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A FRAMEWORK TO STUDY HUMAN RESPONSE TO WHOLE BODY VIBRATION

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ABSTRACT

A framework to study the response of seated operators to whole-body vibration (WBV) is presented in this work. The framework consists of (i) a six-degree-of-freedom man-rated motion platform to play back ride files of typical heavy off-road machines; (ii) an optical motion capture system to collect 3D motion data of the operators and the surrounding environment (seat and platform); (iii) a computer skeletal model to embody the tested subjects in terms of their body dimensions, joint centers, and inertia properties; (iv) a marker placement protocol for seated positions that facilitates the process of collecting data of the lower thoracic and the lumbar regions of the spine regardless of the existence of the seatback; and (v) a computer human model to solve the inverse kinematics/dynamic problem for the joint profiles and joint torques. The proposed framework uses experimental data to answer critical questions regarding human response to WBV.

INTRODUCTION

Human discomfort and health related issues due to vibration exposure are major problems in many occupational fields. Humans are normally exposed to external forces, motions, and accelerations such as those encountered in aircrafts, ships, automobiles, farming machinery, construction equipments, army vehicles, and other moving environments. Many recently published articles conclude that there is strong epidemiological evidence for a relationship between occupational exposure to WBV, low back pain (LBP) and back disorders, hand-arm vibration syndrome, and white finger syndrome [1-3].

In WBV studies, domestic and international guidelines or standards and European Commission laws dictate exposure limits based on measurement of vibration at the interface between the seat and the operator's buttocks using seat-pad accelerometry [4-7]. This has been historically based on the assumption that the only major source of vibration is transmitted through the seat-pan.However, vibration may also be imparted to the head and neck via the steering wheel and/or arm-rest controls and a relatively rigid upper body [8]; thus the seat and its accessories should be included in any WBV study. Another issue with the current WBV studies is that most consider testing seated subjects using generated ride files with vibration signal applied to the seat in a single direction [9-10]; within this process, researchers have developed metrics to measure safety, predict injury, and define standards [5-6]. However, in real-world scenarios, vibration signals are normally complex and composed of signals that have components in multiple directions that may contain impact signals. Another drawback is that most current experiments were conducted using rigid platforms with no means of back support. While this arrangement may facilitate the measurement process inside the lab, it does not reflect what is happening in real-life applications where people are normally sitting on a seat with a seatback with lumbar support. Additionally, current studies in modeling the response of humans to WBV may predict the forces on the subject's body, such as those acting on the spine disks and the endplates of vertebrae [11], but the complexity of the human anatomy and the motion in WBV make it difficult to develop a computer human model without a full description and understanding of what is happening to people in real life. Therefore, the objective of this work is to design a framework for studying WBV where it is possible to understand and reproduce the response of humans more completely than previous methods, as well as to capture and study the critical parameters that contribute to the process.

In this article, a framework for studying WBV is introduced, and its components are described in consequent sections. The first section provides a description of the motion platform used in this work, and the second section provides a description of the motion capture system. The third section introduces a technique for building a skeletal human model within a computer software framework in order to replicate a specific person in terms of link lengths and joint center locations. The fourth section introduces a marker placement protocol for seated operators, and the fifth section presents a proposed commercial software (LifeMOD) for solving the inverse kinematics/dynamic problems. Section six introduces experiments and results, and the last section provides discussion and concluding remarks.

WBV FRAMEWORK

SIX-DEGREE-OF-FREEDOM MOTION PLATFORM

In the study of WBV, it is essential to have a means to accurately play back and reproduce ride files from the field, where workers conduct their tasks. 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 six-degree-of-freedom man-rated shaker table should be used in any comprehensive WBV study. In this work, a six-degree-of-freedom motion platform was used to simulate rides from heavy construction machines conducting tasks on a real site.

