A Biomechanical Design Framework to Improve Spacesuit Boot Fit

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Future space exploration missions will send humans to planetary bodies such as Mars and the Moon. These missions will require spacesuits which enable surface walking, but current spacesuit boot designs have mismatched ankle kinematics and improper contact between the foot and boot. Such issues can make planetary ambulation a difficult task for astronauts due to contact and fatigue injuries. It is hypothesized that these issues stem from poor static and dynamic fit between the foot and boot; while the boot can be designed to fit the foot statically, it does not maintain that fit through gait due to the interaction of pressurization, improper fit, and poor indexing. There is a need for a new spacesuit boot design with better fit and mobility. This work proposes a biomechanical design framework to link specific foot measures to footwear design variables, allowing for the footwear to be designed to typical foot shape, size, and mobility. The framework utilizes traditional measures such as anthropometrics and joint kinematics, and also integrates novel measures such as dynamic 3D scans. The measures are then linked to footwear design variables that make up footwear joint mobility, toe box design, upper design, sole design, and fleet sizing. In addition, the unique challenges of developing a gas-pressurized shoe will be explored. Plans for prototyping and validation of footwear designed from the framework will be outlined. This framework will act as a basis for future spacesuit boot designs which aim to reduce injury risk through better fit and mobility.

Nomenclature

EVA	=	extravehicular activity
MK III	=	MK III planetary spacesuit demonstrator
EMU	=	Extravehicular Mobility Unit
HUT	=	hard upper torsos
ROM	=	range-of-motion
xEMU	=	Exploration Extravehicular Mobility Unit
MTP	=	metatarsophalangeal joints
ANSUR II	=	Anthropometric Survey
IMU	=	intertial measurement unit

I. Introduction

Future human spaceflight missions are planning to send crew to planetary surfaces such as the Moon and Mars. The main goal of planetary spaceflight missions is to explore and do science through extravehicular activity (EVA)[1]. Up to 24 hours of EVA per week may be scheduled, which is much greater than any current microgravity EVA schedule[1]. EVA is a very demanding task, requiring crew to walk on unfamiliar terrain in a reduced gravity environment. Spacesuits are necessary to provide life support and protection to crew during EVAs, but current spacesuit designs have resulted in crew member contact and musculoskeletal injury during operations, training, and research studies[2–6]. Combining a high incidence of spacesuit injury with an increase in EVA will result in a greater mission risk. Therefore, there is a need to reduce EVA spacesuit injury risk to ensure future crewmembers stay safe during long-duration planetary missions. As planetary EVAs will require a large amount of ambulation, it is important to recognize how mechanisms for spacesuit injury specifically target the foot and boot interface. A

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design framework can then be developed to develop spacesuit boots which reduce injury risk for future planetary exploration missions.

A. Spacesuit Injury Context

Gas pressurized spacesuits have a history of causing injuries and requiring more exertion to move. Crewmember difficulties with the spacesuit have existed since the first EVA, where Alexi Leonov had difficulties moving the suit to re-enter the spacecraft. Apollo astronauts have commented on the fatiguing reduced mobility of their spacesuits[3]. In-flight spacesuit injuries have been observed through the course of the US space program at the hands, feet, shoulder, arms, wrists, legs, back, neck, and trunk[4]. In addition, similar and additional injuries have been observed in training sessions with the currently-used extravehicular mobility unit (EMU)[5]. Most spacesuit injuries can be classified as contact injuries or musculoskeletal injuries, and the mechanisms leading to these injuries can be identified from the spacesuit's design aspects.

Spacesuit contact injuries, including bruises and abrasions, have been the most reported operational injury mechanism in the US space program[3]. Contact injuries occur through repeated contact between the wearer and a spacesuit. High contact pressure between the wearer and spacesuit can lead to bruises, while shear can lead to abrasions[7,8]. Specific examples of contact injuries include on the feet, where contact occurs between the dorsal surface of the foot, pressure bladder folds, and sizing inserts[5]; wearers' backs, where there is contact with the liquid cooling and ventilation garment (LCVG)[5]; and on the limb joints, where contact is occurring between with the soft suit components while moving the spacesuit[2].

