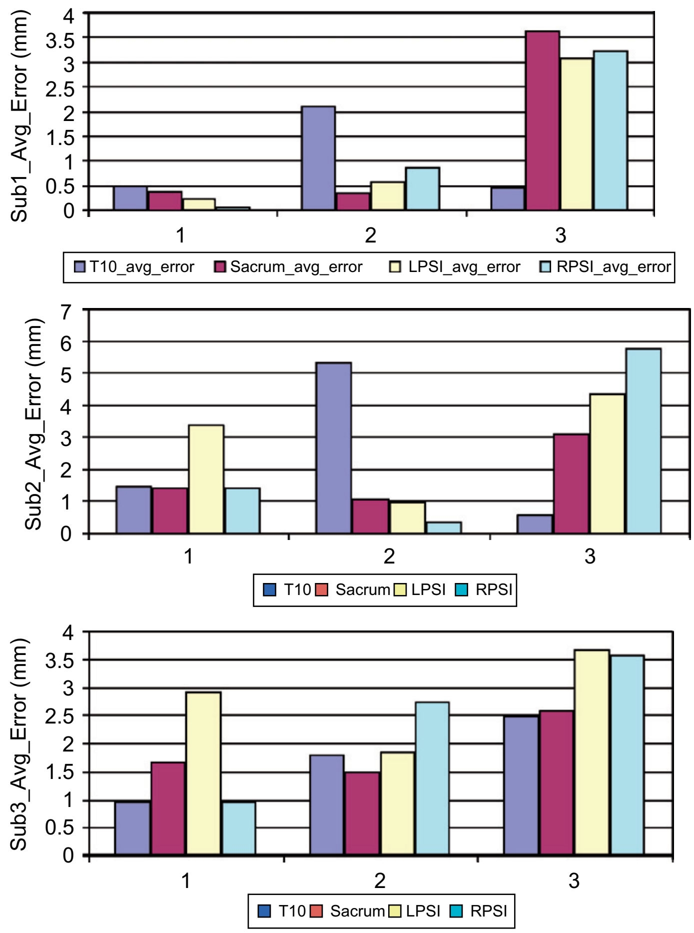

Fig. 9. Average error (mm) between the physical and virtual markers at T10, Sacrum, LPSI, and RPSI for the three subjects during the trials (7000 frames (35 s)).

and $\bar{X}_{calculated}$ are the average values for each one. Fig. 9 shows the distribution of the average error ε_{Avg}, while Fig. 10 depicts the distribution of the maximum error ε_{Max}:

$$\varepsilon_{Avg} = \frac{1}{n}\sum_{n}(X_{physical} - X_{calculated}), \qquad (5)$$

where n is the number of frames throughout the experiments.

Fig. 10 shows that the maximum error for all cases was below 19 mm which represents 12% of the mean displacement; still, this only occurs at some markers and in certain directions and at limited frames. Specifically, the maximum error took place at the T10 in the medio-lateral directions. Interestingly, maximum error is happening for all subjects and all markers at approximately the same time, with respect to the testing reference (between frame 2000 and 3000 and between frame 5000 and 7000) as shown in Fig. 8, in situations where there is relatively severe motion and significant skin movement is expected to take place. The latter observation can also be supported by inspecting Figs. 8 and 9. While Fig. 9 shows that the average error for all tests is below 6 mm, Fig. 8 shows that the distribution of the absolute error throughout the test is normally below 15 mm, except at limited frames where there is an extreme motion.

As described in the previous paragraph, the discrepancy between the physical and virtual markers is strongly associated with the severity of the skin movement. Therefore, the resulting absolute error does not reflect inaccuracy in the virtual markers; some components are associated with the uncertainty of the location of the physical markers due to skin movement. Previous studies have shown that skin movement can cause substantial errors, especially with severe or impact-type motion Reinschmidt et al. (1997). Therefore, the actual error between the trajectories of the virtual markers and the real points on the person's back may be below the apparent error between the virtual and physical markers.

