Applied Ergonomics 58 (2017) 198–207

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Vibrotactile perception assessment for a haptic interface on an antigravity suit

Sang Min Ko [a], Kwangil Lee [b], Daeho Kim [c], Yong Gu Ji [a, *]

[a] Department of Information and Industrial Engineering, Yonsei University, 50 Yonsei-Ro, Seodaemun-gu, Seoul, 03722, Republic of Korea
[b] Jin Air Co., Ltd., 453 Gonghang-dearo, Gangseo-gu, Seoul, 07570, Republic of Korea
[c] Republic of Korea Air Force Safety Center, P.O. Box 8, Yeouidaebang-ro 22-gil 77, Dongjak-gu, Seoul, 07056, Republic of Korea

ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form
16 June 2016
Accepted 24 June 2016

Keywords:
Haptics
Vibrotactile
Anti-G suit

ABSTRACT

Haptic technology is used in various fields to transmit information to the user with or without visual and auditory cues. This study aimed to provide preliminary data for use in developing a haptic interface for an antigravity (anti-G) suit. With the structural characteristics of the anti-G suit in mind, we determined five areas on the body (lower back, outer thighs, inner thighs, outer calves, and inner calves) on which to install ten bar-type eccentric rotating mass (ERM) motors as vibration actuators. To determine the design factors of the haptic anti-G suit, we conducted three experiments to find the absolute threshold, moderate intensity, and subjective assessments of vibrotactile stimuli. Twenty-six fighter pilots participated in the experiments, which were conducted in a fixed-based flight simulator. From the results of our study, we recommend 1) absolute thresholds of ~11.98–15.84 Hz and 102.01–104.06 dB, 2) moderate intensities of 74.36 Hz and 126.98 dB for the lower back and 58.65 Hz and 122.37 dB for either side of the thighs and calves, and 3) subjective assessments of vibrotactile stimuli (displeasure, easy to perceive, and level of comfort). The results of this study will be useful for the design of a haptic anti-G suit.

1. Introduction

The haptic sensation has different characteristics from those of visual and auditory sensations. The latter are perceived by specialized organs, i.e., the eyes and ears, whereas the haptic sensation can occur at any part of the human body via physical contact (Iwata, 2008). Thus, the body surface, the largest organ of the body (~1.8–2.0 m^2 for the average male) (Montagu, 1986), can be used as a channel for communication. Haptic sensations can provide an additional method of communication between systems and operators in environments in which there is visual or auditory overload (Spence et al., 2010). In 1960, Geldard proposed the sense of touch as a means of communication (Geldard, 1960) and there have been considerable advances and developments in this research area over the past 50 years. Recently, haptic (or tactile) interfaces have been studied and applied in diverse fields, including the medical sciences (Mayer et al., 2007), mobile devices (Qian et al., 2011), vehicles (Baldwin and Lewis, 2014; Gu Ji and Jin, 2010), virtual environments (Hale et al., 2009; Lahav and Mioduser, 2008), simulator training (Gerling and Thomas, 2005), and assistive technologies (Kim et al., 2013; Nam et al., 2012). The use of haptic technology in military aviation also has been studied (Albery, 2007; Salzer et al., 2011; van Erp et al., 2006).

The design of modern fighter aircraft continues to trend toward significantly enhanced technical capabilities, complexity, and sophistication to ensure the safety and reliability of the aircraft. As a result, pilots often face increasing demands on their perceptual, cognitive, and physiological abilities (Hettinger and Haas, 2000). Fighter pilots have to maintain the proper altitude, course, and speed of the aircraft in addition to performing tactical actions such as managing weapons, communicating, and monitoring the environment of the aircraft. To perform these tasks successfully, pilots need to acquire and combine information from different sources, including the flight system, local airspace, and the terrain (Tannen et al., 2004). Under such circumstances, the pilot could experience physical stress and mental overload. These difficulties can be made worse by high levels of fatigue, sustained acceleration, hypoxia, and very poor visual conditions (Van Erp and Self, 2008). The visual channel is the dominant method of communication between the flight system and the pilot. In addition, the auditory channel is considered an alternative or supplemental to the visual channel.

* Corresponding author.
E-mail address: yongguji@yonsei.ac.kr (Y.G. Ji).

http://dx.doi.org/10.1016/j.apergo.2016.06.013
0003-6870/

The flight system provides a great deal of information to the pilot in visual and auditory formats (Veen and Erp, 2001). Both channels of a pilot, working under extreme pressure, are considerably loaded with data so the ability of the pilot to process the data is degraded (van Erp and Verschoor, 2004).

