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Biomechanical response of the musculoskeletal system to whole body vibration using a seated driver model

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ABSTRACT

Objective: This study aimed to assess the effects of backrest inclination and vibration frequency on muscle activity in a dynamic environment using a musculoskeletal model.
Method: The muscle activity modeling method was used to analyze a full body musculoskeletal system of a seated person with a public domain rigid body model in an adjustable car seat. This model was established using AnyBody Modeling System, based on the inverse dynamic approach. And the min/max criterion in dealing with the muscle redundancy problem. Ten healthy subjects were exposed to whole body vibration (WBV) with five frequencies (3, 4.5, 6, 7, and 8 Hz) in the vertical direction in a randomized order on three separate days. The displacement of the seat-pan and head was measured using a hybrid Polaris spectra system to obtain the seat-to-head (STH) transmissibility. Muscle oxygenation was measured using near-infrared spectroscopy. The validity of the model was tested using STH transmissibility and muscle oxygenation.
Results: Increased vibration frequency caused high muscle activities of the abdomen and the right leg with a backrest forward inclination angle. The muscle activities of the left leg decreased at a backrest backward inclination except at inclination angles of 15° and 30°. Muscle activity of the lumbar suddenly increased at a backrest inclination angle of 5° and vibration frequency of 5 Hz. Muscle activities were higher under vibration than that without vibration.
Conclusion: Vibration frequency significantly affected the muscle activity of the lumbar area. Likewise, the inclination degree of the backrest significantly affected the muscle activities of the right leg and the abdomen. The combination of vibration and forward inclination of the backrest can be used to maximize the muscle activity of the leg, similar to the abdomen and lumbar muscles.
Relevance to the industry: The musculoskeletal model established in the present study provides a method that can be used to investigate the biomechanical response of seated drivers to WBV. This model helps protect drivers from occupational injury.

1. Introduction

Studies have shown that vibration can be harmful for seated workers and, in some cases, leads to permanent injuries (Kelsey and Hardy, 1975; Griffin, 2012). Since drivers are often exposed to vibration for a long time, the vibration characteristics of the human body have been the subject of interest in many studies. The study on the biodynamic responses of humans can be classified into experimental and analytical methods. In the past few decades, a number of experiments have been conducted by various researchers under extensively varying test conditions, involving vibration excitations, postural constraints, and subject population (Basri and Griffin, 2012; Carcone and Keir, 2007; Jang and Griffin, 2000; Nishiyama et al., 2000; Shibata and Maeda, 2010). Although experimental studies were able to measure some parameters, they are normally invasive and may be harmful to the experimental subjects. To address the limitation of experimental studies, a variety of biodynamic models have been developed to describe the responses of the human body. Pankoke et al. (2001) presented a numerical approach for the prediction of vibration-

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related spinal loads. Bazrgari et al. (2008) investigated the effect of posture, co-activity in abdominal muscles and changes in buttocks stiffness and the results showed that the flexed posture in sitting increased the net moment, muscle forces and passive spinal loads while improving the trunk stability. Based on inverse dynamics, Ma et al. (2010) analyzed the muscle activities and joint forces of the lower limb with knee normal and knee lock postures under vertical whole body vibration using AnyBody Modeling System.

Based on different modeling techniques, the models can be grouped as lumped parameter models (Kim et al., 2005; Muksian and Nash, 1976; Qassem, 1996), finite element models (Siefert et al., 2008), and multibody models (Ippili et al., 2008; Teng et al., 2006). These approaches are able to provide estimates for some parameters that are difficult to obtain via direct measurements. However, the muscular and skeletal systems of the human body was challenging for mechanical systems to model because the human body is a sophisticated dynamic system, which does not provide any information regarding the level of muscular activity.

To address the limitation of the mechanical model mentioned previously, various human body computer models and computational analyses have been proposed. Rasmussen et al. (2009) used a detailed musculoskeletal model to investigate the consequences of variations in the seat pan angle, friction coefficient of the seat surface on spinal joint forces and muscular activity. Grujicic et al. (2010) established a musculoskeletal computational model to analyze the influence of car seat design/adjustments on muscle activation, joint forces, and soft tissue contact normal and shear stresses. Aliah et al. (2011) established a musculoskeletal computational model to analyze the interactions between the driver and the vehicle in various combinations of seat pan/backrest inclinations and pedal spring stiffness. Although these studies investigated the effects of posture on the human body, the analyses were not conducted in a dynamic environment.

