The Effect of Sitting Posture on Human Movement in Whole-Body Vibration

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Abstract—The effect of sitting posture on human biomechanical response to whole-body vibration (WBV) was investigated in this work. Two popular sitting postures in the construction industry, standard back supported and bent forward (unsupported), were considered in this study (N = 4). A six-degree-of-freedom man-rated vibration platform, a twelve-camera Vicon motion capture system, three AMTI force plates, and four EMG sensors were used in the testing. The testing environment included the seat-pan, seatback, armrests, hand controls, and foot pedals. Each participant was exposed to multiple simulated ride files, including unidirectional swept sine motions (0.5 Hz-10 Hz) in the fore-aft and side-side directions, and random frequencies in multiple directions. The results demonstrate that subject responses are dependent on vibration direction and seated posture. During the fore-aft motion, subjects with unsupported forward postures experienced the greatest trunk motion at 3-5 Hz, whereas with the standard back-support posture, considerable increases in the seat-pan forces, pedal forces, seatback forces, and back muscle activation occurred at 6-8 Hz. During the random vibration trials, subjects experienced larger trunk motion with the forward posture, but greater neck flexion-extension motion with the standard supported posture.

Keywords-3D motion; whole-body vibration; sitting; posture; motion captur; muscle activation; EMG

1. INTRODUCTION

It is well known that sitting posture is associated with a number of musculoskeletal disorders such as low back pain [1-3]. In whole-body vibration (WBV) encountered in aircrafts, ships, automobiles, farming machinery, construction equipment, army vehicles, and other moving environments, the problem becomes more acute as operators are subjected to a multiple-axis form of vibration, which may include low-amplitude sudden impact signals. While developments in seat design and control have helped minimize the effect of the transmitted vibration on the lumbar spine area, several issues still need to be considered in order to achieve better seat design and decrease the discomfort and fatigue levels of operators.

One drawback of the current testing methodology is that human response to WBV is normally perceived and analyzed with the assumption that people sit in an upright posture while conducting their daily tasks. While this could be true for some people, many operators choose postures that are favorable to them, without being aware of the potential long-term consequences of that posture on their musculoskeletal system. The choice of a preferable posture may be due to various underlying reasons, such as the limitation of a person’s anthropometry and vision, constraints imposed by the surrounding equipment, or merely personal choice. In construction equipment with seat-mounted controls, for example, operators may choose a standard back-supported posture, where they sit with their backs resting against the seat back. Other operators may choose a forward posture, where they lean their trunks forward away from the seat back (unsupported sitting). While a wide range of
posture variations are possible, the focus of this article will be on these two basic options: the standard (supported) and the forward (unsupported) postures.

Efforts have been made to better understand the role of sitting posture and seat configuration on human response to WBV. Mansfield and Griffin (2002) studied the effect of posture variation and vibration amplitude for nine sitting postures on the operator apparent mass and seat to pelvis transmissibility during vertical vibration. Their studies found that changes in vibration magnitude produced larger effects than variations in sitting postures. Hinz et al. (2002) conducted experiments on 39 male subjects sitting on suspension seats with and without backrests during vertical WBV, using a finite element based human model to calculate the internal spinal loads. These authors concluded that backrest and posture conditions play an important role and should be included in any assessment on health during WBV. Further, Wang et al. (2004) found a significant effect of sitting postures on the biodynamic response under vertical vibration, considering 36 different sitting postures and different seat configurations. They used the apparent mass to analyze the effects of sitting postures on the biodynamic response and the effect of that on the resonant frequency under whole-body vertical vibration. In 2006, Wang et al. used the concept of power absorbed (damping) by the human body during vibration, first presented by Pradko et al. (1965), to study the effect of seat geometry and sitting postures on the mechanical energy absorption under vertical vibration. The results showed important combined effects of inclined backrest and hand position on the absorbed power characteristics. Thus, although somewhat varied, most prior studies have demonstrated the importance of considering back support and seated postures when investigating WBV.

A second drawback of many of the current WBV studies is that investigations have been limited to vibration signals applied in a single direction (Mansfield and Griffin, 2002; Wang et al, 2004). These and other related unidirectional studies may provide information that is used to develop metrics to measure safety, predict discomfort and injury, and define standards (ANSI S3.18, 2002; ISO 2631, 1997). However, in real-world scenarios, vibration signals are normally composed of multi-directional signals and may contain impact signals that may significantly alter the human response scenario. Researchers have recently realized this problem and start working in the direction of using vibration with multiple axes (Mansfield and Maeda, 2007).