The military aviation community and researchers from diverse fields have begun to investigate the use of a haptic (or tactile) interface to counteract the challenges of sensory and cognitive overload. The United States Air Force (USAF) developed the spatial orientation retention device (SORD), a multisensory system meant to reduce spatial disorientation. Navathe and Singh (1994) reported that "spatial disorientation is the failure of a pilot to correctly sense the attitude or motion of the aircraft, or of him or herself, resulting from inadequate or erroneous sensory information (from the receptors)." Spatial disorientation is a primary concern to both civil and military aviation because it is a major cause of fatal accidents. The SORD consists of head-mounted display (HMD) symbology, three-dimensional audio, and tactile vest, all of which provide visual, auditory, and tactile cues to the pilot. As a result, the SORD can help reduce pilot workload by providing complementary cues and thus improve aviation performance (Albery, 2007). The Naval Aerospace Medical Research Laboratory (NAMRL) developed the tactile situation awareness system (TSAS) to help the pilot maintain spatial orientation and effective control of the aircraft with no visual cues. The TSAS was flight-tested on a U.S. Navy T-34 aircraft. The test demonstrated that it is possible to improve pilot performance by providing intuitive three-dimensional spatial orientation and awareness information via a tactile display. Following the success of the T-34 TSAS project, the U.S. Army integrated the tactile display into a UH-60 helicopter (Chouvardas et al., 2005; McGrath, 2000). Van Erp et al. (2003) investigated whether a tactile torso display could compensate for degraded visual information when flying while wearing night vision goggles and found that it improved the performance of subjects under reduced (night) vision and full-vision conditions. The study of Van Erp et al. provided evidence that information can be delivered effectively to subjects via somatic tactile sense.

Previous studies demonstrated the possibility of the use of a haptic (tactile) interface in military aviation. Haptic technology in military aviation can improve performance and reduce workload, thereby reducing the risk of aviation accidents. However, previous studies on the subject had some limitations. Most had presented the effectiveness of the haptic (tactile) interface in military aviation only through a proof-of-concept, without any practical data for use in the development of actual equipment. Therefore, the aim of the present study was to obtain and provide preliminary data for use in developing a haptic (i.e., vibrotactile) anti-G suit to be worn in the fighter aircraft environment. We made a prototype of the suit and recruited currently serving Air Force fighter pilots to participate in the study. The experiments were conducted in the fixed-based flight simulator to ensure ecological validity.

2. Methods

2.1. Participants

Twenty-six fighter pilots (24 men) from the Republic of Korea Air Force (ROKAF) were recruited for the study after participating in regular safety education. The mean age of the participants was 31.9 years (range = 29–35 years), mean height was 172.4 cm (range = 162–186 cm), and mean weight was 69.5 kg (range = 57–82 kg). The flying experience of the participants varied; the aviation careers ranged from 5 to 12 years (mean = 8.5 ± 1.9 years) and total flight time ranged from 514 to 1592 h (mean = 965.8 ± 271.8 h). Previous studies generally classified study participants on the basis of their flying experience. Wiggins and O'Hare (2003) classified participants in their study on the basis of their cross-country flying experience. Those who had more than 1000 h of cross-country flying experience were classified as experts and the remainder were classified as novices. In addition, Schriver et al. (2008) classified their participants (28 pilots) on the basis of their flight-related expertise and flying experience. Participants were divided into two groups: "less expert" (14 pilots) and "more expert" (14 pilots). The more-expert group had more total flight hours (481.9 vs. 110.5 h) and more total instrument flight hours (80.5 vs. 10.8 h) and outperformed the less-expert group on the pilot skills test (14.6 vs. 13). The differences between the total flight hours and total instrument flight hours for the less-expert and more-expert groups were statistically significant. However, there was no statistically significant difference in the pilot skill test scores.

Participants in the present study were formally trained to become fighter pilots and are currently serving as fighter pilots in the ROKAF and participating in the regular classes. Based on their flying experience (aviation career and total flight time), 13 of our participants were less expert and 13 were more expert pilots. There was one woman in each group. The more-expert group had a longer aviation career (10.2 vs. 6.8 years) and more total flight time (1194.3 vs. 737.1 h) than the less-expert group (Table 1).

2.2. Apparatus and materials

2.2.1. Vibrotactile actuator

The vibrotactile stimuli were generated by a bar-type (cylinder-type, 21.9 mm long) ERM vibration motor comprising a direct current (DC) motor and a rotor with an eccentric mass of 4 g. The ERM vibration motor has been used extensively to generate vibrotactile stimuli in various studies and commercial products because of its low cost and structural simplicity. The generation of vibrotactile stimuli depends on the revolutions per minute (rpm) of the DC motor and the weight of the eccentric mass. Small DC motors are simple to control and can produce vibrations, but they have limited power-to-mass ratios and the frequency and amplitude of the vibrations are difficult to control independently. Therefore, small DC motors are generally activated at a fixed frequency and amplitude (Jones and Sarter, 2008).

We used the following instruments to identify the relationship between the voltage input and the physical characteristics of the vibrotactile stimuli, i.e., frequency and amplitude. The acceleration sensor (8692C50 triaxial accelerometer, Kistler Group, Winterthur, Switzerland) measured vibration along the *x*, *y*, and *z* axes simultaneously. Data acquisition (NI USB-6251, National Instruments, Austin, TX, USA) translated the sampling data into digital signals to be manipulated by a computer. The power supply and signal processor was type 5134B1 from the Kistler Group, and the data were acquired and analyzed using LabVIEW 2012 software (National Instruments). These instruments acquired, measured, amplified, and converted the vibrotactile stimuli generated by the vibration motor (Ji et al., 2011). During the experiment, the vibration motor, which was attached to the acceleration sensor, was suspended in air to measure the data without any interference. After analyzing the measured data, we estimated the relationship between the input voltage (V), the output frequency (Hz), and the output vibration level (dB) of the vibrotactile stimuli (Fig. 1). Consequently, when the input voltage throughout the main experiment was recorded, it was possible to identify the frequency and the vibration level.

2.2.2. Flight simulator

To ensure the ecological validity of the experiments, we used the