Musculoskeletal injuries have also been reported with the current EMU and technology demonstrator Mark III (MK III) spacesuits, some of which have required surgery to repair. Musculoskeletal injuries can occur due to overuse and fatigue; the stiff pressurized structure of the spacesuit has been shown to significantly increase the metabolic cost required to move, making it more difficult to perform tasks while suited[9,10]. While suit weight and suit pressure play a large role in this increased metabolic cost, other factors such as inertial mass, stability, and poor biomechanics contribute significantly[9]. A gas-pressurized spacesuit also resists movement due to additional rigidty occurring through changes in suit volume and fabric stiffness when bent[11–14]. This resistance to movement has been specifically seen in the EMU shoulder and elbow joints[15]. Another contributing factor to musculoskeletal injury is poor joint programming; where the natural motion of the crewmember is not aligned to the spacesuit's movement capabilities[16]. Poor joint programming is especially evident in the EMU's hard-upper torso (HUT), where the design restricts the natural movement of the shoulder joint; in extreme cases this has led to rotator cuff tears[5,6,17].

Contact and musculoskeletal injuries stem from inadequate static and dynamic fit between the spacesuit to the human. Static fit refers to the alignment between the wearer and the spacesuit, while dynamic fit refers to the coordination of the wearer to the spacesuit during motions[18]. A combination of poor static and dynamic fit can lead to both contact and musculoskeletal injuries. Poor static fit leads to empty space around the wearer, which allows the wearer to move inside and repeatedly contact the spacesuit. However, improving static fit is not as easy as filling this empty space; this would hamper wearer mobility and lead to poor dynamic fit and difficulty for the wearer to move the suit. Poor spacesuit-crewmember fit is a factor of both difficulty in sizing the suit to the crewmember, as well as ensuring that suit movements match desired human movements. Current suit fit processes do not use objective measures to define proper fit; a baseline fit is prescribed from anthropometric measures and then iterated through subjective feedback[19]. However, limits in suit mobility still make it impossible to perfectly match the alignment and mobility of the wearer.

Many of the injuries identified in both operational and training environments have been concenetrated around the shoulder/HUT interface since the microgravity EVA environment is dominated by upper-body tasks. The transition to planetary missions will require much more walking, and therefore use of the lower torso, than current microgravity missions. Therefore, it can be expected that there will be a higher incidence of lower-torso injury in future planetary missions. The MK III has been tested in simulated planetary walking scenarios, where it was shown that the metabolic cost of suited gait is greater than that of unsuited gait[10]. Fineman et al. (2018) found that the range-of-motion (ROM) of the human inside the MK III is limited compared to their unsuited performance[20]. In addition, there were coordination differences between the spacesuit and human. During motion, the suit may be limiting human motion and at times, even drive against the human. For anticipated lunar and Martian surface exploration, the Exploration EMU (xEMU) and future spacesuits have a similar architecture to that of the MK III. All these factors point to the potential for high risk for lower torso musculoskeletal injury. While these specific injury mechanisms may not occur exactly as in the upper-torso, it is important to study and ensure proper human-spacesuit interaction for future high-use lower-torso spacesuit components such as the boot.

