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Kinematic compatibility between the body and a mock spacesuit during basic upper body motions

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ABSTRACT

In this study, a novel conceptual method was tested to study the kinematic mismatch between the body motion of an occupant with respect to a rigid suit. It was hypothesized that differences between body and suit motion would require extra body movement to achieve the desired suit motion. To quantify the mismatch in kinematics, mock upper body suits with an open structure were used in conjunction with a marker-based motion capture system. A 3D motion modeling software was used to determine the range of motion of the suit and body segments of nine participants performing seven basic arm and trunk motions. In general, range of motion of the body segment was found to be higher than the corresponding suit segment range of motion. Differences in range of motion of up to 21.3% were found between corresponding body and suit segments, and significance was found in five of the seven motions.

Relevance to industry: Development of a method of determining kinematic misalignment of protective suits will assist evaluation and development of more appropriate protective suits. Better kinematic alignment will not only reduce the risk of injury, but can also improve comfort and benefit performance.

1. Introduction

Protective suits are used in many occupations and serve to protect the user from potential hazards such as fire, explosions/blasts, chemicals, low-oxygen environments, and other extreme environmental conditions. While protective suits are often crucial to performing a job, they can impose other risks and difficulties. Many protective suits are used in hot environments, and can increase the risk of thermal strain and heat stress (Nunneley, 1989). Additionally, many types of protective suits can restrict motion and increase risk of musculoskeletal injuries (Coca et al., 2010).

Like most protective suits, spacesuits worn outside the spacecraft, called Extravehicular Mobility Units (EMUs), are designed to protect the occupant from dangers presented by the environment. EMUs provide a supply of breathable oxygen, a consistent internal pressure, protection from radiation, and temperature regulation to the occupant (Jordan et al., 2006). However, despite their necessity, EMUs also pose risks to the occupants.

Scheuring et al. (2009) analyzed medical records and post-flight debriefs from the U.S. space program to identify 219 in-flight musculoskeletal injuries. Injuries of the hands, back, and shoulders were found to be most frequent. In addition to actual space travel, astronauts face many hazards during training exercises performed terrestrially using EMU. Strauss (2004) reported that suit symptoms were reported in 352 out of 770 (45.7%) training runs at the Neutral Buoyancy Lab (NBL), an underwater training area used to replicate zero-gravity conditions. In a similar study, Viegas et al. (2004) reported 280 complaints during 548 training sessions (51.1%) at the NBL. In both studies, the majority of the suit complaints involved the upper extremity. Due to the misalignment of the body and suit joints, extra volume and weight of the suit, and the pressurization of the suit, suited operations are much more demanding compared to performing the same tasks unsuited. Additionally, Gonzalez et al. (2002) found an average decrease in the work done until fatigue of 48% and 41% while working maximally (100% maximum voluntary torque (MVT)) and submaximally (80% MVT), respectively, when participants were suited. Gonzalez also found a significant decrease in range of motion due to the EMU.

Due to the pressurization of the suit, bearings are used to improve ease of movement. However, the bearings often do not align perfectly with the joints of the body, creating a kinematic misalignment between the suit and the occupant. While differences in the body and suit kinematics are evident, the differences have not been explored. This is partially due to the difficulties in

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tracking the motions of the user's body and the suit accurately at the same time. Systems that are used for motion capture and/or motion analysis are of two basic styles, marker-based and sensor-based.

Marker-based systems are regarded as the gold standard in motion capture (Kim and Nussbaum, 2012), as they can provide the ability to track markers with millimeter accuracy. However, one major drawback of these systems is the requirement for the markers to remain visible to multiple cameras in order to be tracked. Tracking the body motion of a person in an actual EMU would be difficult with this method.

Sensor-based systems rely on sensors consisting of gyrometers, accelerometers, and/or magnetometers, affixed to the body, to track the orientation and/or position of each sensor. However, these systems have their limitations, as well, and often exhibit errors in orientation measurement (Kim and Nussbaum, 2012). Sensor-based systems that incorporate magnetometers are prone to inaccuracy due to electromagnetic fields and other ferromagnetic material, while gyrometers and accelerometers suffer from integration drift, which causes a consistent decrease in accuracy with time (Roetenberg et al., 2007). Additionally, systems incorporating multiple types of sensors are larger and may interfere due to their size.