Finally, current WBV testing has predominantly focused on the transmissibility of vibration through the seat pan to the low back region of the body. While this is an important area due to the association of low back disorders with WBV, and tremendous work has been done toward this end, it does not necessarily translate to real-world environments and other regions of the body. For example, most tests preclude the effect of vibration transmitted by the arms and feet through the control/steering wheels and the pedals. The latter may interfere with the transmitted vibration through the seat and generate a complex coupled motion that may significantly differ from the assumption that vibration is solely transmitted through the seat. Further, the head, neck and shoulders, also common regions for musculoskeletal pain and fatigue, may not be considered in many tests. These omissions may have significant consequences for detecting human discomfort levels and risks for injury in the process of seat isolator design.

Therefore, the objective of this work was to study the difference in human biomechanical response to WBV under two different sitting postures in multiple vibration directions. The first posture was the standard posture, where the subject sat supported by the seatback; the second posture was the forward unsupported posture, where the subject leaned forward away from the seatback. Fore-aft, side-to-side, and random vibration ride files were used to further investigate the role of vibration direction. In all cases, and as a practical situation, the seatback, pedals, arm-rests, and hand controls were included in the experiments to demonstrate the effect of the coupled motion (human/equipment) on the human’s biomechanical response.

2. METHODS

Four healthy male subjects with a mean age of 39.7 years, ranging from 25 to 47 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 two 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. Subjects were seated in rigid seats rigidly mounted to a vibration platform (Fig. 1). Two sitting posture configurations were considered, one with the subject sitting in a standard posture, supported by the seat back, and the second in a forward unsupported upright posture. Vibration was generated using a six-degree-of-freedom man-rated vibration platform (the Moog-FCS 628 six-degree-of-freedom electrical system). Three different ride files were used in the testing: one random ride file in multiple-axis with a duration of 90 seconds and two single-axis (fore-aft and side-to-side) ride files in the form of swept sine (0.5 Hz-10 Hz) with durations of 120 seconds. In the latter, the frequency was increased linearly from 0.5 Hz-10 Hz for the first 60 sec, and then decreased from 10 Hz-0.5 Hz in the next 60 sec. During every ride, subjects were asked to perform a virtual (game-like) construction task using the arm-mounted controls to ensure similar attention and upper extremity activity between rides.

Three force plates, AMTI; one installed underneath the seat-pan, the second one was attached to the seat back, and the third one was attached to the foot pedal. The 3D motion of selected points on the subjects was acquired using a twelve-camera Vicon motion capture system (Rahmatalla et al., 2008). Based on the motion capture marker positions, the motion of various body segments can be calculated. Additionally, the markers can be used to measure the global and the relative positions of the surrounding equipment (seatback, armrests, hand controls, and foot pedals). Muscle activation of four erector spinae trunk muscles (bilaterally at the L3 and the C5 regions) was collected using the Delsys Bagnoli Electromyography (EMG) System (Boston, MA). The motion, forces, and EMG data were all synchronized using a data acquisition system as part of the Vicon system. EMG and force were collected at 1000 Hz, and motion data at 200 Hz. The raw EMG data was processed using a 200 ms window, root mean square. The 120 sec swept-sine ride files (fore-aft and side-to-side) were divided into forty, 3 sec epochs, based on the underlying frequency component. Thus each epoch averaged frequencies increasing by 0.5 Hz (e.g. 0.5 Hz, 1.0 Hz, 1.5 Hz). For each 3 sec epoch, the peak EMG values and the variation and the mean in forces (seat-pan, seat back, etc) were analyzed. These results were then plotted relative to the mean frequency during each 3 sec epoch to evaluate the influence of frequency on the biodynamic response (muscle activity, motion, and resultant forces) for the fore-aft and side-to-side vibration directions.

Figure 1: A subject sitting in the standard posture and using the armrest control to perform a drilling task on a task simulator during WBV. The white dots represent reflective markers used by the motion capture system.
3. RESULTS

The results show significant differences between the standard and the forward sitting postures for both trunk and head motion that varied with the different vibration directions (ride conditions). Figure 2 shows the trunk and head motion for the standard and forward postures during fore-aft and side-side ride files. For the fore-aft condition, the trunk experienced larger motion for the forward posture at frequencies of 2-5 Hz, but the difference in the head motion was minimal. For the side-side ride file, while the trunk for the forward posture experienced larger movements from 3-6 Hz, the lateral head movement for the standard posture was considerably larger.

![Figure 2: Variation (N=4) of the trunk (top row) and head (bottom row) motion for standard (solid blue line) and the forward (dotted red line) postures throughout the first 60 sec ride file during fore-aft (left) and side-side (right) ride files. Upper left: Trunk motion for standard posture during the fore-aft. Lower left: Head motion for standard posture during the fore-aft. Upper right: Trunk motion for forward posture during the side-side ride. Lower right: Head motion for standard posture during the side-side ride.](image)

Meanwhile, for the fore-aft direction, the variation and the mean of reaction forces at the pedal, seat-pan, and seatback show noticeable increases in magnitude at frequencies from 6-8 Hz (Fig.3 and Fig.4). The standard posture resulted in larger forces than the forward posture for the three aforementioned forces. The resulting forces for side-side ride file showed a similar trend for both postures with peaks occurring in the frequency range of 4-6 Hz.