B. Boot-Specific Fit Issues

The current spacesuit boot designs have resulted in foot contact and musculoskeletal injuries, with specific mechanisms for this interface that are unique. Contact injuries have been reported in MK III walking trials as bruises on the foot occurring from excessive contact pressure and strain from boot components[10]. Similar injuries have occurred in the EMU spacesuit during microgravity operations, including one injury where the pressure bladder was reported to have caused a "searing, knife-like pain" to a crew member. The intensity of pain almost caused the reporting crewmember to halt the EVA[4]. The injury can be attributed to the pressure bladder used in gas-pressurized spacesuits; when the pressure bladder is pressurized, it becomes a hard and inflexible material which creases when bent, causing a pressure point to act on the foot. When poor fit between the boot system and the foot results in empty space around the foot, the foot can rub against the inside of the boot with each step leading to shear injuries such as abrasions. These were also reported during the MK III walking trials[10] as well as during microgravity EVA operations[5]. While the design of a microgravity boot is fundamentally different than that of a planetary walking boot, some contact injuries appear to be caused by pressure bladder, a component shared between the two. Contact injuries would compound over each step taken as the crewmember walks, leading to more severe injuries which may cause the crewmember to stop the mission.

Figure 1. Heel slip mechanism during spacesuit gait

The specific mechanism for kinematic mismatch in the spacesuit boot is heel lift and slip, described as the heel popping out the boot during heel-off by subjects during walking trails in the MK III spacesuit[10,20]. Heel-slip has been quantified in Earth-gravity walking trials as between 1-2 cm in each step[21]. Heel-slip can occur due to poor fit and indexing at the knee and hip joints[20], but can be alleviated through better static and dynamic fit of the heel and foot in the spacesuit boot. When such kinematic mismatch occurs at a high frequency during long-duration planetary surface EVAs, there is a risk of musculoskeletal injury due to the extra exertion needed to overcome the mismatch.

A spacesuit-human interface with mismatched kinematics and contact injuries can increase injury risk to crewmembers performing EVA, compromising mission success. Poor fit and indexing lead to the contact injuries and mismatched kinematics we see in current planetary spacesuit design. Injuries specific to the boot are especially important for planetary EVA due to the large amount of crewmember walking necessary.

The design for any new spacesuit component should aim to match the required human motions for the intended actions, as well as be sizeable for the intended population. This allows for the component to provide proper fit and mobility to the wearer, but requires a proper understanding of human size and movement to design. Novel techniques have recently been developed to measure human dimensions, both statically and dynamically. These techniques, along with existing measurement tools, provide the capability to better fit spacesuit components to the human. However, there is not a clear process for integrating all available data to drive spacesuit component design with a focus on improved fit and mobility. This work aims to define that process specifically for the spacesuit boot, enabling the design of a better fitting boot suitable for future planetary missions.

II. Anthropometric measurement tools

A variety of static and dynamic anthropometric measures are used to characterize the shape and size of the crewmember. Population anthropometric measures can be derived through large studies such as the 2012 Anthropometric Survey (ANSUR II)[22]. Subject-specific measurements can be taken using scanning methods. These methods are outlined in the following section to provide a baseline to extract foot-specific measures from.

A. Static Measurements

Three-dimensional (3D) laser scans are taken of the crewmember and used to derive a number of anthropometric measures. Scans can be used to also characterize the body shape of the crewmember. A large database of scans can be used to develop fleet-sizing analyses through statistical body shape models, which show how the static body shape or anthropometric measurements of the crewmember population varies[23].

Static measurements taken from 3D scans do not always capture the changes in anthropometric measures and body shape that occur with human movement. While static scans can be taken at multiple postures, such as shoulder fully flexed and fully extended, these require the subject to pose at a specific part of the motion for the scan to be reliably captured. Posing is not possible for all motions, such as gait, as it is nearly impossible to reliabily have subjects pause at the same point during the motion for a scan to be taken. Therefore, there is a need for dynamic measurements to accompany static measurements.

B. Dynamic Measurements

Joint angles and joint angular velocity characterize how limbs move relative to each other. These can be measured through inertial measurement units (IMUs) or a motion capture system. However, since limbs are modelled as rigid bodies, further measurement techniques are needed to characterize changes in body shape with motion.