Figure 1: A six-degree-of-freedom Servotest motion platform that has been used in the WBV experiments

MOTION CAPTURE PROCESS

There are many techniques and devices on the market for measuring 3D motion data. Examples include electromagnetic sensors, optical sensors, fiber-optic–based sensors, and inertia sensors. Some of these devices, such as the electromagnetic sensors, may suffer from interference problems with other equipment in the testing environment; others, such as fiber-optic-based and inertia sensors, are normally capable of producing only local information and therefore may need to be supplemented with global positioning devices such as gyroscopes. In addition, all existing sensors have coupling effects with the seatback when they are placed on the subject's back, especially if lumbar support is present. The sensors may end up artificially measuring the skin movement relative to the seat rather than the spine motion. This coupling process may become more involved in WBV due to the complexity of the motion and the interaction.

Historically, accelerometers have proven to be an effective tool for collecting motion data in the WBV field [12]. However, theoretically, six accelerometers should be used to describe the three-dimensional motion of each body segment. Furthermore, due to the nonlinear relationship between the linear and angular kinematics variables, and the influence of the gravity-related terms, multiple accelerometers (9-12), placed in a specific configuration, are needed to resolve its complete kinematics [13]. As a result, a very high number of sensors are required for whole-body motion analysis, and this may impact a subject's normal movements.

Another method, one that is both effective and efficient, for collecting objective data for 3D motion analysis is to use optical motion capture systems. Today, optical systems have many applications in biomechanical studies [14-18]. These systems have been shown to be accurate, repeatable, and consistent [19] and, as an additional benefit, there is no pain or risk involved in using such systems. In the motion capture process, a number of reflective markers are attached over bony landmarks on the participant's body, such as the elbow, the clavicle, or the vertebral spinous processes. As the participant walks or carries out a given physical task or function, the position history of each marker is captured using an array of infrared cameras.

There are many advantages to using optical motion capture systems to collect motion data in WBV environments. First, the markers are passive sensors, meaning that they are merely reflective surfaces and can be attached easily to any area on the body of the subject without requiring wires to connect them to a data collection system. Second, theoretically, only three markers are required to define the three-dimensional velocity and acceleration of each body segment. However, four markers were used in this work to provide the most accurate results [13].

In the WBV environment, however, markers cannot be used alone to obtain velocity and acceleration data due to the level of noise presented at various frequency ranges. Therefore, a guide such as an accelerometer is needed for subsequent filtering and smoothing operations.

In this work, the time history of the location of the reflective markers was collected at a rate of 200 frames per second. Additional markers were also used to define the location of the platform and the seat. Tri-axial accelerometers were attached to the motion platform, the head, and torso of the subjects. Power spectrum analyses were conducted on the accelerometers' signals and a cut-off frequency of 15Hz was identified for subsequent data smoothing

COMPUTER SKELETON MODEL

Computer models that predict the response of a human to WBV may provide a chance to predict the forces on the subject's body, such as those acting on the lumber region of the spine. These predicted forces may be utilized with finite element models to approximate the details in the region of interest and to predict the stress level and therefore injury risk due to vibration [11].

One important aspect of human modeling, though, is determining the capability of the model to simulate real-life responses. In this regard, researchers normally use experiments to measure a person's responses to certain tasks; then, they compare these measurements with the computer model results. One critical factor in assuring the accuracy of this process is determining the degree of similarity between the skeletons of the human model and the live human.

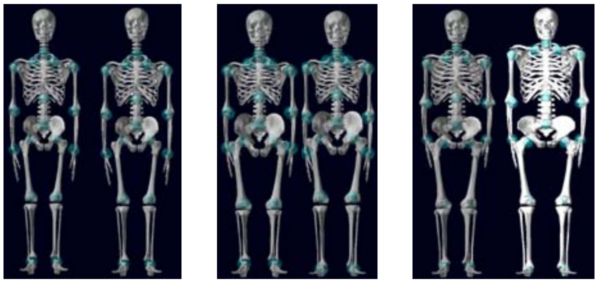
Methodologies for calculating the joint center locations and link lengths of humans are available and have been somewhat successful [20-21]. However, it is very hard to accomplish this goal with a high degree of accuracy, especially in a complex environment such as WBV.

