Challenges in Quantifying Heel-Lift During Spacesuit Gait

Abhishektha Boppana; Steven T. Priddy; Leia Stirling; Allison P. Anderson

INTRODUCTION: Heel-lift is a subjectively reported fit issue in planetary spacesuit boot prototypes that has not yet been quantified. Inertial measurement units (IMUs) could quantify heel-lift but are susceptible to integration drift. This work evaluates the use of IMUs and drift-correction algorithms, such as zero-velocity (ZVUs) and zero-position updates (ZPUs), to quantify heel-lift during spacesuited gait.

METHODS: Data was originally collected by Fineman et al. in 2018 to assess lower body relative coordination in the spacesuit. IMUs were mounted on the spacesuit lower legs (SLLs) and spacesuit operator's shank as three operators walked on a level walkway in three spacesuit padding conditions. Discrete wavelet transforms were used to identify foot-flat phase and heel-off for each step. Differences in heel-off timepoints were calculated in each step as a potential indicator of heel-lift, with spacesuit-delayed heel-off suggesting heel-lift. Average drift rates were estimated prior to and after applying ZVUs and ZPUs.

RESULTS: Heel-off timepoint differences showed instances of spacesuit-delayed heel-off and instances of operator-delayed heel-off. Drift rates after applying ZVUs and ZPUs suggested an upper time bound of 0.03 s past heel-off to measure heel-lift magnitude with an accuracy of 1 cm.

DISCUSSION: Results suggest that IMUs may not be appropriate for quantifying the presence and magnitude of heel lift. Operator-delayed heel-off suggests that the SLL may be expanding prior to heel-off, creating a false vertical acceleration signal interpreted by this study to be spacesuit heel-off. Quantifying heel-off will therefore require improvements in IMU mounting to mitigate the effects of SLL, or alternative sensor technologies.

KEYWORDS: spacesuit, gait, biomechanics, inertial measurement, extravehicular activity.

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Future planetary spaceflight missions will require spacesuits which not only provide life support and environmental protection for crewmembers, but allow for mobility to perform extravehicular activity (EVA) tasks. However, spacesuit operators frequently report difficulty in working with the spacesuit during EVAs and on-ground training sessions, leading to occupational injuries risking mission success.[4] Poor operator-spacesuit interaction is a symptom of improper fit, hypothesized as one of the leading causes of spacesuit injuries.[4] Improper fit can be a factor of misalignment between the operator's and spacesuit's joints (indexing), and excessive internal gaps between the operator and spacesuit (sizing).[6,12] Poor indexing can lead to overuse of operator joints, risking musculoskeletal injury. Both poor indexing and poor sizing can lead to excessive internal contact between the operator and spacesuit, risking contact injuries such as bruising and abrasions.[4] As future spacesuit designs aim to reduce injury risk, they should target fit issues by understanding operator-spacesuit interactions.

Operator-spacesuit interactions have been shown to be dynamic and are best evaluated objectively with regards to the

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task the operator is expected to perform in the spacesuit.[6,12] Future planetary surface exploration EVAs will rely on crewmember ambulation, requiring that crewmembers are able to walk comfortably in their spacesuits. Therefore, designing spacesuits to accommodate lower body and foot motion while properly fitting an anthropometrically diverse range of crewmembers is crucial in reducing injury risk during suited ambulation.

Ground-based testing of the Mark III Advanced Space Suit Technology Demonstrator EVA Suit (MK III) has resulted in subjective reports of heel-lift, where the operator's heel rises inside the boot before the boot's heel lifts off the ground at heel-off.[6] Heel-lift can be represented as a lag between the operator's and spacesuit's heel-off times, and is an indicator of improper fit; the statically-determined indexing between the operator's and spacesuit's ankle joints does not allow for dynamic alignment during heel-off. Since the foot freely moves within the boot during heel-lift, this could lead to injury through excessive contact or ankle joint overuse when taking a step. Foot contact injuries and discomfort were reported during simulated planetary walkback testing with prototype boot designs.[4] Designing a planetary spacesuit boot to mitigate heel-lift requires a quantitative understanding of its presence and magnitude. However, heel-lift has only been subjectively reported by spacesuit operators and has yet to be quantified through in-suit motion measurement techniques.

