Objective Metrics Quantifying Fit and Performance in Spacesuit Assemblies

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INTRODUCTION: Human-spacesuit fit is not well understood, especially in relation to operational performance and injury risk. Current fit decisions use subjective feedback. This work developed and evaluated new metrics for quantifying fit and assessed metric sensitivity to changes in padding between the human and hip brief assembly (HBA).

METHODS: Three subjects donned the Mark III (MKIII) spacesuit with three padding thicknesses between the lower body and HBA. Subjects performed a walking task with inertial measurement units on the thigh and shin of both the human and suit. For each step, cadence, human knee task range of motion (tRoM), difference in human and suit tROM (ΔtRoM), and the relative coordination metric (ρ) between the human-suit femur and tibia were computed.

RESULTS: The MKIII significantly reduced user cadence by 20.4% and reduced tRoM by 16.5% during walking with subject-dependent changes due to added padding. In general, the addition of padding significantly altered ΔtRoM; however, variability did exist between subjects. Mixed-effect regressions of dynamic fit (ρ) reflect distinct positive spikes in ρ around heel strike (human-dominated motion) and negative dips following toe off (suit-dominated motion).

DISCUSSION: There were mixed effects of padding on gait performance and dynamic fit measures. Differences in dynamic fit between subjects may be more reliant on alternate aspects of fit, such as suit component sizes and designs, than padding level. Subjective feedback supported quantitative observations, highlighting metric utility. Future work will explore the effects of suit sizing components on measures of fit and performance.

KEYWORDS: human performance, suit fit, human-spacesuit interaction, coordination.

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Human spaceflight and exploration beyond low-Earth orbit requires providing crewmembers with life support systems in the form of extravehicular activity (EVA) spacesuit assemblies (SSA) that simultaneously protect the user while maintaining mobility. Critical to mission success is the ability for users to effectively accomplish a series of mission-related operational tasks while reducing risks to health and injury.[2,17] Human performance during mission-related tasks is limited by the ability of the user and the restrictions due to the SSA being worn. Newer SSA designs aim to increase mobility and reduce deviation with unsuited human kinematics, thereby reducing injury risk and metabolic cost of transport.[9,27] However, these designs still tend to limit mobility and add torque to the system. These extra torques arise from bearing resistances, torques added by soft goods and rolling convolute joints, and inertial changes of heavy components.[11]

Injury risk and operator performance, however, are not just dependent on SSA design, but also how the human operator interacts and fits with the system as a whole. Ross et al.[27] describe how designing SSAs with joint-specific mobility and range of motion does not necessarily guarantee the ability to perform specific mission-related tasks. Inappropriate fit can lead to misalignment between the human and suited joint, thereby decreasing overall mobility. Discomfort can also arise due to human-suit interaction pressures and can result in reduced mobility.[27] Therefore, mobility, fit, and comfort of the suited operator are all related to overall task performance and

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mission success. Suit mobility has been quantified by evaluating suit joint ranges in motion and gait parameters. Cullinane et al.[11] compared unsuited to suited gait kinematics using the Mark III (MKIII) planetary SSA and showed that the MKIII system-imposed gait characteristics significantly deviated from unsuited gait properties. Meyen et al.[24] used a representative robotic system to test SSA mobility and demonstrated that pressurized SSAs add resistive joint torques that would potentially increase the effort necessary to actuate SSA joints. Di Capua and Akin[8] first proposed using inertial measurement units (IMUs) to evaluate human positioning inside of SSAs. Bertrand et al.[5] expanded on this work and used IMUs to measure upper extremity human and suit kinematics as a means of understanding suit mobility and how humans move inside SSAs. IMUs have also been implemented to measure other aspects of human biomechanical performance, such as agility,[7,30] balance,[13] and stair climbing.[25] Comfort is typically evaluated subjectively from user feedback. However, Anderson et al.[3] have built pressure sensors to measure the interaction forces between the shoulder, arm, and forearm of suited subjects and the shoulder bearings in the MKIII. The human-suit interaction has also been modeled using computer-aided design (CAD). The Anthropometry and Biomechanics Facility at NASA Johnson Space Center has created digital models of the suit and human manikins to observe how different human anthropometries affect the alignment with suit joints and components.[1,20]

While these efforts have examined suit mobility and comfort, suit fit is an area of the human-suit interaction that is not well understood and has not been objectively measured in experimental settings. Apollo era SSAs were custom built based on individual crewmember anthropometry. Newer SSA designs, such as the Extravehicular Mobility Unit (EMU) and MKIII, have components of different sizes that can be interchanged to fit individual subjects. Next-generation suit designs have also explored greater degrees of customization, such as the PXS prototype with the ability to adjust shoulder bearing angles.[1] However, it is unclear how changing the suit component sizes affects operational performance. NASA internal documentation has suggested that suit operators have noticed changes in arm length greater than 6 mm (~0.25 in).[1] In addition, suit operators with large gaps between the human and suit report difficulty in performing certain mission-related tasks.[1,27] SSAs also add mass and resistive torques to the human operator, which can fundamentally change natural operator kinematics.[11,24] However, it is unclear how the operator will handle these changes in mass and resistive torques based on the task they are performing and the environment in which they are being performed (i.e., microgravity vs. planetary environments). A better understanding of the relationship between suit component size, overall suit fit, and mission-related performance will aid design requirements for the degree of customization necessary for SSAs. Therefore, while there is evidence that spacing within the suit (indexing) and sizing of soft goods (arm and leg length) play a role in perceived suit fit, quantified methods for evaluating fit are warranted to aid in the evaluation of different design solutions on operational performance.

A key challenge in creating these measures is that it is not obvious what characteristics define acceptable fit in a task and environment-specific manner. Fineman et al.[14] began defining characteristics relevant to suit fit through a modified Cognitive Task Analysis (CTA) adapted from Stirling and McLean.[28] CTA aims to understand information required, thinking processes, and goals used to make decisions within observable environments. Current decisions regarding fit are made qualitatively by crewmembers and engineer experts during fit-checks and familiarization runs. Fineman et al.[14] used this human-centered approach through observations of fit checks and discussion with crewmembers and engineers at NASA Johnson Space Center to generate suit fit decision workflow diagrams (an updated version of these workflow diagrams can be found in Supplemental Figs. A, B, and C available online at https://doi.org/10.3357/AMHP.5123sd.2018). These diagrams highlight information used to make decisions regarding fit, which can be leveraged to generate candidate quantified suit fit metrics.

