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Comfort evaluation of a subject-specific seating interface formed by vibrating grains

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ABSTRACT

Sitting is the most common posture for work in offices, and spinal cord injury (SCI) patients who are wheelchair dependent spend 10.6 h per day seated in wheelchairs. Thus, the comfort of subject-specific interfaces is increasingly important for the well-being of patients and office workers. This paper introduces a new method of forming a subject-specific interface, based on vibrating grains. Twenty subjects (10 females and 10 males) participated in the sitting test. Interface comfort was evaluated using the pressure distribution and subjective rating methods. Five seating interface types were compared. The results showed that compared with a flat interface, the interfaces formed by vibrating grains had a significantly reduced peak contact pressure (PeakCP) (by more than 58.03%), and that PeakCP was highly correlated with the comfort rating ($R = -0.533$) and discomfort rating($R = -0.603$). This new method shows promise for guiding the future development of customized seating interfaces.

1. Introduction

In the industrialized world, sitting is the most common working posture for working adults, who spend approximately 50% to 86% of their workdays seated (Weston et al., 2017; Jans et al., 2007; Katzmarzyk et al., 2009; Toomingas et al., 2012). Improved seat comfort is an important factor that manufacturers use to their products from those of their competitors (Grujicic et al., 2009; Reinecke et al., 2002). Employers should provide employees with comfortable seats (De Looze et al., 2003), and more comfortable office chairs are needed. In addition, seat discomfort can lead to missed work and reduced work efficiency or productivity (Johansen and Johren, 2002). With an aging population and an increased prevalence of disability, the demand for wheelchairs that fit the personal needs and physical abilities of consumers is growing (Chaves et al., 2004). According to research, individuals whose mobility depends on wheelchairs, particularly spinal cord injury (SCI) patients, spend 10.6 h per day in wheelchairs (Sonenblum et al., 2008). The cushioning and shape of a seat are important factors for comfort during long - duration tasks (Groenesteijn et al., 2009). Sustained mechanical loading, such as pressure, causes pressure ulcers over a bony prominence (Oomens et al., 2015). Pressure ulcers are enormous financial healthcare burden, and the cost of treating them is estimated at more than $11 billion per year in the US (Young et al., 2012). A support surface (with the aim of minimizing the interface pressure) can reduce the probability of developing pressure ulcers (D.Bader et al., 2005; Olesen et al., 2010). This evidence supports the importance of a subject-specific seat pan design that fits the needs of different people and improves the mechanical properties of seats. Researchers are increasingly conducting seat interface and comfort research. Some researchers have sought to optimize the shape of the seat pan to approximately match the outer body anatomy of the buttocks and upper legs (Hewett and Bates, 2017). It is very expensive and time-consuming to build a subject-specific 3D human body. Moreover, the contour of the buttocks without self-weight loading differs from that in a sitting posture. Therefore, it is important to record the contour of the buttocks while seated. Furthermore, to improve the pressure distribution, the contour design should reduce soft tissues pressures. his type of interface is not only appropriate for subject-specific buttocks but also provides an even pressure distribution. Based on these findings, this paper assumes that vibrating grains are a better choice for a seat interface design.

The comfort of this new design interface must be measured. There are many subjective means of evaluating the comfort level of a chair. Several subjective rating schemes have been investigated to determine which might be the most effective for use in designing and evaluating seats (Kyung et al., 2008). The three main methods used to indicate a chair's comfort level are anthropometry, subjective assessment and objective measurements (Vergara and Page, 2002). According to

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previous work (Zemp et al., 2015; Branton, 1969; Helander et al., 1987), compared with quantitative measurements, subjective evaluations present interpretation difficulties. First, chair users must be aware of their comfort level. Different people have different sensitivities to comfort or discomfort of the buttocks. Consequently, it would be better to use pairs or groups of chairs and one variable for comfort testing so that subjects could more clearly distinguish between and more easily rate the chairs. Second, many factors can affect subject sensation, such as temperature, air quality, and noise (Gameiro da Silva, 2002), which might have obscure effects on the subjects' ratings and consequently on the standard deviation of the scores. Thus, the average score of each chair or seat interface should be used to evaluate comfort. Finally, because subjects come from different living environments and have had different life experiences, their original understanding of comfort might be different which might affect the results. In this study, the subjective rating was only focused on comparing the five interfaces and no other features.

However, objective measurements have been used to evaluate seating interfaces because subjective ratings have many limitations. Objective measurements are used to obtain quality values that can indirectly indicate subjects' physical functionality and comfort. Such methods include electromyography (Andersson and Ortengren, 1974; Gregory et al., 2006; Kingma and van Dieen, 2009; Van Dieen et al., 2001), magnetic resonance imaging (Baumgartner et al., 2012; Fryer et al., 2010; Zemp et al., 2013; Sonenblum et al., 2013), and pressure distribution measurements of the seat pan and backrest (Carcone and Keir, 2007; Groenesteijn et al., 2009; Kyung and Nussbaum, 2008; Gil-Agudo et al., 2009), and heart rate variability measurement (Le and Marras, 2016; Weston et al., 2017). Measuring the pressure distribution of the seat pan and backrest is one of the most common objective methods for analyzing and comparing chairs and sitting positions (Zemp et al., 2016). Hochmann et al. (2002) found that pressure mats are sensitive to different surface area properties. In addition, the Tekscan CONFORMat User Manual suggests that the sensor mat should calibrate for different interfaces and different subjects. We also used the method introduced by (Zemp et al., 2016) to understand the interrelationships between the pressure parameters and determine the most significant parameters to represent the properties of the interface formed by vibrating grains.