To measure fatigue, discomfort can also be an important indication of the state of the driver during long-duration driving (El et al., 2003). The commonly used method to assess discomfort is mechanical, which is based on acceleration measurements (Mansfield, 2004). By contrast, subjective measures of discomfort can sometimes correlate better with the static characteristics of a seat than more direct measures. The maximum muscle activity was considered to reflect the maximum voluntary contraction (MVC), which can reflect muscle fatigue directly.

In this study, a musculoskeletal model based on the AnyBody Modeling System is proposed to investigate the effects of vibration frequency and inclination degree of the backrest (0°–30°) on the muscle activities of the driver based on the inverse dynamic approach. The AnyBody Modeling System is musculoskeletal modeling and simulation software developed at Aalborg University (AnyBody Technology A/S, 2012). The model contains >1200 individual muscle elements and can be considered as a highly detailed description of the human musculoskeletal system. It can analyze the individual muscle forces, joint forces and moments, metabolism, elastic energy in tendons, and antagonistic muscle actions. The parts of the whole body musculoskeletal model have been tested separately (e.g., Wibawa et al., 2013; De Jong et al., 2006; Wilke et al., 2001). However, little information on these models is known under whole-body vibration condition.

2. Material and methods

2.1. Musculoskeletal model

2.1.1. The AnyBody Modeling System

AnyBody™ uses the inverse dynamics approach to minimize the workings of the central nervous system (CNS). Muscles are activated by the CNS via a complicated electrochemical process. The number of muscles available is generally larger than strictly necessary to drive most motions. This problem is often referred to as the redundancy problem of muscle recruitment. AnyBody™ solves the redundancy problem by means of the min/max criterion. Based on this criterion, all muscles are distributed positively to balance the external load, which makes the maximum relative load of the muscle in the system as small as possible.

In the musculoskeletal model, many muscles share the same activity level and contribute to carry the load corresponding to their individual strengths, which can be referred to as "the muscle activity envelope." The muscle activity envelope served as a convenient and simple design criterion encapsulating the combined load on the muscle. Considering that muscle activity represents the maximum muscle activation in the model, muscle activity can be interpreted as the percentage of MVC necessary to carry the imposed load (Damsgaard et al., 2006). The MVC can be expressed as a measure of the force in a muscle relative to its strength, as follows:

$$A = \frac{F}{S}, \tag{1}$$

where A is muscle activity, F is muscle force in the current case, and S is the maximum muscle force. The muscle feels more fatigue with higher muscle activity degree. A given muscle is loaded to its maximum strength when its activity is 100%.

2.1.2. Problem definition

The musculoskeletal model of the human body used was built using the AnyBody Modeling System. This scaling produces a model with default parameters for mass and size (corresponding roughly to the 50th percentile European male). The model can be scaled to facilitate analysis of different populations. The data used in this model were from the National Standard GB10000-88 "Human Dimensions of Chinese Adults," which provided the 95th percentile Chinese male's size as equivalent to a height of 177.5 cm and weight of 75 kg.

The model comprises the following rigid bodies: backrest, seat pan, steering wheel, and pedal. To analyze the biomechanical response of the human body in a dynamic environment, the human body was positioned in accordance with the seating posture of a vehicle driver. In order to be able to reflect the driver in the driving state, the need for the driver cab model of human body model and boundary conditions are set (Table 1). The contact interface included Back-Rest, Seat-Pan, Foot-Rest, Pedal and Steering-Wheel. This model takes about 10 s to calculate each muscle force in AnyBody Modeling System.

Fig. 1 shows the musculoskeletal model of seated driver. The human body model was placed in the car seat with a lumbar support, and the driver's hands were positioned on the steering wheel with his right foot on the accelerator pedal and his left foot on the vehicle floor. To minimize the action of constant pressure on the

Table 1
Boundary conditions of the model.

Item	Boundary conditions
Back-Back Rest	Through a series of supporting point, the coefficient of friction (0.2–0.5)
Thigh-Seat Pan	Through a series of supporting point, the coefficient of friction (0.2–0.5)
Hand-Steering Wheel	Determined by hand gripping point
Foot-Foot Rest	The right pedal force 60 N, direction and perpendicular to the plane
Foot-Pedal	Foot-rest position and angle