In addition to the error assessment operations, which support the strength of the proposed methodology, Fig. 7 demonstrates the closeness between the trajectories of the virtual and physical markers throughout the trial in all directions. In some cases, however, as that of the z direction in Fig. 7, there is a constant offset between the trajectories of the physical and virtual markers due to the difference in their starting positions. This offset, while small, means that the virtual marker is moving very

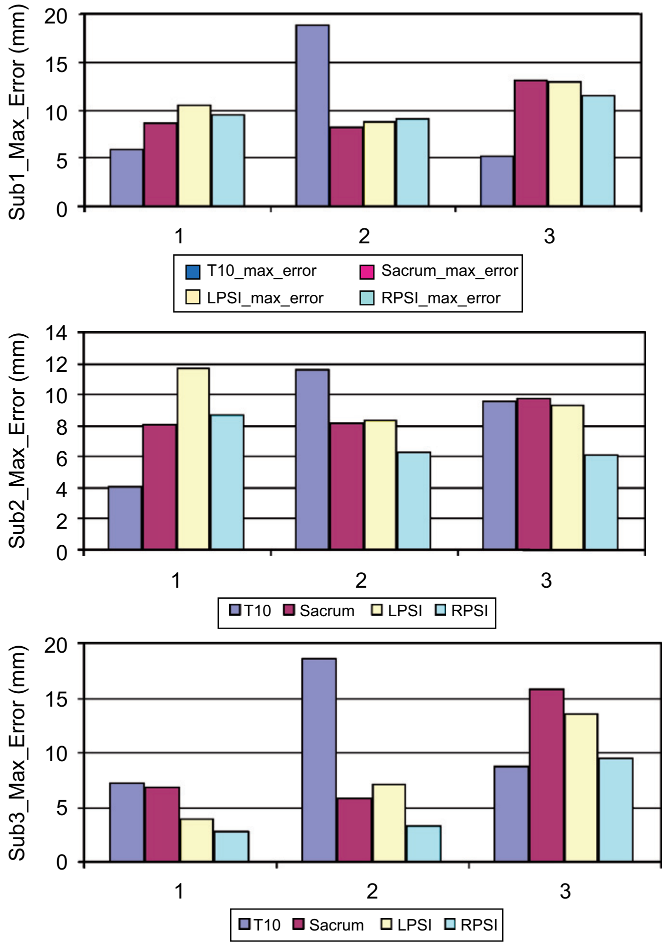

Fig. 10. Maximum error (mm) between the physical markers and the virtual markers at T10, Sacrum, LPSI, and RPSI for the three subjects during the trials (7000 frames (35 s)).

similarly to the physical marker (relative change in position) but is estimated to be sitting a small distance away from the actual marker. A similar situation could occur experimentally when detaching and reattaching a physical marker to a particular spot, as could occur between repeated trials.

5. Conclusion

In this work, a new methodology to capture the 3D motion of seated operators in WBV scenarios is presented. The proposed methodology is based on using optical motion tracking with a marker placement protocol that can effectively capture the motion of all points of interest on the subject's body, specifically those on the lower thoracic and lumbar regions of the spine. In the proposed methodology, virtual markers obtained from redundant markers are used to substitute for the physical markers that cannot be seen by the camera due to the existence of the seatback. The proposed methodology was tested on three seated subjects conducting simulated tasks in a WBV environment using a complex (6 d.f.) ride. The error assessment operations show that the maximum error between the physical and virtual markers took place in the medio-lateral directions where there was a great tendency for skin movement.

Therefore, the proposed methodology, which is based on the assumption of rigid-body relationships between the markers on the thoracic and iliac bone regions, may give realistic results because it is less sensitive than physical markers to skin movement. Additionally, because the proposed methodology has shown encouraging results in the WBV environment with relatively severe motion, it can be applied with more confidence to other seated-position applications.

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