

Philosophies Applied in the Selection of Spacesuit Joint Range-of-Motion Requirements

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ABSTRACT

Space suits are the most important tool for astronauts working in harsh space and planetary environments; suits keep crewmembers alive and allow them to perform exploration, construction, and scientific tasks on a routine basis over a period of several months. The efficiency with which the tasks are performed is largely dictated by the mobility features of the space suit. For previous space suit development programs, the mobility requirements were written as pure functional mobility requirements that did not separate joint ranges of motion from joint torques. The Constellation Space Suit Element has the goal to make more quantitative mobility requirements that focused on the individual components of 'mobility' to enable future suit designers to build and test systems more effectively. This paper details the test planning and selection process for the Constellation space suit pressure garment range of motion requirements.

INTRODUCTION

As mobility requirements are decomposed from Level I, which is the highest Programmatic level, down to Level IV, the Element level, the Element is forced to decide what level of fidelity is required to produce the functionality that is desired in an end product. Past programs such as Apollo and Space Shuttle determined that their functional, or task oriented, mobility requirements were sufficient to ensure that the suits could enable and would not prevent astronauts from conducting tasks as specified in their respective Concepts of Operations and did not decompose requirements further (1). The benefit of ending decomposition at the functional task level is that, at the

end of suit system certification, a designer has directly verified that the suit does not inhibit the target population from completing the discrete functional tasks required to meet mission objectives. However, by opting for a direct correlation between mobility requirements and human performance during verification, one loses the ability to test components individually and accepts some level of risk for the ability to complete tasks other than those specifically called out in the requirements.

An alternative to accepting functional mobility requirements at the Element level is to further decompose the tasks into the specific components of mobility, range of motion (ROM) and torque, required to complete the functional tasks. Writing mobility requirements in terms of individual joint ROM and joint torques is more conducive to the "build a little, test a little" approach to suit design as it allows designers to test pressure garment patterning at the component level as opposed to the system level. This approach also increases the likelihood that crewmembers will be able to complete tasks that are not explicitly stated in the requirements. Yet, this approach is still more complex in that it has never been done before so there is no standard against which to compare nor are joint by joint ROM and torque verifications alone a guarantee that all functional tasks can be achieved.

The Constellation Space Suit Element elected to write Element (CSSE) level mobility requirements in terms of joint ROMs and torques with the understanding that the Level III requirements will be verified by test and not merely by analysis ("Level IV requirements verified therefore Level III verified"). The decision to take this

route for CSSE requirements ultimately rested on the idea that, in the light of a relatively immature operations concept, quantitative mobility requirements would be more likely to ensure the ability of the suit systems to meet mission objectives.

STUDY APPROACH

The Pressure Garment Subsystem (PGS) was tasked with leading mobility requirements development for CSSE. The PGS team began by requesting support from the NASA Anthropometry and Biomechanics Facility (ABF) to determine how to benchmark the capabilities and limitations of existing pressure garments with respect to the Constellation Level III functional mobility requirements.

The first step in the process was to pare down the complete list of functional activities into smaller, easily understood activities that encompassed the maximum ROMs that were required by more complex tasks. For example, the Extravehicular Activity (EVA) System requirement EVA2055 states, "The Suit Element shall provide the mobility for use of microgravity EVA tools." This is a complex task that drives mobility in the shoulder, elbow, wrist, and fingers. Furthermore, it is a somewhat ambiguous task as the design and use of EVA tools were undefined at the time of this test series. Thus, to encompass the unknowns that were associated with "mobility for use of microgravity EVA tools," tasks that were redundant in terms of gross mobility (e.g., the use of several different hand tools) were reduced to a single task that encompassed the motion of the complete set. Lastly, the team removed all minor tasks that were highly unlikely to maximize a joint range of motion and tasks that would be exceedingly difficult or impossible to collect data on using existing motion capture technology. The final set of tasks tested included 45 functional activities and 18 isolated joint movements (2).

Once the tasks were determined, the PGS team selected five suits to use for the evaluation based on their ability to meet the gross ROMs that were expected to be inherent in the EVA System Reference 2 (ESR2) design concepts. The two main areas of concern for the Configuration 1 (C1) design were hip and shoulder mobility while pressurized, and the ability to conduct pre- and post-landing survival tasks while unpressurized. To that end, the Advanced Crew Escape Suit (ACES), Enhanced Mobility Advanced Crew Escape Suit (EM ACES), and D-suit were used to represent the C1 mobility.

The EM ACES is the closest pressurizable representation of ESR2 C1, with the notable exceptions that it does not include thigh disconnects, a modular helmet, or a ganged umbilical connector for consumables delivery. The key mobility features designed into the EM ACES are scye bearings (shoulder flexion/extension), upper

arm bearings (arm internal/external rotation), hip convolutes (flexion/extension), wrist bearings (used for supination/pronation) and the neck bearing (internal/external head rotation). The primary requirements drivers for EM ACES were launch, entry, and abort (LEA) operations but it was also expected to exhibit ability for simple pressurized EVA tasks. The approximate total mass of EM ACES, as tested, is 38 lbs.