Various sensor technologies have been used to estimate relative motion between the spacesuit and operator, including pressure sensors,[4] strain sensors,[13] and inertial measurement units (IMUs).[2,6] IMUs measure acceleration, angular velocity, and magnetic field; estimating orientation from these values. IMU Spacesuit applications include Fineman et al.'s[6] analysis of in-suit lower-body angular velocities of subjects walking with the MK III spacesuit, and Bertrand et al.'s[2] estimation of in-suit upper-body joint angles during isolated joint motions. IMUs can detect heel-off points during gait,[7,11] and therefore may be able to identify heel-lift instances where spacesuit heel-off lags operator heel-off. However, IMUs can be subject to error in their orientation estimates due to the magnetic field inside the spacesuit environment, and integration drift when calculating linear displacement and velocity quantities from acceleration measurements. Digital filtering methods, zero-velocity (ZVUs), and zero-position updates (ZPUs) have been used in the biomechanics field to correct for integration drift at every step,[5,11] but these methods have not been evaluated in their ability to be robust against spacesuit-environment induced error.

Therefore, this work aimed to evaluate the ability of IMUs, ZVUs, and ZPUs to quantify the frequency and magnitude of heel-lift in the spacesuit. Heel-off times were detected using spacesuit lower leg and operator shank IMU data during suited walking trails. Delayed spacesuit heel-off times compared to operator heel-off times were identified as potential occurrences of heel-lift. Then, ZVUs and ZPUs were evaluated for their ability to reduce integration drift and reliability quantify the heel-lift magnitude.

METHODS

Data Collection

Experimental data collected by Fineman et al.[6] was reanalyzed for this study. Subject naming was kept consistent with Fineman et al.[6] for cross-reference of results, with subjects numbered 2-4 as Subject 1 did not complete all trials. IMUs were placed on corresponding locations on the lower body of the spacesuit and operator (**Fig. 1**). Padding levels varied across configurations,[6] but were not expected to affect boot fit. It is assumed that the IMUs' x-axis was aligned with the long-axis of the shank and SLL; this axis was considered the vertical task axis. Three subjects walked in the MK III spacesuit along a 10-m walkway in each of four conditions: unsuited, MK III with no padding (configuration 0), MK III with one padding layer (configuration 1), and MK III with two padding layers (configuration 2). All subjects wore the same size MK III lower body assembly, but Subject 3 wore a BOA-laced boot with fit adjustment at the tongue and heel, while other subjects wore a standard strap-laced boot with only tongue fit adjustment. This work only analyzed a total of 216 suited trials, each with data from the left and right sides of the operator and spacesuit, yielding 432 datasets to analyze. Data from Subject 2's left leg during configuration 2 was not included due to data loss from the IMU.

Data Analysis

The IMUs' vertical acceleration along the shank and SLL's long axis, and the IMUs' pitch angle data were analyzed. It was assumed that the shank and SLL have a rigid connection to their respective ankle joints. Therefore, the difference between the shank's and SLL's vertical position taken after the operator's heel-off time is the magnitude of heel-lift. Data analysis focused on isolating each individual step from the dataset, detecting heel-off points for the operator and spacesuit, and then implementing drift correction techniques to measure the vertical position of the shank and SLL.

Operator IMU Placement	Spacesuit IMU Placement
Sacrum	Bottom of HUT
Right thigh	Right Upper Leg
Left Thigh	Left Upper Leg
Right Shank	Right Lower Leg
Left Shank	Left Lower Leg

Fig. 1. Location of IMUs (squares, placed on both the spacesuit and operator) and padding (gray). The sacrum IMU is placed on the back of the operator and spacesuit, where the upper-most black band is located, and is therefore out of view in this diagram. The table on the right outlines the IMUs' corresponding locations between the operator and spacesuit.

Individual steps in each trial were identified to begin analysis. The shank and SLL IMUs' pitch angles were smoothed using a 10-sample window moving average filter. Individual steps for each trial were then identified by detecting peaks in each IMU's pitch angle, corresponding to the max posterior flexion/extension of the shank/SLL during swing phase. Each step was defined as the time between each step's max extension to the following step's max extension. The first and last peaks of the trial were removed from further analysis to ensure only complete steps were analyzed.