Studies have modeled dynamic body changes by creating posable statistical body shape models[24]. Subjects are scanned in a series of static postures which represent points along the desired motion. The Anthropometry and Biomechanics Facility at NASA's Johnson Space Center has digitally tested poseable body shape models with hard spacesuit components, helping identify potential interaction concerns with current suit design[24]. However, as stated earlier, not all motions can be represented in a series of static postures, as humans cannot always pause during a motion to have a scan taken.

Recent technological advancements by the authors have allowed for four-dimensional (4D) scanning to be feasible with commercial depth cameras[25]. A depth camera uses stereo vision to obtain 3D views of the scene at up to 90 frames-per-second; views from multiple depth cameras are stitched together to create a 4D scanner. Four-dimensional scanning allows for body shape scans to be captured while the body is in motion, negating the need for subjects to pause in specific postures to be scanned. This capability allows for the 4D body shape capture of any motion, such as walking. This differs from digitial image correlation techniques, which focus on capturing surface deformation and not the volumetric body shape changes[26]. Studies to understand how foot shape changes during the gait cycle are underway, and are expected to present a statistical body shape models which can predict how dynamic foot shape varies across the population[27].

III. Foot-specific Measures

From the described anthropometric measurement tools, several foot measurements can be derived to describe foot shape. Specific foot measures which are directly related to fit and mobility need to be identified to feed into the proposed design framework. Many of these measurements have been characterized through previous analyses[28–31]. The following sections describe each of these specific foot measures and provide their population-derrived nominal values. Figure 2 highlights these foot-specific measures.

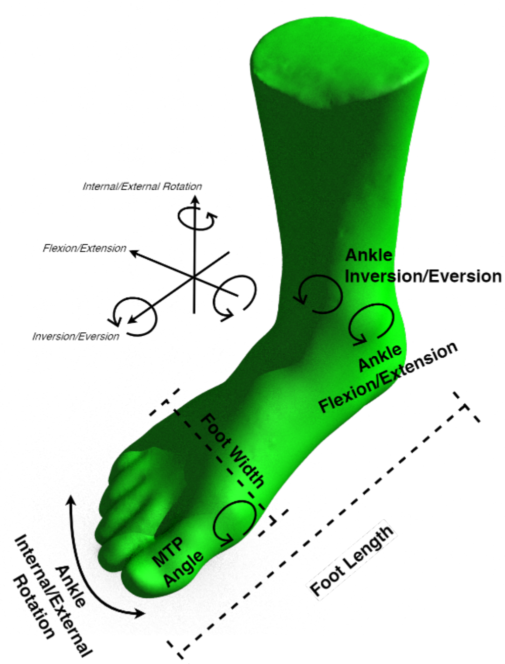

Figure 2. Foot-specific measures which directly affect mobility and comfort

A. Linear Anthropometry

The ANSUR II survey collected a number of foot-related measures which can be analyzed to provide a baseline for foot shapes and sizes[22]. Three of these measures are directly related to fit and mobility. Foot length and foot width define the outer bounds of the foot shape. Foot length and width are directly correlated to US shoe sizes for both width and length. Since females generally feature smaller feet than males, female shoe size is typically 1.5 units less than the calculated male size. Figure 3a shows that this offset does not sufficiently align the female population to the male population. Therefore, it is important to use foot length as a direct measure when fitting or selecting a shoe as opposed to shoe size.

Arch length denotes the location of the metatarsophalangeal (MTP) joints on the foot, one of the important joints during gait. Since power is transmitted through the MTP joints, the