In this work, a technique is introduced for constructing a human skeleton model that is as close as possible to that of a real human. The proposed technique is based on a modified version of an existing well-known database (GEBOD) [22-23]. The database can predict joint centers, link lengths, and inertial properties of a person using three approaches. In the first approach, the user enters the height, weight, age, and gender of the subject. The second approach depends on 32 physical measurements of the person. In the third approach, the user enters the physical locations of the joint centers measured from the floor level.

The first approach is very general and may miss significant information due to the natural variations in individual's ethnicity and anthropometry, such as the location of the hip centers [23], shoulder height, and shoulder width. The second and the third approaches can require considerable time for the measurements and are susceptible to human errors due to the difficulties of conducting the measurements in a repeatable manner. However, the third approach requires fewer measurements and can be more clearly defined than method two. Therefore, the third approach, based on joint center locations, is used in the current work to generate the human skeleton inside the computer within the proposed WBV framework.

In order to reduce the inter-tester variability of placing the markers on the subject's body, a marker placement protocol is introduced. Markers are placed on well defined locations to measure the distance from the floor to various joint centers (Fig. 2). In this process, the subject is instructed to stand in the motion capture lab in a neutral position for about 5 seconds. Then, the average time history of the location of the joint centers is found. This protocol has been tested on eight subjects (three females and five males) and results in more realistic, individual-specific values than the database approach. Table 1 demonstrates these findings quantitatively where the database column refers to method one and the joint center column refers to method two. Figure 3 depicts the skeletons that result from using both this approach and the database approach for the three principal subjects shown in Table 1.

Figure 2: Marker placement protocol used to measure the positions of the joint centers and link lengths using an optical motion capture system



(a) (b) (c) (d) (e) (f)

Figure 3: Skeleton models resulting from the database (a, c, e) and joint centers (b, d, f) approaches

	Female						Male									
	Subject 1		Subject 2		Subject 3		Subject 4		Subject 5		Subject 6		Subject 7		Subject 8	
Joint Center Name	Database	Marker	Database	Marker	Database	Marker	Database	Marker	Database	Marker	Database	Marker	Database	Marker	Database	Marker
Upper Neck	54.47	55.05	56.01	55.05	55.88	55.71	62.93	62.89	64.67	64.12	60.50	59.90	64.17	64.98	64.97	65.01
Lower Neck	49.61	50.78	51.07	50.78	51.05	51.31	57.16	57.71	59.24	61.11	55.05	56.05	58.39	59.14	59.31	60.38
Thoracic	39.02	39.16	40.18	39.16	40.09	40.87	43.87	45.26	44.41	47.79	41.77	44.29	44.65	46.54	44.98	47.90
Lumber	36.67	34.74	37.76	34.74	37.65	36.15	40.92	39.40	41.12	41.52	38.82	38.98	41.60	41.33	41.79	41.68
Left Shoulder	47.22	47.76	48.60	47.76	48.61	49.24	54.42	55.28	56.36	57.47	52.40	54.21	55.59	57.26	56.45	57.78
Left Elbow	38.83	37.70	39.96	37.70	40.11	38.19	44.06	43.76	46.58	45.52	42.79	42.09	45.18	44.80	46.21	44.88
Left Wrist	30.46	29.78	31.37	29.78	31.58	30.36	33.59	34.07	36.11	36.59	32.80	32.37	34.57	34.96	35.57	34.87
Left Hip	32.17	32.15	33.20	32.15	33.24	34.20	36.94	36.60	38.64	38.05	35.54	36.65	37.86	38.92	38.59	38.86
Left Knee	16.13	17.13	16.65	17.13	16.59	17.20	20.00	19.03	20.39	20.63	19.06	19.19	20.39	20.40	20.60	20.48
Left Ankle	2.76	2.53	2.89	2.53	2.88	2.68	3.08	4.14	3.12	3.47	2.82	2.87	3.17	3.26	3.20	3.19
Left Metatarsal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Right Shoulder	47.22	47.76	48.60	47.76	48.61	49.24	54.42	55.28	56.36	57.47	52.40	54.21	55.59	57.26	56.45	57.78
Right Elbow	38.83	37.70	39.96	37.70	40.11	38.19	44.06	43.76	46.58	45.52	42.79	42.09	45.18	44.80	46.21	44.88
Right Wrist	30.46	29.78	31.37	29.78	31.58	30.36	33.59	34.07	36.11	36.59	32.80	32.37	34.57	34.96	35.57	34.87
Right Hip	32.17	32.15	33.20	32.15	33.24	34.20	36.94	36.60	38.64	38.05	35.54	36.65	37.86	38.92	38.59	38.86
Right Knee	16.13	17.13	16.65	17.13	16.59	17.20	20.00	19.03	20.39	20.63	19.06	19.19	20.39	20.40	20.60	20.48
Right Ankle	2.76	2.53	2.89	2.53	2.88	2.68	3.08	4.14	3.12	3.47	2.82	2.87	3.17	3.26	3.20	3.19
Right Metatarsal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Measured From Body Center																
From left shoulder	6.65	6.53	6.75	6.39	6.74	6.79	7.59	7.39	7.78	8.88	7.46	7.03	7.68	7.06	7.76	8.06
From right shoulder	6.65	6.53	6.75	6.39	6.74	6.79	7.59	7.39	7.78	8.88	7.46	7.03	7.68	3.33	7.76	8.06
From left hip	3.27	3.47	3.34	3.36	3.42	3.75	3.21	3.35	3.36	4.03	3.15	3.45	3.28	7.06	3.34	3.85
From right hip	3.27	3.47	3.34	3.36	3.42	3.75	3.21	3.35	3.36	4.03	3.15	3.45	3.28	3.33	3.34	3.85