Foot-flat phase, where the foot is flat between toe-strike and heel-off, was identified to discriminate heel-off events. This phase is characterized by near-zero anterior-posterior acceleration; since the foot is flat on the ground, there is very little vertical movement of the shank.[11] Raw shank and SLL IMUs' vertical acceleration data was preprocessed for foot-flat detection by

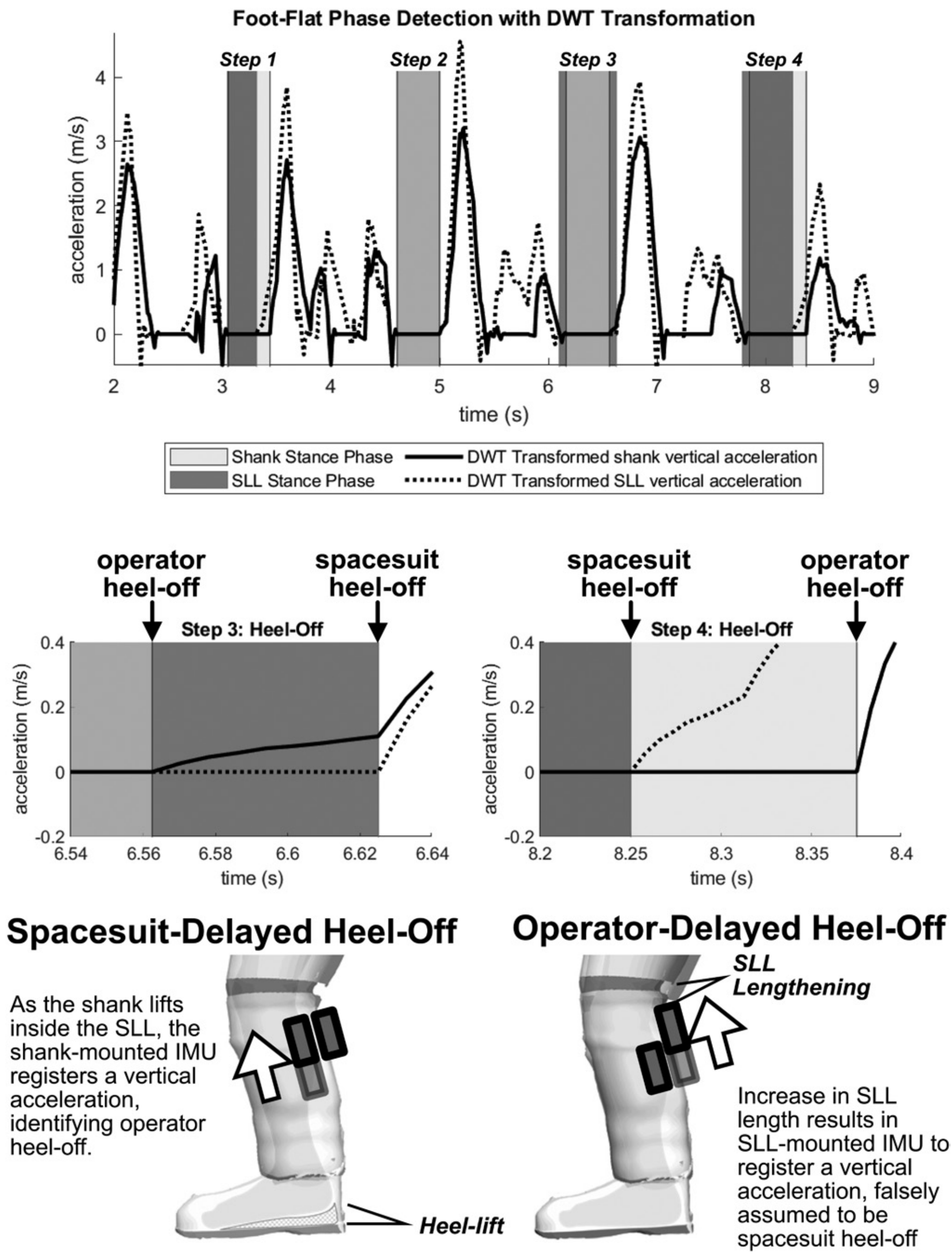

Fig. 2. (Top): DWT IMU vertical acceleration data for shank and SLL. Shaded regions represent the detected foot-flat phases of zero-acceleration regions for each step. (Middle) Zoomed-in view of the foot-flat phase for two steps, with annotated spacesuit and operator heel-off points. When the shank IMU registers a vertical acceleration in foot-flat phase prior to the SLL IMU (middle-left), this could suggest heel-lift (bottom-left). When the SLL IMU registers a vertical acceleration in foot-flat phase prior to the shank IMU, this would ordinarily suggest that the SLL experiences heel-off prior to the operator (middle-right). However, there may be pressure forces which allow the SLL to extend, registering a vertical acceleration for the SLL-mounted IMU and falsely suggesting that the spacesuit is experiencing heel-off (bottom-right).