From the workflow diagrams, two categories of suit fit are observed: static and dynamic (**Fig. 1**). Static fit refers to how the suited subject sits within the suit in a neutral posture. One of the most relevant measures for static fit is indexing, which is the amount of space the subject has between certain anatomical landmarks and components of the suit architecture (Fig. 1A). Other relevant considerations of static fit include the length of soft goods and locations where the human rubs against the suit when not moving. The indexing can be altered by adding layers of padding between the human and suit component. Dynamic fit refers to how the human and suit move and interact with each other in dynamic settings (Fig. 1B). Relevant measures for dynamic fit include differences in human and suit joint angles

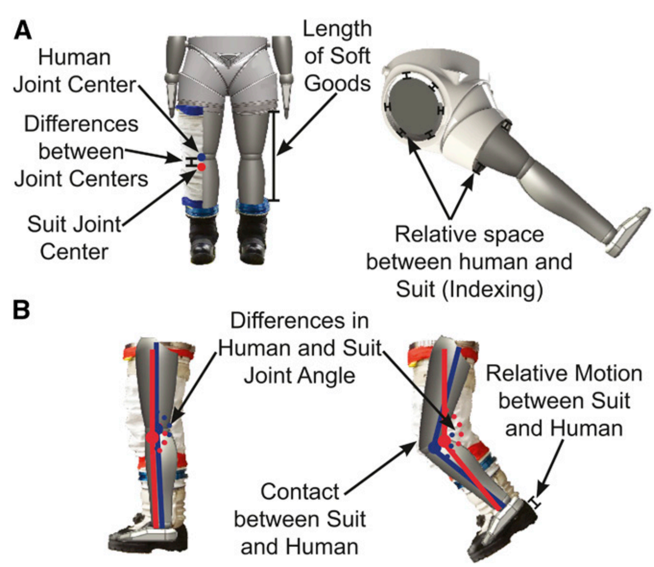

Fig. 1. Schematics highlighting aspects of: A) Static Fit, and B) Dynamic Fit extracted from a CTA of MKIII fit checks (more factors contributing to static and dynamic fit can be found in Supplemental Materials online at https://doi.org/10.3357/AMHP.5081sd.2018).

while moving and the relative motion between the suit and human. The human-suit interaction, when and where the human and suit come into contact, is also an important consideration when evaluating dynamic fit. It is often unclear how static fit might affect dynamic fit. Furthermore, it is unclear how static and dynamic fit might affect suited performance in operationally relevant conditions and what injury risks (if any) might be associated with changes in these two categories of fit.

Most decisions regarding suit fit are made qualitatively; there exist no objective, quantitative metrics of suit fit that aid in sizing subjects to these SSAs. Quantitative measures could augment subjective feedback currently provided when SSAs are fitted to new subjects and aid in understanding how tasks and environments affect performance as a function of the selected static and dynamic fit parameters. This paper presents quantitative metrics of suit fit that were derived from observing suit fit checks. A pilot study was performed to evaluate the sensitivity of these proposed new metrics to changes in nominal fit. Specifically, we assess the sensitivity of our metrics to detect how changes from nominal static fit (padding at the hip and thigh) cause potential changes in dynamic fit in the lower extremities during a simple gait task. The sensitivity analysis was accomplished by evaluating the hypotheses that adding padding between the human and hip brief assembly of the MKIII spacesuit would affect measures of a) gait performance and b) dynamic fit.

METHODS

Subjects

A pilot study was performed with three male subjects. Due to time constraints and SSA availability, an incomplete dataset was collected on a fourth male subject. Thus, here we present results from three subjects (**Table I**). All three subjects were novice suit operators and performed a fit check with the MKIII spacesuit on a separate day prior to this study. All subjects were cleared with a Class I medical exam to participate as a suit operator. The study protocol was approved by the NASA Johnson Space Center IRB and the MIT Committee on the Use of Humans as Experimental Subjects. Subjects provided written informed consent prior to performing the experiment.

Equipment

This study was performed in the Anthropometry and Biomechanics Facility (ABF) at the NASA Johnson Space Center. Subjects wore a long-sleeve compression shirt and pants below the liquid cooling garment (LCG). Five strap-on IMUs (Opal IMU, APDM, Inc. Portland, OR), with embedded accelerometers, gyroscopes, and magnetometers (sampling rate of 128 Hz) were placed above the LCG on the left/right tibia, left/right femur, and sacrum of each subject (**Fig. 2**). Five IMUs were also secured to the MKIII spacesuit with tape and coflex to the left/right upper leg, left/right lower leg, and hip brief. Custom sleeves at the hips and thighs were stitched into the LCG to add padding between the suited subject and MKIII spacesuit. Foam padding (Viton) was inserted into these sleeves to alter the indexing between the subjects and MKIII at these two locations (Fig. 2B and C). Volumetric scans were obtained at the U.S. Army Natick Army Center and ABF to obtain subject anthropometry. A combination of these anthropometric scans and a CAD model of the MKIII hip brief was used to determine the level of padding added to the LCG between the subject hips/thighs and MKIII hip briefs (Table I).

Procedure

Subjects performed a series of walking tasks on an elevated walkway (10 m long and 1 m wide). For the unsuited condition, subjects donned the compression shirt, pants, LCG, and human IMUs, and performed 12 walking trails. For the suited condition, the MKIII was pressurized to nominal suit pressure (4.3 psi) in a tethered configuration; i.e., no closed-loop portable life support system (PLSS) was used. Subjects donned the MKIII with all 10 IMUs 3 times, each with different padding configurations at the hips and thighs: no (C0), single (C1), and double (C2) layer of padding (Fig. 2, Table I). The C0, no padding, configuration served as a control and was the nominal component sizing fit configuration for each subject acquired from fit checks performed prior to this experiment. The approximate weight of the MKIII without a human inside or PLSS attached is 59 kg;[2] the actual total weight of the human and MKIII varied based on the subject and configuration. For each suited condition, subjects performed 24 walking trials, resting as needed in between all trials. All 10 IMU sensors were wirelessly synchronized using manufacturer's software at the beginning and end of each walking trial. In addition to walking tasks, participants performed single and double leg balance tasks while unsuited and suited, but these data were not analyzed within the scope of this paper. Following each suited configuration, subjects were asked to subjectively evaluate their perceived fit compared to the other padding configurations. Subjective feedback was recorded by the test conductors. The order in which unsuited and suited

Table I. Subject Data and Testing Order.