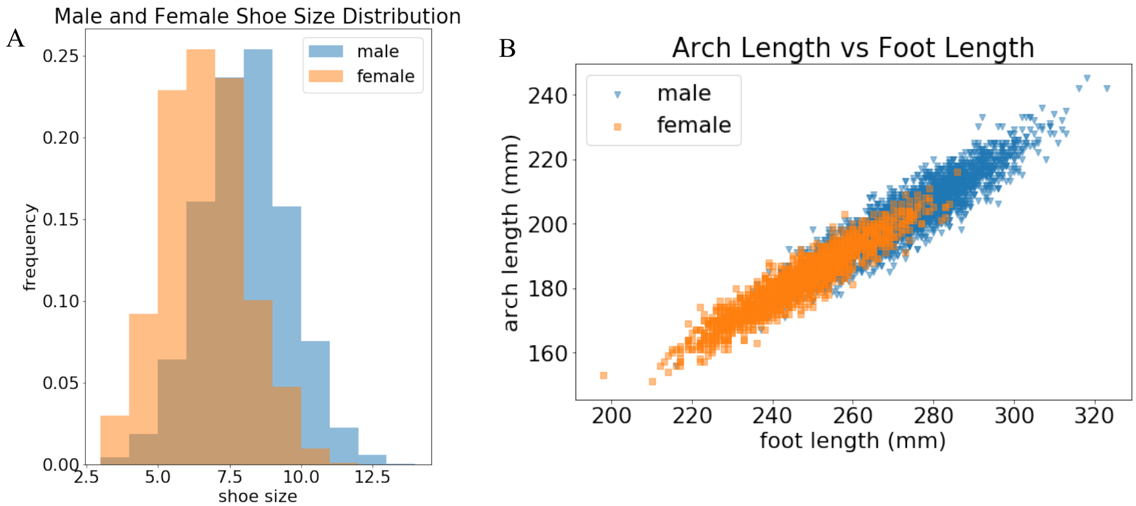

Figure 3. (A) Inequality in distribution of equivalent shoe size between male and female, (B) relationship between foot length and arch length; visualizations developed from the ANSUR II Dataset[21]

alignment of the MTP joints with the ball of the shoe is important to ensure power is properly transmitted during heel-off. Therefore, the arch length measurement is correlated to standard shoe sizes and if larger, will be selected over the length measurement. Figure 3b shows that while arch length is correlated to foot length for both males and females, there is still high variability in this relationship. Therefore, arch length is an important measure to consider to ensure proper indexing and dynamic fit between the wearer and spacesuit boot.

B. Gait Joint Kinematics

The foot's main function during gait is to transmit power against the ground, ensuring that the human pushes off and initiates a step. During each step, the ankle pushes off from the ground to iniate a step. Intrinsic foot muscles help stiffen the foot to assist the push-off from the ankle against the ground[28]. The MTP joint not only exhibits flexion in the saggital plane, but provides the necessary stiffness to allow for the ankle power to translate into push off[32]. Ankle joint rotation may also help balance and stability during gait, particularly on slopes[31]. Neither the ankle joint nor the MTP joint should be restricted in its movement to enable efficient push-off and stability. However, free movement of the ankle joint can increase the risk of injury from instability caused by external forces from walking on an uneven surface. Therefore, there is a balance to be struck between allowing for movement while preventing potentially injurious movements.

Nominal values for the foot MTP and ankle joint movement during gait can be derived from the numerous studies conducted on human gait. Voloshina et al. (2013) found that during gait on uneven surfaces, the ankle does not flex past +/- 20 degrees[30]. Wannop et al. (2014) reported peak foot-floor angles which suggest that on level and sloped surfaces, subjects dorsiflex their ankle up to 40 degrees, and flex their MTP joint up to 60 degrees[31]. The MTP joint has been shown to flex between 70-90 degrees during gait[29]. There is very little ability of the MTP joint to extend or move in the frontal or transverse plane[29]; these motions therefore do not have to be limited by an MTP joint on the boot.