de-trending to remove bias by removing the best straight-fit line from the data vector. A 30-sample window moving average filter, equivalent to 0.23 s, was then used to remove noise, within the range used for walking-speed estimation.[3]

Discrete wavelet transforms (DWT) were used to detect gait events from acceleration signals.[9] A 3-level DWT was applied to the preprocessed shank and SLL anterior-posterior acceleration signals. A Symlets 2 wavelet was then used as the mother wavelet for the transform, due to its high performance in detecting initial-contact and final-contact points during stance phase.[9] After transforming to wavelet space, a threshold was applied where values below 2% of the maximum wavelet coefficient were set to zero. The wavelet coefficients were then reconstructed back into a signal and used to detect foot-flat phase.

Foot-flat phase was detected by looking for the zero regions in the shank and SLL's acceleration's derivative.[10] A threshold of $0.01\ \mathrm{m \cdot s^{-1}}$ was set to account for small amounts of noise in the DWT signal.[3] Acceleration points within this threshold were identified as zero-acceleration points. Zero-acceleration points less than 3 samples long were removed, since foot-flat phase is expected to be much longer. **Fig. 2** shows an example of isolating foot-flat phase from DWT transformed signals. The difference in shank and SLL heel-off times was used to detect instances of heel-lift; a positive value corresponds to operator heel-off prior to spacesuit heel-off, suggesting heel-lift. Heel-off lag times < -0.2 s and > 0.2 s were manually inspected, and if detection times were visually noted to be misaligned with the zero-acceleration period, these steps were removed from analysis. A total of 32 of the 1381 steps met the criteria for removal.

The vertical acceleration signals from the IMUs are subject to integration drift when converted into positional estimates using double integration. The raw vertical acceleration signals were preprocessed by a 10 Hz low-pass filter to remove high-frequency noise.[1] ZVU and ZPUs were used to reduce integration drift and improve the accuracy of the positional estimate of the shank and SLL. It is assumed that the shank and SLL's vertical velocities were zero just prior to heel-off, when the operator and spacesuit are in stance phase. Using this assumption, a linear correction is applied retroactively for each step between heel-off times. At the identified heel-off times, the vertical velocity was set to zero, and the vertical velocity during the step prior to heel-off was subtracted by the velocity reported at heel-off weighted based on the distance from the heel-off timepoint. The following step's vertical velocity was then corrected to the heel-off velocity. This process is summarized in Eq. 1:

$$v'_{x,i} = \begin{cases} v_{x,i} - v_{HO_c} \times \dfrac{t_i - t_{HO_p}}{t_{HO_c} - t_{HO_p}}, \; for \; HO_p \le i \le HO_c \\ v_{x,i} - v_{HO_c}, \; for \; i > HO_c \end{cases} \qquad \text{(Eq. 1)}$$

where at timestep t_i, $v'_{x,i}$ is the corrected velocity, $v_{x,i}$ is the original velocity, v_{HO_c} is the velocity at heel-off, t_{HO_p} is the previous step's heel-off timepoint, and t_{HO_c} is the current step's heel-off timepoint. Integrating the corrected velocity signal to obtain the IMU's position can similarly be subject to integration drift. It was assumed during stance phase that both the operator's foot and the spacesuit boot are flat on the ground and therefore the shank and SLL are not moving vertically. ZPUs can use this to correct for drift by zeroing the position estimate for both the SLL and shank at heel-off. The shank and SLL were assumed to be rigidly connected to their respective ankle joints. Heel-lift magnitude can be then defined as the vertical displacement difference between the shank and the SLL at the SLL's heel-off timepoint.