SUBJECT #	AGE (years)	HEIGHT (inches)	CROTCH HEIGHT (inches)	KNEE HEIGHT (inches)	HIP BREADTH (inches)	THIGH CIRCUM (inches)	SUIT LEG LENGTH	BOOT SIZE (Type)*	TESTING ORDER**	C1 (inches)	C2 (inches)
2	26	66	29	18.5	14.5	22	Large	8-10 (S)	US-C0-C1-C2	0.375	0.75
3	25	69	31	19.5	14.5	22.5	Large	11-13 (B)	C2-C1-C0-US	0.375	0.75
4	27	68	32	20	16	23	Large	8-10 (S)	C2-C1-C0-US	0.25	0.50

* S = strap-based boot design; B = boa-based boot design.
** US = unsuited, C0 = Configuration 0 (no padding), C1 = Configuration 1 (one layer of padding), C2 = Configuration 2 (two layers of padding).

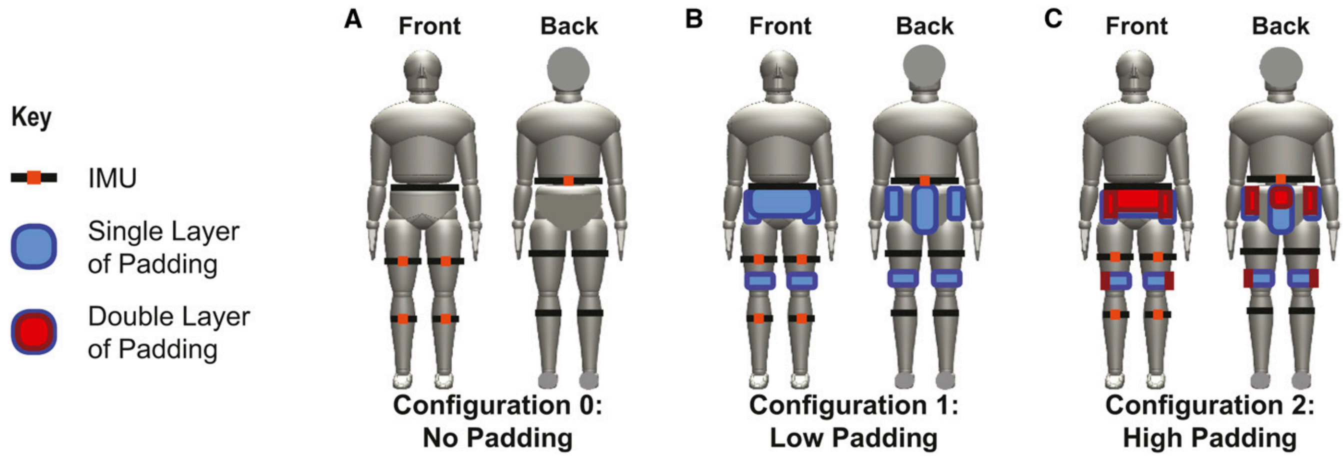

Fig. 2. Locations of padding and inertial measurement unit sensors on humans for Configuration 0 (C0), Configuration 1 (C1), and Configuration 2 (C2).

trials were performed was counterbalanced between all subjects (Table I).

Data Analysis

This section provides the physics-based rationale behind the selection of new metrics for suit fit. First, it was necessary to define task performance metrics and fit metrics. A simple gait task was utilized in this study; therefore, two metrics were selected to evaluate task performance: 1) cadence; and 2) human knee range of motion. These metrics can be computed and compared between suited and unsuited trials to understand how the MKIII affects task performance. An ideal SSA design and fit should minimize deviation from unsuited kinematics.[11,27]

Fig. 2B highlights three aspects of dynamic fit, with more aspects presented in the Supplemental Figs. A, B, and C online at https://doi.org/10.3357/AMHP.5123sd.2018. This work defines two metrics to quantify: 1) the difference in suit and human knee angle ($\Delta tROM$); and 2) relative motion between the suit and the knee [$\rho_{HS}^{n}(t)$]. The difference in the suit and human knee angles is computed by comparing knee task-specific range of motion (tRoM) during each step. $\Delta tRoM$ is defined by:

$$\Delta tRoM = tRoM_S - tRoM_H \qquad \text{Eq. 1}$$

where $tRoM_S$ is the tRoM of the suit knee and $tRoM_H$ is the tRoM of the human knee. Positive values of $\Delta tRoM$ are indicative of steps during which the suit had a greater tRoM, while negative values of ΔRoM represent steps when the human had a greater tRoM. $\Delta tRoM$ is computed for each step.

Relative motion between the suit and human was quantified by adapting the methodology from Fineman and Stirling[15] that quantified coordination in the context of rehabilitation, termed the relative coordination metric (RCM, ρ):

$$\rho_{HS}^{n}(t) = 2\tan^{-1}\left(\frac{\Omega_H(t)}{\Omega_S(t)}\right) - 90° \qquad \text{Eq. 2}$$

where $\rho_{HS}^{n}(t)$ represents the RCM between the human and suit body segment n at time t. $\Omega_H(t)$ and $\Omega_S(t)$ are the angular velocity magnitude of the human and suit:

$$\Omega_{H/S}(t) = \sqrt{\omega_x^2(t) + \omega_y^2(t) + \omega_z^2(t)} \qquad \text{Eq. 3}$$

where $\omega_{x/y/z}$ are the angular velocity readings from IMU x, y, and z axes. By definition, $\rho_{HS}^{n}(t)$ ranges between 90 and −90°, where $\rho_{HS}^{n}(t) = 0°$ represents motion in which both the human and suit are moving completely synchronously, $\rho_{HS}^{n}(t) = +90°$ represents a movement in which the human is moving while the suit is not, $\rho_{HS}^{n}(t) = -90°$ represents a movement in which the suit is moving while the human is not, and values in between represent motions with varying degrees of coordination between the human and suit. The time-series nature of $\rho_{HS}^{n}(t)$ allows for the observation of how relative motion between the human and suit evolves over time and at various phases of the gait cycle.

Walking trials were parsed using recorded UNIX timecode stamps. For each trial, a wavelet analysis was performed using the human tibia accelerometer and gyroscope data to identify the following gait phases: stance (ST), heel-off (HO), toe-off (TO), swing (SW), and heel strike (HS).[22,26] Steps were parsed from heel strike to heel strike and compiled for each subject. A total of 72 steps were recorded for each subject. The final 20 steps in each of the conditions were used for the remainder of the analysis to aid in minimizing learning effects from adapting to the MKIII suit. Cadence (steps per minute) was estimated by taking the number of samples in each step and dividing by the IMU sampling rate. For each subject, all unsuited and suited (C0-C2) cadence values were then normalized by the mean unsuited cadence for each subject. Knee angles of the human and suit were estimated using a Principal Component Analysis (PCA) method to estimate the knee hinge axis and Davenport algorithm to estimate the angle with respect to the axis.[12,23] This method requires a static period with straight legs to define the zero-degree flexion datum. Since this static offset was not incorporated into the original study design, absolute values for the angles could not be shifted to the standard datum. However, task-specific range of motion (tRoM) was possible to assess. Thus, human and suit knee tRoM were computed for each unsuited/suited configuration and step. This measure does not reflect the full range of motion of the human and suit knee, it represents the range of the knee specific to the task performed. For every suited step, Eq. 1 was used to compute $\Delta tRoM$.