Table 1: Joint center locations and key body dimensions for 9 subjects using markers

MARKER PLACEMENT PROTOCOL

With advances in technology, humans now conduct many of their tasks while they are in seated positions. Examples include people sitting at their desks and working on computers, operators working in the industry, and drivers and occupants inside vehicles and heavy equipment. These technologies have increased people's productivity and performance in many respects to a certain extent. Yet, many occupational problems have accompanied these developments, and it is now believed that prolonged periods in a sitting posture can be associated with many potential health problems, including low back pain [24]. In WBV, the situation becomes more involved, as the operators are subjected to vibration and low-impact signals that may generate additional stresses at the lower back area of the spine; therefore, studying the motion of the spine is one of the most critical and important factors in any WBV study.

Most existing studies in WBV use rigid platforms with no backrest or seatback to simulate real-life seated scenarios. The reason for this arrangement may be related to the difficulties associated with placing sensors on the subject's back with the presence of the seatback. However, this approach may give erroneous results when compared with the real-life application where the seatback and lumbar support exist and have considerable effects on the resulting motion. Therefore, the seatback and lumbar support, if relevant, should be included in any WBV study. To circumvent this problem, a new technique is presented in this article for studying seated operator response in spite of the seatback, lumbar support, and arm rest. In the proposed technique, reflective markers supplemented with calculated markers are used to capture the 3D motion of seated subjects in WBV.

Several marker placement protocols have been introduced in the literature for studying various types of motion. Among these protocols, plug-in gait is a typical protocol that has been adopted by systems such as Vicon and LifeMOD. 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 of the body. While the protocol is very efficient for the standing posture, it provides incomplete data in the seated position; there are four markers (T10, Sacrum, LPSI, and RPSI) on the subject's back that cannot be seen by the cameras due to the existence of the seatback (Fig. 4). This resulting lack of data is considered significant in any ergonomic study for seated people where considerable motion and postural changes may 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 be used to obtain this information.

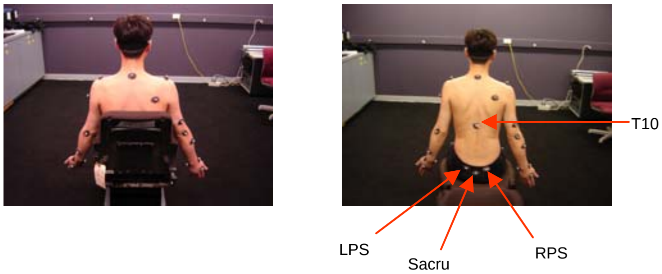


Figure 4: Physical markers on subject's back where the seatback is upright (left) and fully reclined (right)

This work introduces a methodology to enhance the plug-in gait protocol and make it useful for studying the motion of seated people. The enhancement process adds redundant markers to the zones of interest and then uses these markers to create local coordinate systems that can be used to retrieve the trajectory of the occluded markers due to the existence of the seatback.