In this paper, we investigated forming a subject-specific seat-pan that can be used for wheelchairs and office chairs. Vibrating grains were chosen as the medium to form the seat pans. The hypothesis was that grains show improved fluidity under vibration and that the vibration destroys the original force chains, thereby leading to pressure redistribution under loading of the human buttocks. We verified the effects through interface pressure measurement. We also combined subjective ratings with objective measurements to determine which type of seat pan was optimal.

2. Methods

2.1. Participants

Twenty healthy subjects (10 females and 10 males) with an average age of 25.05 years (SD 2.72 years), an average height of 171.60 cm (SD 6.72 cm), an average weight of 69.7 kg (SD 15.481 kg) and an average BMI of 25.59 kg/m^2 (SD 4.83 kg/m^2) participated in this study. Subjects with musculoskeletal disorders or those receiving medication for a prolonged time were excluded from the study. All subjects provided written consent prior to their participation. As clothing could affect the interface pressure, the subjects were asked to wear soft and comfortable clothes, particularly stretchy sports clothing (Dan Bader et al., 2005).

2.2. Experimental designs

The novel interface was formed using an electromagnetic vibration table with a container filled with plastic grains (5 mm in diameter, 0.65 g/cm^3 in density). Five types of seats were tested in the experiment and evaluated based on interface pressure and subjective ratings. To control variables, all types of interfaces were formed by grains. The flat seat interface (FI) and the seat interface with a shallow profile formed by the subjects' own weight (WFI) were all formed by grains, without vibration. The remaining interfaces were formed with different vibration frequencies, 23 Hz (acceleration of 1.4 g), 24 Hz (acceleration of 1.3 g), or 25 Hz (acceleration of 1.1 g). These frequencies should ensure not only a fit to the subjects but are also sufficient to break the original force chain of the grains. Acceleration values greater than 1 g can overcome the inertia of the grains and provide fluidity to the movement of the grains to form to the contour of a subject's buttocks. The five types of seats were provided to the subjects in a random order.

2.3. Experimental apparatus

All experiments were performed with the same testbed. The grain container was sealed with a soft sealing film, and a vacuum pump was used to fix the geometry formed by the grains. For simplicity, the interfaces formed using the different frequencies were defined as 23 Hz-VFI, 24 Hz-VFI and 25 Hz-VFI. The Tekscan CONFORMat (Tekscan,Boston, USA), which has 1024 sensors in a 32 × 32 matrix and has dimensions of 539.24 mm (L) x 618.38 mm (W) in size, was used to measure the pressure distribution of the series of interfaces.

2.3.1. Experimental procedures

During the sitting test, all subjects sat with an upright posture and placed their hands on their thighs (Fig. 1). The subjects were asked to remain in this position and to relax their whole body. This study focused on comprehensively evaluating the properties of the seating interfaces by analyzing the pressure data and any associations with the subjective responses.

The experimental procedures for the FI and WFI seats slightly differed from those for the other seats, and the test procedures for the FI seat were introduced first. First, the grains were smoothed out before the sensor mat was placed on the surface. Then, a vacuum pump was used to make the FI rigid. The subjects were told to hold on to the edge of the container as a handle and then to slowly sit down. The sensor mat was highly influenced by the material properties and geometry of the interfaces. Therefore, it was essential to calibrate the mat to the different interfaces (Zemp et al., 2016). First, the subject were asked to pick up their feet and not to touch any other surface while the sensor mat was calibrated for 90 s. An adjustable footrest was offered, and sensitivity adjustments were performed before calibrating the sensor (Tekscan CONFORMat User Manual). The sensor mat was calibrated to all five interfaces for each subject.

Second, after the force calibration, the subject placed their feet down and stood up using their hands to support their own weight and protect the formed interface; then, they slowly sat down. Approximately one minute was required for the subject to adapt to the interface, and four minutes were required for the sensor values to become steady under static conditions. After four minutes, a short recording of the pressure values was captured. Then, the sensor mat was removed, and the subject sat down for 1 h before providing their ratings. During the test, magazines and a computer were available for the subjects to pass time; posture shifts were also allowed. Upright, reclined, and forward inclined sitting positions were allowed during the test. Subjects chose to read magazines or a computer to browse webpages or to learn something online that would not lead to boredom.

Notably, the ratings were based on the subjects' own feelings of comfort or discomfort and compared among the five seat interfaces (Kyung et al., 2008). The second type of interface was formed using the subject's own weight. As the remaining three interfaces were all formed with vibrations, additional procedures were required. Approximately five to ten seconds (the average time for the subjects to feel that the