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The effects of pressurized partial pressure suits on operational ergonomics☆

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ABSTRACT

A study on capstan partial pressure suits (PPSs) was conducted to determine their effects on pilots' operational performance on a series of ergonomic measures at different pressure levels using objective and subjective approaches. Tests of range of motion, operational performance and operational strength were carried out on ten male subjects wearing PPSs under 6 different pressure conditions. Subjective tests related to pressure tolerance and operational performance were also conducted. A video-based motion capture and analysis system was used to record the trajectories of body motions. Analysis of variance was used to test the effects of the different pressures. It was concluded that a pressurized PPS had a significant impact on the pilot's range of motion (ROM) and operational performance, but no significant effect on their operational strength. Range of motion and operational performance decreased as pressure increased, but they were affected differently. The results may provide mission planners, suit designers and human factors engineers with better insight into the understanding of pilots' operational function, mobility and strength capabilities when wearing pressurized PPS.

Relevance to industry: This paper presents pilots' range of motion, operational performance and operational strength with pressurized PPS dressed and can help mission planners, suit designers and human factors engineers to improve PPS' performance.

1. Introduction

The development of higher-performance fighter planes has increased the protective capability requirements of partial pressure suits (PPSs) in areas such as compensation, anti-gravity, anti-penetration and cold-resistance, leading to an increased conflict between function and efficiency (Tripp and Larsen, 1996; Jeon et al. 2011). When a fighter plane accelerates quickly or the cockpit leaks in high-altitude flight, the PPS needs to be pressurized, which greatly restricts the pilot's movement and this results in a significant reduction of the pilot's operational performance (Berson, 2002; Tripp et al., 2007). Consequently, it is important to know which parts of the PPS have the greatest effect to the pilots' performance and then to improve the design of the PPSs in order to enhance its ergonomics performance. Therefore, research on pressurized PPS ergonomics is needed in order to improve the design of PPSs and increase operational efficiency.

A PPS must be fitted closely to meet the requirements of anti-G and pressure compensation, causing constriction and hindrance to the wearers' joint movements, making the fit of PPS essentially important (Scott and Simpson, 1989; Huck et al., 1997; Jeon et al., 2011). Scott studied a number of pilots' anthropometric data and put forward a range of fit for compensatory vests and anti-G pants, and suggested fitting them independently. Wheeler et al. (1994) studied a sizing system suitable for fitting a PPS by measuring the fit of an advanced technology anti-G suit and size recommendations for women were made based on that analysis. Crist et al. (1995) and Burns (1995) analyzed the fit of female pilots' PPSs and suggested, respectively, providing lumbar support and

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lowering the position of the abdominal gasbag. By studying the fit of personal protective equipment, Liu et al. (1998) established a fuzzy comprehensive evaluation method based on the pilots' subjective feelings. Jeon et al. (2011) used subjective feelings to improve the design of the neck circumference and crotch. Operational performance and range of motion (ROM) are also widely applied to the quantitative evaluation of PPSs' ergonomic features. For example, Albery and Chelette (1998) designed an experiment in which subjects tracked a simulated "bogey" aircraft on a visual display and performed a secondary task to test the effect of a G-suit on cognitive performance, and found that more advanced protective systems not only allowed longer G endurance, but provided adequate support for maintained cognitive performance throughout the extended exposure. Kozycki (1998) developed a 3D graphical anthropometric model and individual protective equipment numerical model to analyze the effect of a PPS on pilot performance. He compared the simulation results and the measured data using a 3D motion-capture system and proved the feasibility of this model. Hicks et al. (2010) created a digital human model to assessing the convenience in the wearers' operational performance and range of motion (ROM), which has been used to assess and improve the ergonomic design and usability of all modernized Army Aviation systems, as well as to reduce analysis and development timelines. In order to learn more about the influence of pressurized suits on efficiency, Berson (2002) studied the effects of inflating U-2 pressurized suits and concluded that the larger surface area greatly restricted pilots' movements and their normal operations, affecting almost all emergency operations. Tripp et al. (2007) studied the issue of gravity-induced loss of consciousness (GLOC) under high-G conditions and pointed out that using a pressurized PPS can reduce the duration of a GLOC episode. Guofu et al. (2006) put a pressure reduction device and a pressure discharge valve separately between the abdominal bladder and the capstan bladder in a capstan anti-G suit and the pressure in the abdominal bladder was reduced to approximately 40% of the capstan pressure. Adopting the new-styled pressure reduction technology could help relieve a pilot's abdominal pain caused by wearing an anti-G suit, improve comfort and enhance $+G_z$ protective capabilities. Eiken et al. (2011) studied the protective principles of the abdominal bladder and concluded that during positive airway pressure (PPB) incidents the abdominal bladder acted as a counter pressure for the airway, thereby facilitating pressure transmission from the airways to the thorax, improving G protection.