Raw angular velocities from IMU 3-axis gyroscopes were mean subtracted based on individual sensor static noise offsets obtained every day prior to testing and were then filtered using a 6th order Butterworth 30-Hz low-pass filter. $\rho^{n}_{HS}(t)$ was then computed between the human femur-suit upper leg (ρ^{F}_{HS}) and human tibia-suit lower leg (ρ^{T}_{HS}) using Eq. 2. Small values of $\Omega(t)$ can amplify measurement noise, which can represent inaccurate favoring of one segment over another. Therefore, for differences between $\Omega_H(t)$ and $\Omega_S(t)$ less than 0.05 rad $\cdot$ s^{-1}, $\rho^{n}_{HS}(t)$ was set to 0. This value was determined based on the maximum static noise offset of the gyroscope magnitude for all 10 IMU sensors. Values of $\rho^{F}_{HS}(t)$ and $\rho^{T}_{HS}(t)$ were extracted at all five gait phases (ST, HO, TO, SW, HS) and all 20 steps for statistical analysis. For the present analysis, right-sided sensors and body segments are presented due to an incomplete left-sided dataset.

In summary, for each step taken while the user was wearing the spacesuit, the following metrics were obtained: 1) normalized step cadence; 2) human knee tRoM ($tRoM_H$); 3) $\Delta tRoM$; 4) $\rho^{F}_{HS}(t)$; and 5) $\rho^{T}_{HS}(t)$.

Statistical Analysis

To assess sensitivity of the fit metrics, we evaluated the hypotheses that the addition of padding between the human and hip brief assembly of the MKIII SSA would affect a) gait performance (H1 – normalized cadence and H2 – the tROM) and b) measures of dynamic fit [H3 – the differences in human and suit knee tRoM ($\Delta tRoM$) and H4 – the relative motion between the human and suit at various phases of the gait cycle as measured using $\rho^{n}_{HS}(t)$].

Three mixed-effect analysis of variance (ANOVA) models were fit to assess hypotheses 1–3. Two mixed-effect ANOVA were used to test H1 (normalized cadence) and H2 ($tRoM_H$), where subject (3 levels) was modeled as a random effect and unsuited/suited configuration (4 levels) was modeled as a fixed effect. To evaluate differences in $\Delta tROM$ between subject and degree of padding (H3), a two-factor ANOVA was implemented with subject (3 levels) as a random-effect and suited configuration (3 levels) modeled as a fixed effect. Post hoc comparisons were performed using Tukey's honesty criterion when significant main and/or interaction effects were found. Significance was set at $P < 0.05$ for all tests. Cohen's d effect sizes were computed for all significant posthoc comparisons.[10] All ANOVA statistical tests were performed using MATLAB 2017b (The Mathworks, Inc., Natick, MA).

The effect of gait phase and padding on femur $\rho\ [\rho^{F}_{HS}(t)]$ and tibia $\rho\ [\rho^{T}_{HS}(t)]$ (H4) was evaluated using mixed-effect regression models due to their temporal nature. The data were modeled by fitting a random-effect intercept for each subject-by-configuration and, for the random-effect slope, fitting the RCM trajectory across gait phase. The inclusion of this random-effect slope improved model fit, $P < 0.0001$. The fixed effects included the higher-order interactions Gait Phase × Step Number and Configuration × Segment × Gait Phase, modeling Segment (femur and tibia), and modeling Gait Phase and Step Number in terms of 4th-order orthogonal polynomials. All lower-order interactions and main effects were included. The 4th-order orthogonal polynomials for Gait Phase was an ordinal variable whose five values required all four polynomial terms to properly account for nonlinearity. The 4th-order polynomial's interaction with Gait Phase significantly improved model fit, $P < 0.05$. There were 33 observations per number of predictors, which is above the 10 observations per predictor heuristic observed in the literature.[4,16,18] A post hoc bootstrap power analysis revealed that this model had adequate power (i.e., > 80%) for all significant effects.[29] These models were created using the statistical software package R (Release 3.4.3, The R Foundation).

RESULTS

An ANOVA for the dependent variable normalized cadence supports significant main effects of Configuration ($F(3228) = 266.839$, $P < 0.0001$) (**Table II**). Post hoc comparisons of the Configuration revealed that all subjects had significantly greater normalized cadences when unsuited than when suited (20.4% reduction when suited compared to all padding configurations

Table II. Knee ROM and Cadence by Subject and Configuration.

SUBJECT AND CONFIGURATION	HUMAN KNEE ROM (deg)	*ΔROM* (deg)	CADENCE (spm)	NORMALIZED CADENCE
2				
US	65.8 (2.4)	N/A	106.0 (6.3)	1.00 (0.06)
C0	46.8 (5.5)*	1.9 (1.8)†	79.6 (3.7)	0.75 (0.04)‡
C1	50.1 (5.8)*	9.9 (2.0)†	83.8 (4.2)	0.79 (0.04) ‡
C2	49.7 (6.4)*	24.7 (5.5)†	88.0 (4.6)	0.83 (0.04) ‡
3				
US	61.4 (2.4)	N/A	84.7 (3.8)	1.00 (0.04)
C0	54.9 (10.5)*	49.0 (6.2)†	68.7 (3.9)	0.79 (0.04) ‡
C1	45.6 (6.3)*	2.0 (2.7)†	67.8 (4.6)	0.80 (0.05) ‡
C2	50.5 (8.9)*	12.4 (5.7)†	71.4 (3.8)	0.84 (0.05) ‡
4				
US	53.2 (2.7)	N/A	99.1 (5.7)	1.00 (0.06)
C0	54.0 (5.6)	4.4 (6.4)	77.2 (5.3)	0.78 (0.05) ‡
C1	52.7 (7.0)	3.1 (8.2)	78.1 (4.0)	0.79 (0.04) ‡
C2	47.2 (5.9)	4.2 (6.3)	79.4 (6.3)	0.80 (0.06) ‡

All values are presented as MEAN (STD), US = unsuited, C0 = Configuration 0 (no padding), C1 = Configuration 1 (one layer of padding), C2 = Configuration 2 (two layers of padding).
* Indicates significant difference from unsuited condition for that subject.
† Indicates a significant difference from the other two suited configurations.
‡ Indicates significant difference between subject pooled suited condition and unsuited condition.

pooled with all subjects pooled, Cohen's d = 3.87). C2 had significantly greater normalized cadence than both C0 and C1 (Cohen's d = 0.97 and 0.45, respectively). There was no significant difference in normalized cadence between C0 and C1.