Drift is not completely eliminated with the outlined methods. An upper bound was calculated to inform the time limit past the heel-off correction point where heel-lift magnitude can be quantified with confidence that the magnitude is not largely due to drift. While drift is not a linear process, an assumption was made that calculating the drift magnitude between two known timepoints, and dividing by the elapsed time, would be a reasonable approximation to quantify drift accumulation. During stance phase, it was expected that both the SLL and shank would have the same vertical position at toe-strike and heel-off. During swing phase, it was expected that both IMUs would return to the same vertical position after each step. Drift magnitude was calculated for each detected step by subtracting the post-ZVU/ZPU position values at the beginning and end of stance phase and swing phase from each other, and then dividing by time of each phase to average drift rate. This rate represents the amount the IMU's positional estimate has drifted over each phase following correction from ZVU/ZPUs, when it is expected to return to zero. Analyzing the distribution drift rates across all trials allowed for the upper time-bound to be defined where drift magnitude is minimal and can ensure accuracy in the calculated position values.

RESULTS

Fig. 3 shows the distribution of heel-off lag measurements across conditions, subjects, and sides. Subject 2 experienced spacesuit-delayed heel-off in 97 [20 left (13%), 77 right (33%)] out of 382 (151 left, 231 right) total steps. Subject 3 experienced spacesuit-delayed heel-off in 305 [155 left (76%), 150 right (73%)] out of 410 (204 left, 206 right) total steps. Subject 4

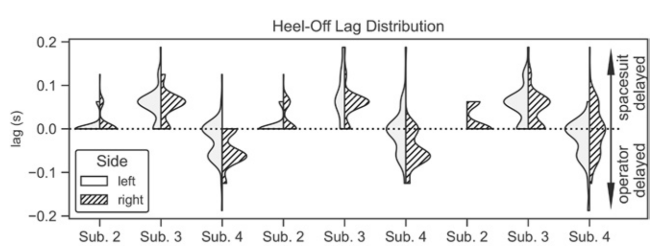

Fig. 3. Heel-off lag distributions between all subjects and configurations, with discrete heel-off lag measurements being represented as black dots. Positive lag values are indicative of spacesuit-delayed heel-off, while negative lag values are indicative of operator-delayed heel-off.

Table I. Drift Rate Estimations (Mean ± SD) Of Raw, Filtered, and Post-ZVU/ZPU Positional Estimates for IMUs Mounted on the Spacesuit Lower Leg Assembly and Shank.

PHASE	IMU	RAW	ZVU/ZPU
Stance	Shank	43 ± 63 cm · s^{-1}	5 ± 6 cm · s^{-1}
	SLL	241 ± 130 cm · s^{-1}	16 ± 11 cm · s^{-1}
Swing	Shank	67 ± 59 cm · s^{-1}	32 ± 16 cm · s^{-1}
	SLL	265 ± 103 cm · s^{-1}	66 ± 40 cm · s^{-1}

experienced spacesuit-delayed heel-off in 45 [21 left (9%), 24 right (10%)] steps, and operator-delayed heel-off in 226 [87 left (37%), 139 right (57%)] steps out of 481 (237 left, 244 right) total steps.

Mean drift rates after correction for both the SLL and shank IMUs are presented in **Table I**. An upper confidence bound of 0.03 s (1/32 cm · s^{-1}) was found to take a heel-lift measurement with an accuracy of 1 cm, based on the mean shank IMU swing phase. Average step duration across all trials was 1.6 ± 0.2 s; therefore, drift accumulated over 1 cm on average within 2% of the step duration.

Heel-lift magnitude was not calculated due to the operator-delayed heel-off lag noted in Subject 4, and high drift rates following correction resulting in a low upper time-bound for calculating heel-lift magnitude after heel-off.

DISCUSSION

This study aimed to evaluate the use of IMUs with ZVUs and ZPUs to quantify heel-lift in spacesuit gait. Methods were demonstrated to determine heel-off points on the shank and SLL IMU; where a lag in the spacesuit's heel-off point compared to the operator's heel-off point would suggest heel-lift. All subjects experienced varying amounts of spacesuit-delayed heel-off across conditions, regardless of padding levels. Subject 2 had more counts of spacesuit-delayed heel-off on their right compared to their left side (33% vs. 13%); this could be due to looser boot or spacesuit leg fit on their right side. Heel-lift was subjectively reported only by subject 2.[6] Only subject 4 experienced operator-delayed heel-off. Examples of both operator-delayed and spacesuit-delayed heel-off are shown in Fig. 2.