The ACES is the current Space Shuttle Program LEA survival suit. Its joints are all soft, with the exception of the wrist bearing (used for supination/pronation) and the neck bearing (internal/external head rotation). The flight configuration of ACES includes an external survival and parachute harness that were not included in the ROM evaluations. The approximate total mass of the ACES, as tested, is 34 lbs. For pressurized testing, the suit was inflated to 3.5 psid. The ACES design was optimized for unpressurized mobility and was expected to be most representative unpressurized capabilities of the C1.

For the Configuration 2 (C2), the main mobility concerns center around the crewmembers' ability to perform planetary EVA. This need drives mobility requirements to mimic the capabilities of the unsuited astronaut as closely as possible. The PGS team selected the Mark III Space Suit Technology Demonstrator suit (MK-III) and the Waist Entry I-suit to represent the mobility of a Constellation C2 pressure garment. Both suits are highly mobile when pressurized and optimized for exploration/ambulation, but they use different mobility features to accomplish the tasks.

The WEI was developed in the late 1990's in an effort to produce a suit with pressurized performance characteristics similar to the MK-III but at a significantly reduced weight. It is the closest physical representation of ESR2 in the current Advanced Space Suit Laboratory inventory. The nominal operating pressure of the WEI is 4.3 psid. The WEI's mobility features include scye bearings (shoulder flexion/extension), patterned convolute shoulders (shoulder lateral/medial and adduction/abduction), upper arm bearing (internal/external arm rotation), wrist bearings (supination/pronation), waist patterned convolute (flexion/extension), two-bearing hip assembly (flexion/extension, torso rotation, internal/external leg rotation), and patterned gore joints at the elbows and knees, and patterned convolute at the ankles (flexion/extension). The approximate total mass of the WEI, as tested, is 68 lbs.

The MK-III was developed in the late 1980's as part of an effort to test the feasibility of new joint mobility systems for surface exploration suits; it arguably offers the most pressurized mobility for planetary exploration of all NASA's current space suit inventory. The MK-III varies from the ESR2 in three main ways: suit materials (combination hardgoods and softgoods), shoulder design, and torso mobility features. Its mobility features

pressure range is 4.3 psid to 8.0 psid. The MK-III's mobility features include scye bearings (shoulder flexion/extension), rolling convolute shoulders (shoulder lateral/medial and adduction/abduction), upper arm bearing (internal/external arm rotation), wrist bearings (supination/pronation), waist bearing (torso rotation), waist rolling convolute (flexion/extension), three-bearing hip assembly (flexion/extension, internal/external rotation), lower leg pivot (hip adduction/abduction), ankle bearings, and patterned gore joints at the elbows and knees, and patterned convolute joints at the ankles (flexion/extension). The approximate total mass of the MK-III, as tested, is 115 lbs.

The test subject pool for the series consisted of two (2) females and four (4) males, all of whom were from the engineering test subject database. Their statures ranged from 60% female (2% male) to 60% male (> 99% female). While not inclusive of the entire CSSE anthropometric design range, these statures do represent the practical sizing limits of the space suits that were used for the evaluation. Different suits have varying ranges of sizing capability and it was impossible to 'fit' all of the test subjects within a flight program definition of fit. However, the lack of fit was compensated for by the fact that all of the subjects with suboptimal fit had a good depth of pressurized test experience in multiple suits and facilities.

GENERAL DATA INTERPRETATION

The ABF and PGS teams used the same data sets as the foundation for their interpretations and, ultimately, to guide their recommendations for mobility requirements, but the teams elected to interpret the data in different manners to provide the most appropriate requirements to their respective requirements documents. The PGS team was focused specifically on providing suited mobility requirements for the CxP 72208 Suit Element Requirements Document (ERD) in a way that would be

meaningful to suit designers and applicable across mission phases. The proposed CSSE architecture is a modular system, which means that some components are physically shared across suit configurations within a single mission and are therefore held to requirements in multiple mission phases. The ERD assigns mission phase applicability to each requirement as either LEA, microgravity EVA, Intravehicular Activity (IVA), or Lunar Extravehicular Activity (LEVA), to indicate the configuration in which hardware will be used. Thus, the first task for the PGS team was to determine how to apply the ERD applicability definitions to these specific mobility requirements. After much debate, the PGS team came to the conclusion that the gravity field in which an astronaut operates is a significant driver for the amount of mobility required by any one joint because in reduced gravities in particular, crewmembers have more freedom to orient their bodies to compensate for reduced joint ROMs. Hence, in the final mobility requirements, the standard ERD mission phases were replaced by LEA, MG IVA/ EVA, Lunar IVA and Lunar EVA to make the gravity field distinction clear. The gravity field applicability was then subdivided into all pressure regimes for each scenario to help clarify what capability is expected in the different modes of operation (i.e. joints optimized for IVA operations would not be expected to have high shoulder ROM when pressurized).

The ABF completed post-processing of the raw Vicon data to delete false markers and ensure proper relationships between marker reference frames. The ABF then provided clean, post-processed ROM data for the engineering subjects to the PGS team to use for interpretation. The data were provided in two formats: bar graphs and tables. Bar graphs separated the data into a single chart per joint motion per pressure condition and then provided side-by-side comparisons of each subject's maximum performance in both isolated motion and functional motion in each of the suits, as shown in Figure 1.