The ankle joint exhibits most of its movement in the saggital plane. However, the ankle joint can perform inversion/eversion in the frontal plane and internal/external rotation in the transverse plane. Wannop et al. (2014) found that subjects wearing a low-top shoe with no additional ankle stability had up to 10 degrees eversion and 15 degrees inversion while navigating a slope[31]. However, excessive inversion/eversion may decrease stability and lead to injury. During gait, the human normally exerts energy to stabilize their ankle in this direction[33]. However, any external force can destabilize the ankle, as commonly seen in basketball or hiking[34]. Therefore, it will be desired that any boot stabilizes the ankle in this motion. In addition, freedom in the transverse plane is desired to allow for positioning of the foot when navigating an uneven surface, aiding in balance[31,35]. Wannop et al. (2014) found the ankle internally/externally rotates +15/-20 degrees on a slope [31].

C. Foot Shape

To allow for proper dynamic fit, a shoe will need to fit foot shape throughout the gait cycle. Footwear is commonly designed and fit using a set of representative lasts; models which represent target foot shape for the application[36]. These lasts are typically unique per each footwear manufacturer. Lasts are usually more than just a 3D representative foot scan; they feature design features such as heel rise and toe rise. However, lasts only represent the static foot pose, where the foot is flat on the ground.

It is well known that foot shape changes between loaded and unloaded states, such as in gait[37]. Foot and ankle biomechanics will require the shoe to not just fit the subject, but effectively follow the actions of the foot to allow for efficient gait[38]. Changes in linear and circumfrential foot anthropometric measurements during gait have been quantified[39]. However, these analyses cannot easily be translated into a posable foot model since the measurements do not represent the entire shape of the foot. While specific measures allow for the characterization of foot size in multiple dimensions, and how the foot size may change, an infinite number of measures would need to be taken to represent the entire foot shape and variability. Therefore, a foot shape model is desired to ensure the entire foot shape and variability is accounted for. A posable foot shape model can be developed from our current efforts to develop a statistical time-varying foot shape model that represents shape throughout gait[27]. Example data from this effort is shown in Figure 4. A posable foot shape model can act as a dynamic last; building on traditional lasts by providing information on foot shape changes through motion. Dynamic lasts can act as an input for simulation of foot-footwear interaction[40,41]. In addition, they can drive numerous shoe design variables through their shape information. Therefore, the posable foot shape model will help define the shape of the shoe, and the mechanical properties needed in the spacesuit boot design to conform to the dynamic foot shape.

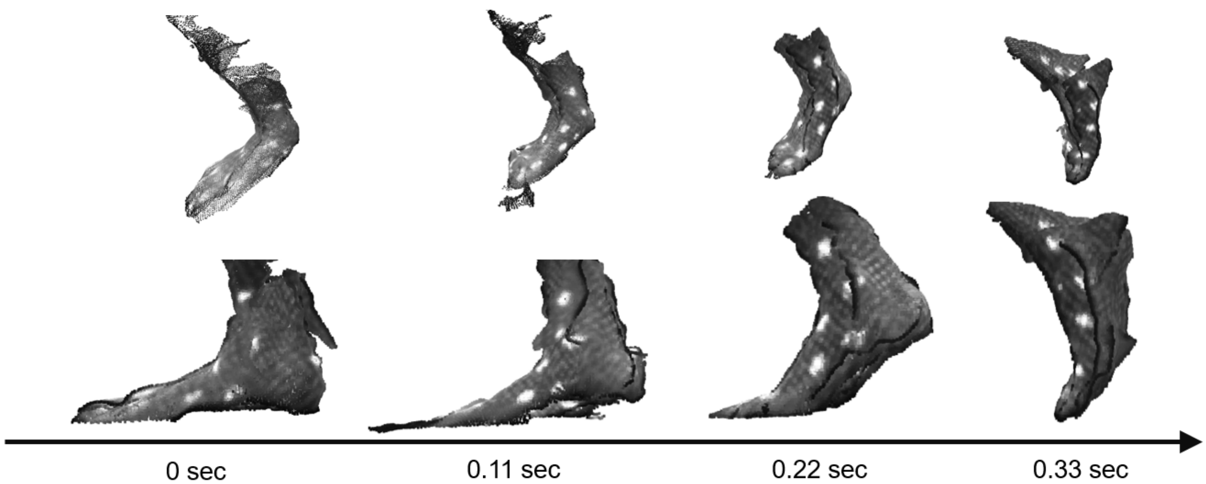

Figure 4. Birds-eye (top row) and side profile (bottom row) views of 4D foot scans taken during the heel-off portion of gait, with relative timestamps from which the images of the scans were taken