Operator-delayed heel-off is theoretically impossible; when the spacesuit's boot rises during the spacesuit's heel-off timepoint, it will push on the operator's heel, registering a simultaneous operator heel-off timepoint. The SLL's soft goods can expand and contract in length due to internal pressure forces or interactions from the knee or femur.[8] Longitudinal restraint straps are employed in spacesuit design to balance tension and pressurization forces at joints, but are not usually integrated along nonbending components such as the SLL.[8] Therefore, the initial assumption that the SLL is rigidly connected to the boot is broken. False-positive vertical accelerations due to segment lengthening are not a concern for the shank-mounted IMU, as the shank and ankle are rigidly connected and the IMUs are assumed to be rigidly strapped to their segments. While soft-tissue artifacts may be present, they are likely of a much smaller magnitude.

The SLL may be expanding in length for Subject 4 at heel-off, causing the IMU mounted on the SLL to register a positive acceleration prior to the operator. Subject 4 wore the same size suit lower assembly as other subjects but had taller crotch and knee heights. As such, there would be more room in the lower leg assembly for the soft goods to expand, providing a possible explanation for why only Subject 4 experienced operator-delayed heel-off.

A tighter boot fit, where the heel stays indexed in the boot, allows the operator to overcome expansion forces that push the SLL down, resulting in the SLL extending upwards and registering as operator-delayed heel-off. In contrast, loose boot fit will not allow the operator to overcome these forces, and will push the boot down, keeping it on the ground and registering as spacesuit-delayed heel-off. Fineman et al.[6] summarized that Subject 4 had synchronous motion of the shank and SLL between heel-off and toe-off; Subjects 2 and 3 had motion driven by the suit, suggesting heel-lift. Data from this study similarly suggests that Subjects 2 and 3 experienced more instances of spacesuit-delayed heel-off than Subject 4. Therefore, Subject 4 may have had a tighter boot fit as indicated by operator-delayed heel-off, and operator-delayed heel-off may serve as an indicator for tighter boot fit. Spacesuit boots are graded for a range of sizes (ex. US 8-10), which may not fit as precisely as terrestrial shoes and could contribute to poor boot fit.

Findings from this study suggest that current IMU technology and drift correction techniques alone may not be appropriate for quantifying the presence and magnitude of heel-lift in the spacesuit environment. Drift evaluation showed that the SLL-mounted IMUs had higher drift rates than the shank-mounted IMU. Potential sources of increased drift could be effects from the SLL segment's soft-goods expansion and contraction,[6,8] resulting in different frequency components compared to the shank's movement. While ZVUs and ZPUs did substantially reduce drift in stance and swing phase, drift was still present in this study. Heel-lift magnitude measurements could not be taken with confidence that magnitude differences would be due to heel-lift. Future work may explore the extent of soft-goods expansion on spacesuit kinematics analysis, which may affect positional estimates from optical motion capture. IMUs have been shown to measure spacesuit angular kinematics with a root-mean-squared error of 4.8–5.8°[2] and were used to characterize relative angular coordination within the suit,[6] but have not been evaluated for accuracy in spacesuit positional estimates as conducted in this study. Suit components should only expand longitudinally and should, therefore, not affect angular estimates.[8] Other sensing modalities or improvements to IMU mounting may be more appropriate in quantifying the vertical displacement that defines heel-lift.

Characterization of in-suit motion is desired to develop comfortable and safe planetary EVA spacesuits. This study highlighted the challenges of using IMUs to measure in-suit motion, concluding that IMUs may not be appropriate for measuring in-suit displacement at the magnitude expected during heel-lift. The primary assumption that the SLL was rigidly connected to the ankle joint was not supported; the observed operator-delayed heel-off suggests that the SLL is vertically extending during gait. Fineman et al.[6] hypothesized that lower-body relative coordination may be affected by boot fit issues. Future work can characterize SLL extension throughout the gait cycle, further understanding the forces acting on the SLL due to fit. Sensor technologies can also be evaluated to study heel-lift, such as resistive or capacitive force sensors mounted under the heel to directly measure heel contact, or strain sensors mounted between the human and suit to measure displacement. Such methods can be used to evaluate spacesuit components susceptible to injury, such as the gloves or upper torso.[4] IMUs can be mounted directly to the boot to isolate ankle kinematics from SLL lengthening and accurately detect heel-off points using the presented methods and assumptions. Force plates can directly identify spacesuit heel-off points, therefore not requiring suit-mounted IMUs. Developing and evaluating various in-suit motion measurement techniques will help improve spacesuit design and fit, reducing the risk of injury and ensuring mission success for future planetary EVAs.

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