An ANOVA for the dependent variable $tRoM_H$ supports that there was a significant main effect of Configuration [$F(3228) = 40.24$, $P < 0.0001$] and a significant interaction effect of Subject-Configuration [$F(8228) = 9.662$, $P < 0.0001$] (Table II). Post hoc tests for the effect of Configuration revealed that suited trails significantly reduced $tRoM_H$ compared to unsuited (16.5% reduction when suited compared to all padding configurations pooled with all subjects pooled, Cohen's d = 1.39). Post hoc pairwise comparisons were performed to examine configuration within subject. Subject 2 unsuited $tRoM_H$ was significantly greater than $tROM_H$ in all suited configurations C0-C2 (Cohen's d = 3.14, pooled for all suited and padded configurations); there were no significant differences in $tRoM_H$ between C0-C2. Subject 3 also had significantly higher ROM_H when unsuited than C0-C2 (Cohen's d = 1.34, pooled for all suited and padded configurations); however, C0 was significantly greater than C1 and C2 (Cohen's d = 1.06 and 0.45, respectively). Subject 4 had significantly greater $tRoM_H$ during C0 than C2 (Cohen's d = 1.18); no other significant differences were observed.

An ANOVA for the dependent variable $\Delta tRoM$ supports significant main effect of Configuration [$F(2171) = 27.7$, $P < 0.0001$], and a significant interaction effect between Subject-Configuration [$F(6171) = 35.3$, $P < 0.0001$]. Post hoc pairwise comparisons of the Subject-Configuration interaction effect revealed specific trends for each subject. Subject 2 had significantly greater $\Delta tRoM$ with more layers of padding ($\Delta tRoM_{C2} > \Delta tRoM_{C1}$, Cohen's d = 3.58, $\Delta tRoM_{C1} > \Delta tRoM_{C0}$, Cohen's d = 4.59, and $\Delta tRoM_{C2} > \Delta tRoM_{C0}$, Cohen's d = 5.75) indicating that $tRoM_S$ was progressively larger than $tRoM_H$ with increased layers of padding. Subject 3 had significant differences in ΔROM for all three suited configurations with the trend $\Delta tRoM_{C0} > \Delta tRoM_{C2}$ (Cohen's d = 0.71), $\Delta tRoM_{C2} > \Delta tRoM_{C1}$ (Cohen's d = 2.10), and $\Delta tRoM_{C0} > \Delta tRoM_{C1}$ (Cohen's d = 2.26). Subject 4 had no significant differences in $\Delta tRoM$ with changes in padding.

A mixed-effects model (**Table III** and **Table IV**) was fit for $\rho^n_{HS}(t)$ (**Fig. 3**). Table II highlights all significant fixed-effect intercepts. In general, fixed-effect intercepts indicate that $\rho^T_{HS}(t)$ was negative and significantly less than $\rho^F_{HS}(t)$ during all configurations. A slightly positive cubic component of $\rho^n_{HS}(t)$ across gait phase indicates increases in $\rho^n_{HS}(t)$ over phases of gait. $\rho^T_{HS}(t)$ also showed a negative linear and cubic change across gait phase that femur did not; this negative linear relationship was also present in C2. Finally, there was a significant positive interaction between the quartic change in $\rho^n_{HS}(t)$ over gait phases and the quartic change in $\rho^n_{HS}(t)$ over step number.

In general, random-effect intercept predictions support that subject 4 had the highest values of $\rho^n_{HS}(t)$, while subject 3 had the lowest. Linear terms reveal that subject 3 had the fastest positive growth of $\rho^n_{HS}(t)$ over the gait phase (ST to HS), while subject 2 had negative decline in $\rho^n_{HS}(t)$ over the gait phase. Quadratic terms demonstrate that subject 2 had the highest $\rho^n_{HS}(t)$ over the middle of gait phase (HO, TO, SW), while subject 3 had the lowest $\rho^n_{HS}(t)$ over the middle of the gait phase.

DISCUSSION

This study aimed to develop quantitative measures of suit fit based on observed suit fit checks. In this study, static fit (how the human sits and is indexed within the suit in a neutral static position) was altered and dynamic fit (how the human and suit move and interact relative to each other during dynamic tasks) was quantified. We hypothesized that changes in lower extremity static suit fit as altered through padding around the hips and thighs would affect parameters associated with dynamic fit during a walking task. The specific hypotheses we evaluated were that changes in padding between the human thigh and MKIII spacesuit hip brief assembly would affect measures of the following: a) gait performance (H1 – normalized user cadence and H2 - the tRoM of the human knee); and b) dynamic fit [H3 – the differences in human and suit knee tRoM ($\Delta tRoM$) and H4 – the relative motion between the human and suit at various phases of the gait cycle as measured using $\rho^n_{HS}(t)$]. Statistical analysis of these hypotheses showed the following: 1) that the MKIII SSA reduced user cadence despite changes in padding; 2) that the MKIII SSA reduced human knee tRoM compared to unsuited kinematics with subject-dependent changes due to the added levels of padding; 3) $\Delta tRoM$ was typically positive and varied in a subject-specific manner with padding; and 4) that $\rho^n_{HS}(t)$ varied throughout the gait phase and could potentially be affected by suit components (i.e., boot fit and soft goods length).

Changes in $\Delta tRoM$ and $\rho^n_{HS}(t)$ between subjects and levels of padding illustrate the sensitivity of these metrics to potential changes in fit. While these metrics are sensitive to donning

Table III. $\rho^n_{HS}(t)$ Significant Fixed-Effect Model Predictors and Coefficients.