In spite of all these studies, to date there has been no systematic study on the influence of pressure and operational performance, especially studies on the influence of various pressure levels on PPS ergonomics. Therefore, based on a previous mechanical ergonomic evaluation method (Hu et al., 2008; Li et al., 2013), we designed experiments and conducted systematic research on the performance of a PPS at different pressures (0, 1.96, 3.92, 5.88, 7.84 and 10.49 kPa) aimed at providing an empirical basis for establishing a practical ergonomic evaluation method for pressurized PPSs and optimizing the use of protective equipment. The variables studied were ROM, operational performance and operational strength.

2. Methods

2.1. Subjects

Ten males 24.6 ± 4.9 years old (mean, standard deviation) with a height of 171.6 ± 2.9 cm and a weight of 66.0 ± 4.0 kg volunteered to participate in the experiments. All of the subjects' body sizes and physical condition met the Chinese pilots' recruitment criteria as well the experimental requirements, including no physical disability or limitations and no case histories of heart or lung problems. Only male volunteers were chosen to participate this experiment because the large majority of the Chinese pilots are males. Before testing, all the subjects were trained to master the skills needed for pressurized breathing.

2.2. Experimental design

Mechanical ergonomic studies on protective suits are mostly based on four factors: direction of movement, ROM, moving velocity and operational strength, which are all essential in operating a fighter jet (Ding, 2004). Direction of movement and ROM describe the range of motion in some direction and can be represented by ROM. Moving velocity represents the time to complete a movement which can be described by operational performance on the pilot's actual operations (Adams and Keyserling, 1996; Kebaetse et al., 1999). Operational strength describes the strength needed to operate some device during some movement.

According to the four essential factors, experiments involving ROM, operational performance and operational strength were performed in this study. The test items are shown in Table 1. During the experiments, ROM and HA (helmet adjustment), and operational performance of DBL (drawing back the legs) were captured by an infrared video-motion system (VICON 460). The time to accomplish the whole target-pointing test was recorded by stopwatch. Operational strength was measured by an electronic dynamometer. During the experiment, operational strength was measured firstly, and then the ROM, HA and operational performance of DBL were measured randomly because operational strength was relative with fatigue while the other there tasks were not relative. A medium size PPS was used in the experiment and the pressure was controlled by a pressure breathing trainer. All subjects were asked to complete a questionnaire at the end of the tests.

2.3. Apparatus

2.3.1. Three-dimensional motion-capture system

The VICON 460 system was comprised of a set of network-linked infrared camera units, a workstation and analysis software. In this system, camera units captured the trajectories of the markers attached to the subjects' bodies to indicate the motions of the subjects, and were calibrated dynamically using the software. The sampling frequency of the cameras was 120 Hz (Mavrikios et al., 2006).

2.3.2. Target-pointing board

A rectangular board was specially designed to simulate the movement of pilots performing the required tasks (Fig. 1). On the board, there were two touching points, four single-direction switches, and five buttons arranged from top to bottom.

Table 1
Test items and movements.

Test items		Movement
Range of motion	Head	Neck lateral flexion
		Neck rotation
	Shoulder	Shoulder abduction
	Elbow	Elbow flexion
Operational performance		Helmet adjustment
		Draw back Legs
		Target pointing
Operational strength		Grip strength