Figure 5 shows a schematic drawing of the proposed methodology. In Fig. 5, red markers represent physical markers that would be occluded from the camera's scenery when the seatback is in its upright position. The blue markers are additional markers (redundant markers) that need to be attached to the subject so that they can be seen by the cameras. Using any three combinations of the redundant markers will result in a local coordinate system that can be used to create a virtual marker (calculated marker) to substitute for the missing physical marker. Before the WBV experiment is started, a static test is performed to obtain a relationship between the red and blue markers. In this static position, it is possible to define the local position of the red markers with respect to the corresponding local coordinate systems. Later, in the real experiment, the cameras can see the blue markers but cannot see the red markers. Nevertheless, the global position of the red markers can be retrieved by using the global position of the local coordinate systems and the local positions of the red markers with respect to these local coordinate systems as obtained from the static test.

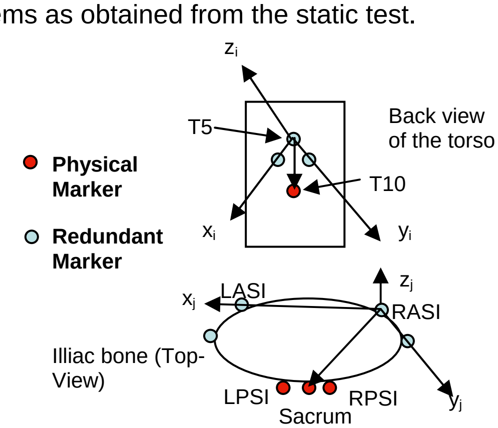


Figure 5: Physical markers (red) and redundant markers (blue)

The proposed methodology was tested on three subjects using ride files played back from heavy machinery containing complex vibration signals. In order to compare the resulting trajectory of the physical markers with that of the calculated markers, the subjects were tested in a seated position with the seatback fully reclined. With this setting, it is possible to find the trajectories of the physical markers and simultaneously use the redundant markers to find the trajectories of the calculated markers that substitute for the physical markers when the seatback is in its upright position. Figure 6 demonstrates the absolute error ε_{Abs} between the trajectories in the x, y, and z directions of the physical markers and the calculated markers for the T10, Sacrum, LPSI, and RPSI markers for one subject as similar behaviors were produced for the other subjects.