Figure 5 demonstrates the peak muscle activity for the four trunk extensor muscles. Muscle activation in the neck region is larger for the forward unsupported posture for both the fore-aft and side-side ride files, while the low back muscles demonstrated considerable activation increases in the range of 7-8 Hz for the fore-aft direction with similar activity at 5-7 Hz but less magnitude for the side-side ride.

For the random multiple-direction ride files, trunk motion increased substantially for the forward posture (see Fig. 6), represented by the relative distance between the seventh cervical vertebra (C7) and the sacrum (S1). In this case, the ratio of the difference in the motion can be more than double, as is the
case for the third subject. On the other hand, the head motion shows different behavior, where the neck flexion-extension motion was greater with the supported standard posture (e.g., greater head movement).

Figure 3: Variation (N=4) of the reaction forces for standard (solid blue line) and the forward (dotted red line) postures throughout the first 60 sec ride file at the pedal, seat, and seatback for standard and forward posture. The three figures on the left represent the forces in the fore-aft direction during the fore-aft ride. The figures on the right represent the forces in the side-side direction during the side-side ride. First row right pedal forces, second row seat forces, and third row seatback forces.
Figure 4: Mean (N=4) reaction forces for standard (solid blue line) and forward (dotted red line) postures throughout the first 60 sec ride file at the pedal, seat, and seatback for standard and forward posture. The three figures on the left represent the forces in the fore-aft direction during the fore-aft ride. The figures on the right represent the forces in the side-side direction during the side-side ride. First row right pedal forces, second row seat forces, and third row seatback forces.
Figure 5: Mean (N=4) peak muscle activity (EMG in volts) for the standard (solid blue line) and the forward (dotted red line) postures throughout the 120 sec ride file. The five figures on the left represent the muscle activity during the fore-aft ride. The figures on the right represent muscle activity during the side-side ride. The four muscles include the cervical region erector spinae (first row right side, second row left side) and the lumbar region erector spinae (third row right side, fourth row left side).
DISCUSSIONS AND CONCLUSIONS

This work demonstrates the importance of considering different types of sitting postures when studying the biomechanics of human in response to WBV. Specifically, two popular sitting postures were considered in this work, the standard posture and the forward posture. The current work also, emphasizes the significance of adding the seat accessories to the testing environments as well as considering ride files with multiple directions that simulate real life scenarios.

As can be seen from the results, the subjects respond differently in the fore-aft ride file during the two sitting postures. For the forward posture (Fig. 2), the results showed considerable increase in the trunk flexion-extension during 2-5 Hz, while less motion has been experienced for the standard posture. The latter could be related to the strategy the operators used by generating some kind of coupling with the surrounding environments: pedal, armrest, and seat back. Interestingly, the subjects stiffen their back muscles (Fig. 5) at a later time in the process and generate bigger forces on the seat and the pedal at a frequency of 6-8 Hz (Fig. 3 and Fig. 4). Similar trends have been noticed for the neck for both standard and forward postures with no significant differences in the magnitude; in both postures, there was clear increase in the motion magnitude at a frequency of 4-6 Hz (Fig. 2).

For the side-side ride file, the standard posture has shown more lateral motion in the trunk area (Fig. 2), but is still less than the forward posture. Again these differences can be contributed to the coupling effect with the seat back and the armrests. In this case the subjects generate less muscle activation in the back area than what they did in the fore-aft ride file. Interestingly, the standard posture has shown considerably more neck lateral motion than the forward posture (Fig. 2). In this case, during the standard posture and while the subjects were trying to support their torsos against the seatback, the head behaves like an inverse pendulum and generates more lateral movement.

For both postures, during the fore-aft and side-side ride files, the back muscle activation was consistent with the increase in the reaction forces at the seat and the pedal, which indicates a strong coupling. While this coupling is weaker for the forward posture in which the subjects may use the armrests to stabilize their body motion, an issue which needs further investigation in future testing.

In the random multiple directions ride file (Fig. 6), the results have shown a significant decrease in trunk flexion-extension motion in the case of the standard posture. Again, this may be related to the mechanical coupling between the subjects and the surrounding equipment. The smaller motion of the trunk has resulted in a higher head flexion-extension motion.
This work has highlighted the importance of including the motion of the whole human body, the effect of two popular sitting postures, and the effect of the coupling with the surrounding equipment, in any design modification that has the objective of minimizing vibration transited to the human or minimizing discomfort level due to WBV. While many seat designers are developing methodologies to minimize trunk motion during resonance, this study has shown more biomechanical activities in a higher frequency range where subjects comprise higher muscle activation and more power consumption which comprise major parameters for possible muscle fatigue and higher discomfort level.

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6. REFERENCES