While both systems would work well for tracking the motion of the suit, the difficulty of tracking the motion of the occupant in the suit is challenging. In this study, a novel conceptual method has been tested to track the body motion of an occupant with respect to a rigid protective suit. Mock upper body suits with an open structure were used in conjunction with a marker-based motion capture system and modeling software to quantify the differences in motion between a spacesuit user and the suit. Findings of this study would prove the method viable for further research on protective suits.

2. Methods

Recruited participants attended two experimental sessions. In the first session, anthropometric measurements were recorded. Subsequently, mock upper body spacesuits were designed for each participant based on the participant's anthropometric dimensions. Participants returned for a second session, during which they donned the suit and performed the experimental tasks.

2.1. Equipment

2.1.1. Optical motion capture system

An eight camera marker-based optical motion capture system by Vicon (MX-Series, Vicon Motion Systems, Oxford, UK) was used to track, in three dimensions, 14 mm retro-reflective markers that were placed on anatomical landmarks of the participant's upper body and specific locations on the mock suit.

2.1.2. Modeling software

Visual3D 4.0 (C-Motion, Inc., Germantown, MD, USA) is a 3D modeling software designed for biomechanics modeling and analysis. Visual3D was used to create dynamic models of the subject's upper body and the mock suit while performing the experimental tasks.

2.1.3. Anthropometry kit

An anthropometry kit by DKSH Ltd. (Zurich, Switzerland) was used to collect upper body anthropometric dimensions of the participants. The kit consisted of various sizes and styles of sliding calipers as well as a measuring tape.

2.2. Participants

Nine healthy, adult male subjects with mean ± SD age, height, and weight of 26.8 ± 5.8 years, 174.1 ± 6.6 cm, and 80.2 ± 15.2 kg, respectively, were recruited for this research. Subjects with any musculoskeletal disorders that could affect mobility or range of motion were excluded from this study. Prior to participation, subjects were familiarized with the study procedures and consent was gained via consent form approved by the local research ethics board.

2.3. Anthropometric measurements

During the first visit to the laboratory, the participants were familiarized with the study procedures and their anthropometric measurements (Table 1) were collected to calculate proper dimensions of the suit. Upper arm dimensions, lower arm dimensions, and trunk circumference and width were measured using procedures described by McConville et al. (1980). The remaining measurements were performed as described in Table 1.

2.4. Upper body mock suit

The mock suit was designed as a rigid frame with the majority of the space left uncovered. This allowed 14 mm retro-reflective markers to be placed on the forearm, upper arm, and trunk of the participant which made it easy to track the segments with an optical motion capture system. Images, models, and dimensions of the mock upper body suit can be seen in Fig. 1.

The trunk segment of the mock suit was created with foam board. First, four octagons were cut from the foam board, and a smaller octagon of the same size was cut from the center leaving a 2.54 cm (1 in.) wide foam octagon. Each pair of the foam octagons were glued together with polyvinyl acetate glue leaving two octagons that are double thickness. Next, six 2.54 cm (1 in.) strips of foam board were cut and used to attach the two foam octagons at six points. Shoulder straps were made by creating four U-shaped 2.54 cm (1 in.) wide foam board pieces and gluing each pair

Table 1
Anthropometric dimensions collected from each participant in order to design their mock spacesuit.

Dimension	Description	Mean ± SD (cm)
Upper arm length[a]:	*Distance from acromion process of the shoulder to the lateral epicondyle at the elbow*	28.1 ± 2.3
Upper arm girth[a]:	*Girth of the upper arm at the largest point*	33.2 ± 3.7
Lower arm length[a]:	*Distance from lateral epicondyle of the elbow to the styloid process at the wrist*	25.6 ± 1.9
Lower arm girth (prox.):	*Girth of the lower arm directly below the elbow*	28.4 ± 2.3
Lower arm girth (dist.)[a]:	*Girth of the lower arm at the wrist*	17.7 ± 1.3
Trunk length (full):	*Distance from C7 vertebrae to L5/S1 junction*	46.8 ± 3.2
Trunk length (top):	*Distance from C7 vertebrae to bottom of the chest*	28.5 ± 3.7
Trunk length (bottom):	*Distance from L5/S1 junction to bottom of the chest*	18.3 ± 1.9
Trunk girth[a]:	*Girth of the trunk at the largest point*	97.8 ± 9.2
Trunk thickness:	*Thickness of the trunk at the thickest point*	25.9 ± 4.0
Trunk width:	*Width of the trunk at the widest point*	32.2 ± 2.5

[a] Measurements as described by McConville et al. (1980).