$$\varepsilon_{Abs} = X_{physical} - X_{calculated}$$

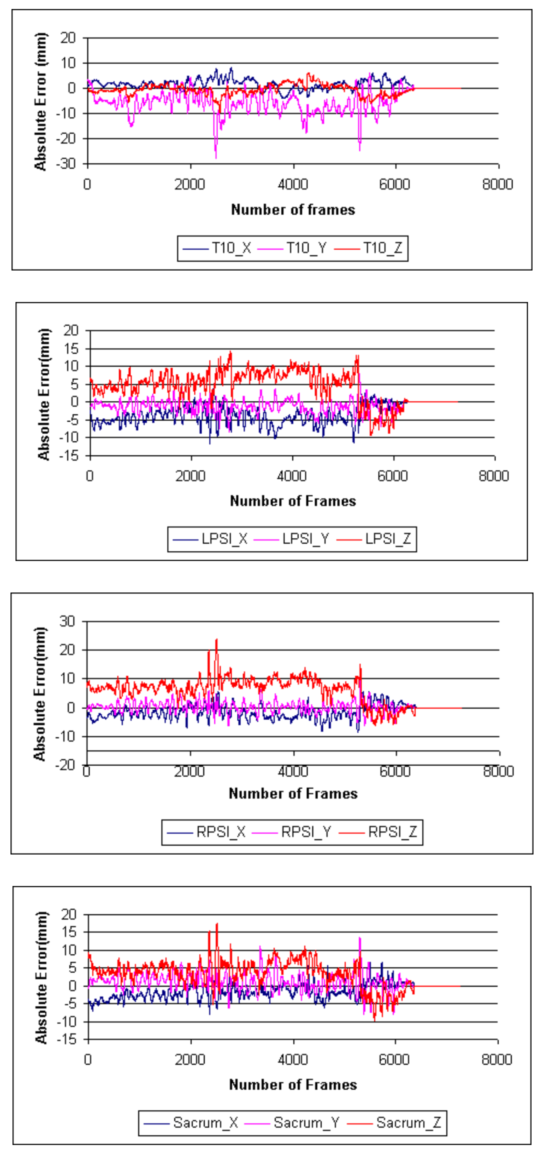


Figure 6: Absolute error in mm between the trajectory of the physical makers and the calculated markers in the x, y, and z directions for the T10, Sacrum, LPSI, and RPSI markers

A COMPUTER HUMAN MODEL TO SOLVE THE INVERSE KINEMATICS/DYNAMIC PROBLEM

There have been many attempts to develop predictive computer human models to study human response to WBV [1,2,3]. Most of these models are based on multi-body dynamic models, and some are supplemented with detailed finite element models. While these models are capable of answering some questions with vibration signal in one direction with some uncertainty, improvement is necessary in order to predict real-life motion. As a result, research continues in an effort to develop more complex and realistic models.

The goal of this research is to use existing computer human models to solve the inverse kinematics/dynamic problem based on motion and force data captured from real-life scenarios. Then, the resulting joint profiles and joint torques from the inverse dynamic problem can potentially be used to solve for the joint dynamics properties. The information gained from this process would be helpful in understanding vibration-induced risk and injury mechanisms and for the development of future predictive computer models.

In the current proposed WBV framework, a commercial software, LifeMOD, is introduced as a potential environment for solving for the inverse kinematics/ dynamic problem. LifeMOD is supported by its multi-body dynamic module, Adams. In addition to this property, LifeMOD contains the GEBOD database, (see section 3), and therefore makes it possible to build a subject's specific skeletal model. The experimental 3D motion data can be imported to this environment in a special format, and the model can then solve for the joint profiles and joint torques.

EXPERIMENTS AND RESULTS

In this work, experiments have been carried out to test the capability of LifeMOD in representing joint profiles from the motion capture data. Two experimental approaches were compared to the LifeMOD approach to validate the accuracy of the LifeMOD representation. In the first approach, markers were placed around the joints of interest (elbow and knee) and the joint angles were calculated based on vector analyses of the markers alone. For the second method, in addition to motion capture markers, electric goniometers were used to directly measure the elbow and knee joint motions (Figure 7)in. The subject was instructed to perform a marching-type motion and the elbow and knee joint profiles were obtained using the three methods: motion capture alone, motion capture with goniometer information, and LifeMod. Figures 8 and 9 demonstrate the resulting joint profiles for the elbow and knee joints, respectively.

While Figs. 8 and 9 show substantial agreement between the trajectories from the LifeMOD, marker, and goniometer approaches, the results also show that LifeMOD is very sensitive to the location of markers on the subject (LifeMOD_Perturbed). In LifeMOD Perturbed, markers between joints were placed at different distances from the joints. Therefore, care must be taken in placing markers at suitable landmarks, or LifeMOD will generate some error (see Figs. 8 and 9, LifeMOD_Perturbed).

Figure 10 demonstrates the resulting human skeleton with the seat and the platform configurations inside LifeMOD. In such an environment, the software backed by a multi-body dynamic model can solve the inverse kinematics/dynamic problem for the joint profiles (similar to those in Figs. 8 and 9) and joint torques.