PREDICTOR	COEFFICIENT	STANDARD ERROR	*t*	*P*-VALUE
Intercept	9.37	1.85	5.06	0.0004
Gait Phase (Cubic)	19.26	3.65	5.27	0.0003
Segment	−15.69	1.01	15.54	< 0.0001
Gait Phase (Quartic) × Step Number Quartic	60.83	27.66	2.20	0.0280
Segment × Step Number Quartic	52.78	24.74	2.13	0.0331
Configuration (2) × Segment	6.40	1.43	4.48	< 0.0001
Gait Phase (Linear) × Segment	−5.83	2.26	−2.58	0.0099
Gait Phase (Cubic) × Segment	−16.49	2.26	−7.30	< 0.0001
Configuration (2) × Gait Phase (Linear) x Segment	−6.29	3.19	−1.97	0.0490

Table IV. $\rho_{HS}^{n}(t)$ Random-Effect Model Predictions for Subject-Configuration.

SUBJECT AND CONFIGURATION	INTERCEPT	LINEAR	QUADRATIC	CUBIC	QUARTIC
2					
C0	0.781	−9.947	−3.9514	5.414	−9.546
C1	−1.730	−10.338	−2.250	6.269	−12.067
C2	3.025	−3.438	−0.861	10.004	−10.539
3					
C0	−4.248	5.465	4.035	−5.258	5.539
C1	−2.600	6.692	3.518	−5.420	7.164
C2	−1.268	3.152	1.152	−4.424	5.377
4					
C0	3.467	4.483	−0.083	−0.156	4.007
C1	4.330	3.646	−1.268	−0.849	4.903
C2	−1.757	0.286	−0.291	−5.581	5.162

the suit and adjusting a component of fit, it is still unclear whether these changes in quantitative metrics are relevant in operational settings (i.e., a Cohen's d effect size of 3.68 comparing unsuited $tRoM_H$ to suited vs. Cohen's d effect sizes of 0.4-1.0 between suited configurations). The results presented here, in combination with subjective feedback from participants, highlight that boot fit and soft goods lengths might be more influential fit components than padding for lower extremity performance.

User cadence and $tRoM_H$ were used as measures of task performance. Brinkmann and Perry[6] found that the human knee has a 60 ± 7° tRoM during normative gait, while Kadaba et al.[19] found a self-paced cadence of 111.6 ± 8.3 steps/min. When not normalized, all three subjects in this study fell within the 1 SD of the reported tRoM during unsuited trials (Table II). While Subject 2 appeared to fall within the cadence ranges also reported by Kadaba et al.,[19] Subjects 3 and 4 appeared to have lower than reported cadences. Slower cadence could be explained by the equipment subjects were wearing during unsuited trials (LCG, TCG, etc.) and precautions taken to stay within the elevated platform. In addition, subjects were instructed to strike a force plate with a specific foot during each trial; the addition of this cognitive element to the study may have created a decrease in cadence. Subjects 3 and 4 also performed all unsuited trials after the suited portion of this study (Table I). The lower cadences observed for these subjects could be lingering effects of donning the MKIII SSA as all subjects had a lower cadence suited than when unsuited. When assessing differences in $tRoM_H$ between unsuited and suited configurations, subjects 2 and 3 had significantly lower knee $tRoM_H$ during all three suited configurations (C0-C2) than when unsuited. Meanwhile Subject 4 had no significant difference in $tRoM_H$ between all conditions (US-C0-C1-C2). It is possible that these changes in stride parameters and knee tRoM could be due to the extra weight and inertial effects of the SSA; however, previous literature has found increases in cadence and knee range of motion due to increased load carrying.[21] The results presented here are consistent with Cullinane et al.[11] who found similar deviations in operator walking kinematics while donning the MKIII spacesuit. They proposed that these changes may be due to degree of freedom limitations within the MKIII hip brief assembly. While Cullinane et al.[11] discussed these restrictions at the hip, torques are required to flex the knee as well; therefore, restrictions of the MKIII could have decreased the ability of Subjects 2 and 3 to fully flex and extend their knees during gait. Subject 4 only had a significant decrease in operator knee tRoM during C2 (highest level of padding), but also had the lowest knee tRoM during unsuited trials and had the lowest values of $\Delta tRoM$. Since Subject 4 had lower unsuited $tRoM_H$, this subject might have had fewer restrictions than Subjects 2 and 3 leading to lower values of $\Delta tRoM$ and similar $tRoM_H$ when suited and unsuited.

In general, the level of padding at the hip brief appeared to have subject-dependent effects on task performance as measured using cadence and $tRoM_H$, with large effect sizes observed comparing unsuited to suited measures (Cohen's d = 1.34–3.87) and smaller effect sizes between suited and padded configurations (Cohen's d = 0.45–1.34). In general, Subject 2 had no significant changes in these metrics with different levels of padding, indicating no observable change in performance due to adding padding. However, Subject 2 subjectively reported the suit being more responsive with high levels of padding. Subject 3 had significantly greater $tRoM_H$ when walking with the no added padding, which could be indicative of better task performance, and potentially a better fit without added padding, aligning with this subject subjectively reporting not enjoying having greater levels of padding at the hip brief. Finally, Subject 4 had reduced $tRoM_H$ when fully padded, which could indicate poorer task performance and poorer fit with greater levels of padding. Subject 4 did not subjectively notice any differences due to levels of padding. These mixed results using gait performance metrics and $tRoM_H$ alone could imply that there are other factors affecting the fit of these subjects, especially when compared to the subjective feedback provided. These results highlight how fit is an integrated task and a few measures alone might not be sufficient for explaining all the variability within a population. Therefore, additional measures of dynamic fit could help broaden a quantitative interpretation of fit in the context of this task and better augment subjective measures, which naturally incorporate these varied factors.

This work introduced a new measure, $\rho_{HS}^{n}(t)$, to quantify the relative motion between human body segments and suit components. Positive values of $\rho_{HS}^{n}(t)$ are indicative of human-dominated motion, while negative values of $\rho_{HS}^{n}(t)$ represent instances where the MKIII has a higher degree of relative motion. With this in mind, $\rho_{HS}^{F}(t) > \rho_{HS}^{T}(t)$ and $\rho_{HS}^{T}(t) < 0$ is indicative that above the knee, the human moved relatively more than the suit and dominated the motion, while below the knee, the suit moved more relative to the human. The quartic change in $\rho_{HS}^{n}(t)$ across gait phase and step number indicated