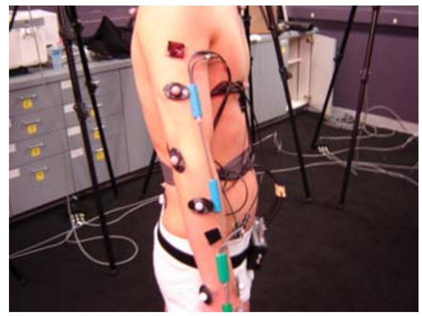


Figure 7: Markers and electric goniometers attached to the right arm of a subject to measure the elbow joint profile

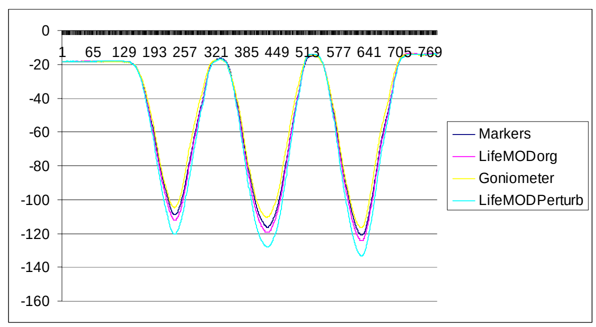


Figure 8: Elbow joint profile resulting from experiments using electrical goniometers and markers and that of LifeMOD using a standard protocol and a perturbed protocol

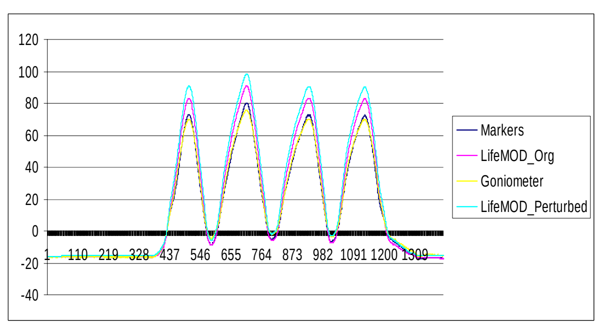


Figure 9: Knee joint profile resulting from experiments using electrical goniometers and markers and that of LifeMOD using a standard protocol and a perturbed protocol

Figure 10: A skeletal model for a subject together with the seat, the platform, and the motion capture markers as demonstrated by LifeMOD

DISCUSSION AND CONCLUSION

In this work, a framework to study human response to WBV is introduced. The proposed framework consists of the following:

(i) A six degree-of-freedom man-rated motion platform that is capable of reproducing complex vibration signals.

(ii) An optical motion tracking system that can efficiently track the 3D motion of the subject and the environment.

(iii) A computer model of a human that can represent people in terms of their dimensions and inertial properties. While many techniques for this are already available, most are suitable only for simple motion and may encounter many difficulties when implemented in WBV applications. One issue is their ability to reproduce the individual dimensions of the specific human subjects. The approach presented in this work presents a method for generating a computer model for a human that is based on the measured location of each subject's bony landmarks. The proposed approach, tested on nine subjects, produces skeleton models that appear to be as or more accurate than previously existing methods, such as the database method , when comparing the subjects' dimensions with the database predictions. As shown in Fig. 3, the resulting skeleton model from the proposed technique is similar to the database for subjects 1 and 2, however, for subject 3 it better represents his dimensions than does the database.

(iv) A marker placement protocol that can effectively measure the motion of points on the thoracic and lumbar regions of the spine. The proposed marker placement protocol in this work is based on the extension of an existing plug-in gait marker placement protocol. While the plug-in gait protocol is unable to capture the motion of the lower thoracic and lumbar areas of the spine due to the presence of the seatback, the proposed technique is based on retrieving the trajectories of the unseen physical markers with calculated markers. The trajectories of the calculated markers are obtained from redundant markers attached to the segments of interest and based on the assumption of rigid body motion. As shown in Fig. 6, the absolute resulting error between the trajectories of the physical and calculated markers is below 10 mm for most cases; however, it reaches a maximum of 25 mm at certain frames when extreme motion occurs. In most cases, the source of this error is not easily identified due to the complexity of the motion. However, this type of error can be as a result of the artificial motion of the physical markers as a result of skin movement. The calculated markers, on the other hand, are based on the rigid body relationship between the markers on the iliac bone and therefore are not affected to a large degree by skin motion

(v) The WBV framework should have a multi-body dynamic human model (LifeMOD was used in this work) that is capable of obtaining human joint profiles and joint torques for various tasks for the purpose of injury prediction and design modification.

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