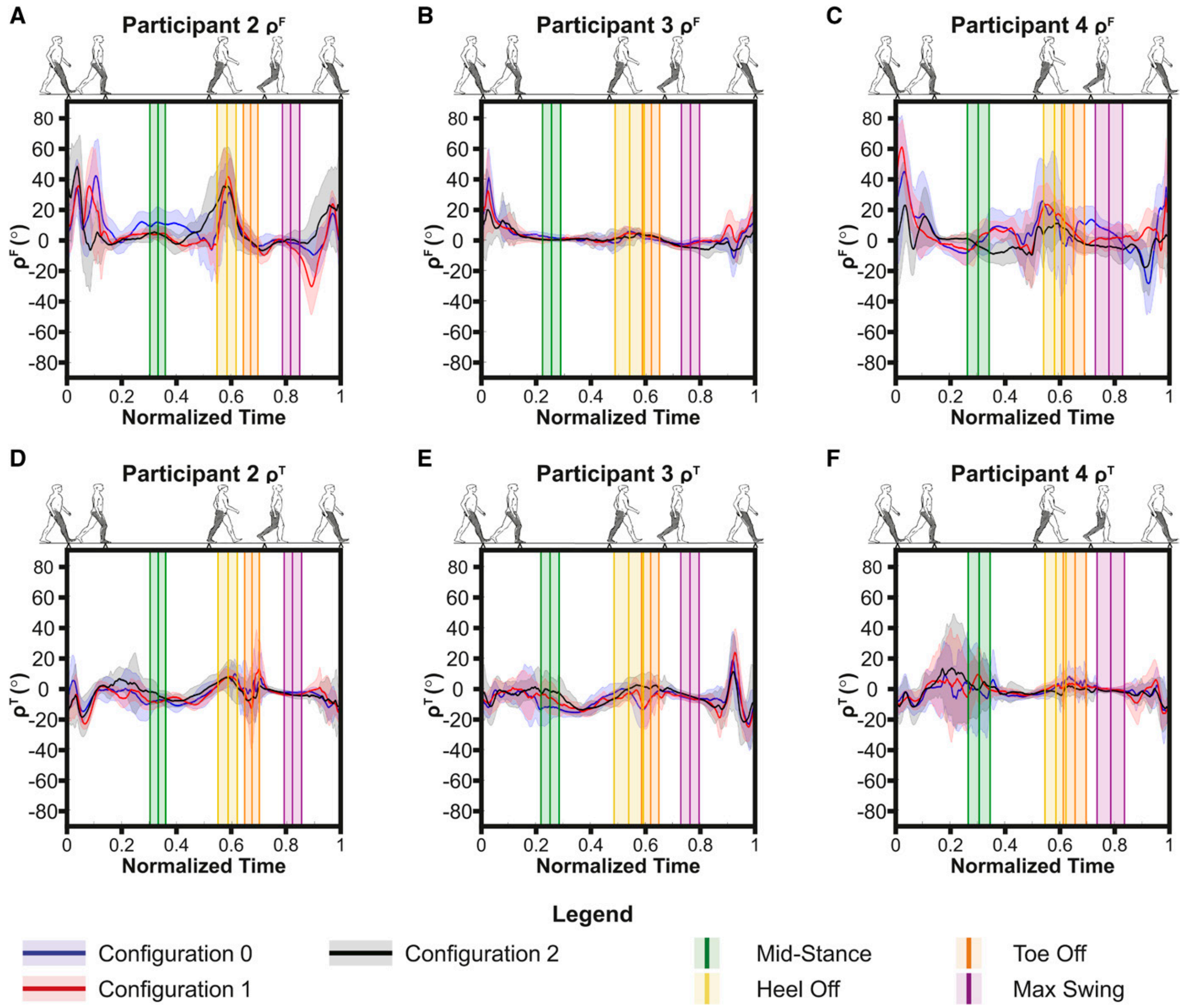

Fig. 3. Time-series representations of $\rho^F_{HS}(t)$ [A-C], $\rho^T_{HS}(t)$ [D-F], and ω_H [G-I] for each configuration: US (light green), C0 (blue), C1 (red), and C2 (black). Vertical lines represent the gait phases stance (green), heel off (yellow), toe off (orange), and max swing (purple). Solid lines represent means across all 20 steps and shaded regions represent 1 SD. For these plots, time-series were normalized and resampled to be the same length based on the trial with the most samples (250 samples, i.e., ~1.95 s).

values of $\rho^n_{HS}(t)$ fluctuated, with more steps taken over the course of the study. This increase could be a learning effect as all subjects were novice suit operators, with only one prior experience within the MKIII SSA and thus were still learning how to properly perform the required programmed motions required by the suit. General changes in $\rho^n_{HS}(t)$ over the course of the last 20 steps analyzed here could also be due fatigue effects. Future work could further examine how fatigue and experience influence the $\rho^n_{HS}(t)$. More experience and training with these SSAs could aid human operators in changing $\rho^n_{HS}(t)$ in a way that is optimized for the desired task performance outcomes and in ways that synergize with the preprogrammed motions the SSA was designed to execute. In this instance, rather than fighting the suit and creating more human motion relative to suit motion ($\rho^n_{HS}(t) > 0$), trained strategies could encourage human kinematics that would be more in line with that of the suit for the specified dynamic task.

Subject-specific random intercepts revealed that Subject 2 had the highest changes of $\rho^n_{HS}(t)$ over the middle of the gait phase (i.e., around HO to SW), while Subject 3 had the smallest changes at these locations within the gait cycle. As shown in Fig. 3A and 3C, Subject 2 and 4 had very large spikes in $\rho^F_{HS}(t)$ right before HO during all three configurations that are absent for Subject 2 (Fig. 3B). Due to availability of suit sizing components, Subject 3 was wearing a different size and design of boot. During suit fit observations, suit engineers discussed a common occurrence in which the operator heel pops out of the boot during gait. If this were the case during HO, the femur would move freely within the suit prior to coming into contact with the leg of the suit and providing an interaction force that swings the suit leg forward. We hypothesize that different fits of boot could be contributing to the different behaviors $\rho_{HS}^{n}(t)$ exhibited during HO for Subjects 2 and 4 that were not present for Subject 3. Subjectively, Subject 2 did report the occurrence of this phenomenon during C0 and C1, while Subjects 3 and 4 never reported issues with their boots. Follow-on studies controlling for boot design and fit are necessary to assess this hypothesis. Data here suggest that improper boot fit at the heel could lead to greater values of $\rho_{HS}^{F}(t)$ and affect task performance.

While looking into these fit metrics individually provides insight into the effect of padding on dynamic fit, synthesizing these results from $\rho_{HS}^{n}(t)$, $tRoM_{H}$, and $\Delta tRoM$ provide a clearer picture of overall task performance and subject fit. Subject 3 had lower values of $\rho_{HS}^{n}(t)$ and Subject 4 had higher values, which could suggest that Subject 3 had a more acceptable fit than Subject 4. However, $tRoM_{H}$ and $\Delta tRoM$ might suggest the opposite since Subject 3 had the highest values of $\Delta tRoM$ and had a greater deviation of $tRoM_{H}$ from unsuited kinematics. These phenomena could be explained by the different boots these two subjects were wearing. The soft components of the suit act as a spring. When the foot is in contact with the ground, a ground reaction force aids in keeping the soft components of the leg compressed. When contact with the ground is removed, a force would be required to keep the suit from extending. If the soft components are able to be sized exactly, the extension force would be smaller than if the soft components are larger than desired. (This sizing condition may be the case as there are a fixed number of soft goods sizes.) The extension force may be a cause of the heel lifting out of the boot during HO. The tighter fitting boot of Subject 3 in combination with the sizing of the soft components may have reduced the motion of the heel, thereby enabling increased fluency between the human and suit. If the heel stays within the boot throughout the entire gait cycle, the suit knee might reach higher degrees of flexion as the soft components of the legs buckle and bend around the knee (as opposed to the expansion when the heel slips). From this point of view, small, positive values of $\Delta tRoM$ close to 0 might be indicative of good suit fit so long as $\rho_{HS}^{n}(t)$ remains close to 0.

The trend for the tibia to have more negative ρ values between HO and TO is consistent with the heel lifting. In general, $tRoM_{S} > tRoM_{H}$ ($\Delta tRoM > 0$) and $\rho_{HS}^{T}(t) < \rho_{HS}^{F}(t)$. If there is some degree of the heel slipping out of the boot and motion is driven from the contact point of the femur with the suit upper leg, expansion of the suit leg soft goods allows any extra soft material in the legs to swing freely around the human foot, resulting in lower values of $\rho_{HS}^{T}(t)$ (more suit dominated motion) and more tRoM in the suit knee. Synthesizing observations made about $\rho_{HS}^{F}(t)$ and $\rho_{HS}^{T}(t)$, a less constrained boot fit can result in the heel slipping out, creating high values of $\rho_{HS}^{F}(t)$ during HO. Meanwhile, the length of soft goods affected the degree of suit dominated motion between HO and TO ($\rho_{HS}^{T}(t) < 0$). Subject 3 had a boa boot design enabling a tighter fit, consistent with the lower values of $\rho_{HS}^{F}(t)$. Meanwhile, all subjects had the same length of leg soft goods, although they had different anthropomorphic crotch heights (S4 > S3 > S2). Subject 4 had the largest crotch height and therefore the smallest difference between soft goods length and crotch height. Greater differences between crotch height and soft goods length allows more room for the soft goods to expand during SW. We hypothesize that this would then lead to values of $\rho_{HS}^{T}(t)$ closer to 0, as observed for Subject 4. Despite tighter boots, Subject 3 still had slightly negative values of $\rho_{HS}^{T}(t)$ at HO and TO, which may be due to the extra length in the leg soft goods based on his anthropometry and soft goods size. Finally, Subject 2 had both looser boots and the shortest crotch height and it is consistent that there were high values of $\rho_{HS}^{F}(t)$ during HO and negative values of $\rho_{HS}^{T}(t)$ between HO and TO.

This work aimed to examine how changing the level of static fit around the hip brief assembly using padding affected metrics of dynamic fit. Emergent in the analysis were underlying differences in the subject objective measures that may be explained by alternate components of suit fit, including boot design and soft goods lengths. The data showed that the effect of padding on objective measures of gait performance (H1-H2) and performance-based measures of dynamic fit (H3-H4) was mixed and subject-specific. While Subject 3 had differences in $\Delta tRoM$ with configuration, there were small changes in $\rho_{HS}^{n}(t)$. Subject 4 showed minimal changes in all metrics due to changes in padding level. It is possible that the level of padding changed how Subject 3 was sitting within the suit (i.e., higher or lower within the hip brief), creating a modified boot fit, altered static alignment, and different slack within the soft goods. Subjects in this study had different boots and underlying anthropometry measurements, but were fitted with a constant lower leg length of soft goods. The addition of padding had a small effect size compared to donning the suit (Cohen's $d = 0.45$–1.18 for padding vs. $d = 1.69$–3.87 for the suit, for normalized cadence, tROM, and ΔtROM metrics); however, it might be the case that boot design and length of soft goods played a greater role in reducing $\rho_{HS}^{n}(t)$ than did padding and that these smaller effect sizes might not be operationally relevant. It would appear that the kind and fit of the boot might be more important during a walking task due to the larger differences of $\rho_{HS}^{n}(t)$ observed between Subjects 2 and 4 compared to Subject 3, who had an upgraded boot design. While there were inconsistencies in the effect of padding between subjects, this work has demonstrated that candidate quantitative metrics for suit fit presented here were sensitive to small changes in fit. Suit fit is an integrative process and multiple metrics are necessary to appropriately interpret how well subjects fit within the suit, including the subjective feedback provided from subjects wearing the SSA. This work does not attempt to assess "goodness" of fit, simply the sensitivity of new candidate metrics to changes in performance due to components of fit. As fit is a function of multiple factors, it is necessary to have multiple metrics to quantify this complex term. The relationship between subjective feedback and quantitative metrics will be important to consider during the development of these new metrics. Quantitative metrics are an additional tool that can be used to objectively compare the different performances achieved when components of fit are changed and may be useful to better understand subjective preferences.

This work was limited in the metrics that could be defined describing the knee angle as the study did not include a formal calibration period. The implementation of more robust joint angle estimation methods, including methods that can decompose joints with higher degrees of freedom, could also allow for deeper insight into how suit fit affects the kinematics of human gait at other joints, such as the hip or ankle. This work was limited in the generalizations that were possible due to the low number of subjects and the varying sizes of suit worn. This limitation is common in studies with space suits due to the limited number and availability of the suits. However, future work should aim to have higher numbers of subjects and control for different anthropometric values across subjects cleared to wear the suit. Future work will also explore the hypotheses of how boot fit and soft goods length affect both $\rho_{HS}^{n}(t)$ and human kinematics by controlling for the boot design subjects wear and the length of the suit leg soft goods. These studies should be performed with a greater variety of tasks where operationally relevant differences in performance can be assessed. While we examined a walking task here, the changes in fit may have more implications on performance in other operational tasks, such as kneeling, digging, or climbing through a hatch. The operationally relevant effects sizes for these tasks will be important to define and could be determined based on mission success criteria or injury risk mechanisms. Further, padding was only used around the HBA in this study. Padding in alternate locations with alternate tasks may have a greater effect on performance. Finally, subjective feedback is still an integral part of evaluating fit and users may have different preferences; therefore, future studies should incorporate subjective ratings of fit in a more comprehensive manner.

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