IV. Boot Design Framework

The proposed design framework will link foot measurements described in the previous section to specific footwear design variables, allowing for the design of a spacesuit boot with proper fit and mobility. The framework assumes the development of a gas-pressurized spacesuit boot to maintain compatibility with the current xEMU architecture. Since gas pressurized spacesuits are stiff when pressurized, they require specially designed joints which allow for flexibility of the stiff structure. The gas pressurized layer does not have the ability to stretch once pressurized, and therefore must be sized specifically to fit the population range.

Footwear design variables are categorized as either population measures or individual measures. Population design variables are used in the general design and selections of materials for the shoe, which will accommodate the range of foot shapes and motions seen by the population. Individual design variables will be sizing specific elements which are changed between sets of boots to fit inter-individual differences (such as shoe size). Figure 5 shows how each foot measurement is mapped to each footwear design variable.

A. Flexibility and Joints

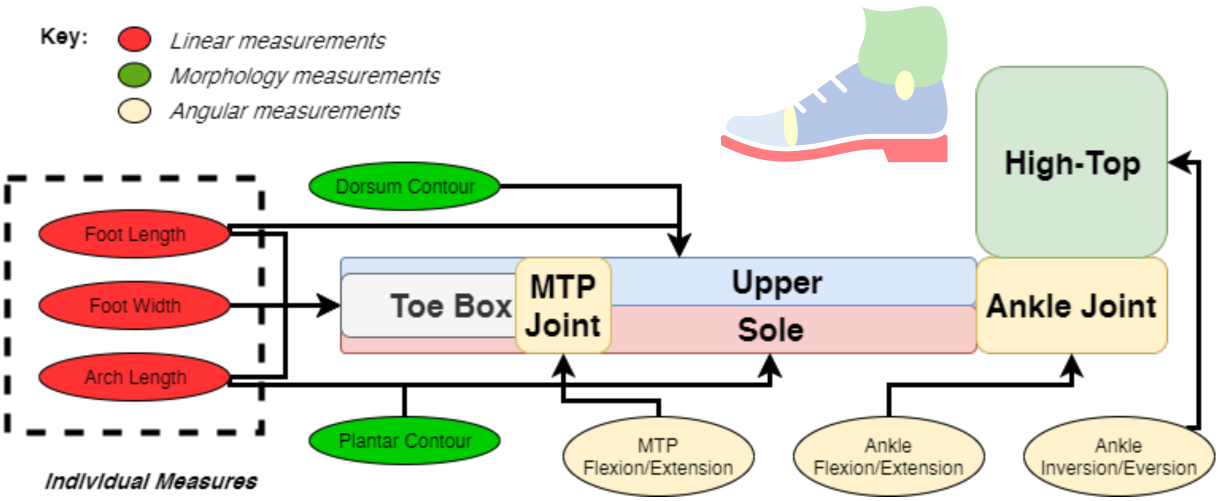

Figure 5. Overview and classification of measurements to footwear design variables with representative shoe

Footwear is flexible at the MTP and ankle joints to allow for effective push-off during gait. Terrestrial footwear normally derrives flexibility from the materials used for that portion of the shoe; the shoe is typically made of softer materials or less reinforcement at the joints. Since altering materials property stiffness is not an option for spacesuit design, rolling convolute or toroidal joints could be used in the spacesuit footwear to allow for flexibility at the MTP and ankle joints[42]. Figure 6 shows the desired flexibility based on foot-specific measures. These population measures will ensure that the boot provides enough flexion to not constrict natural motion.

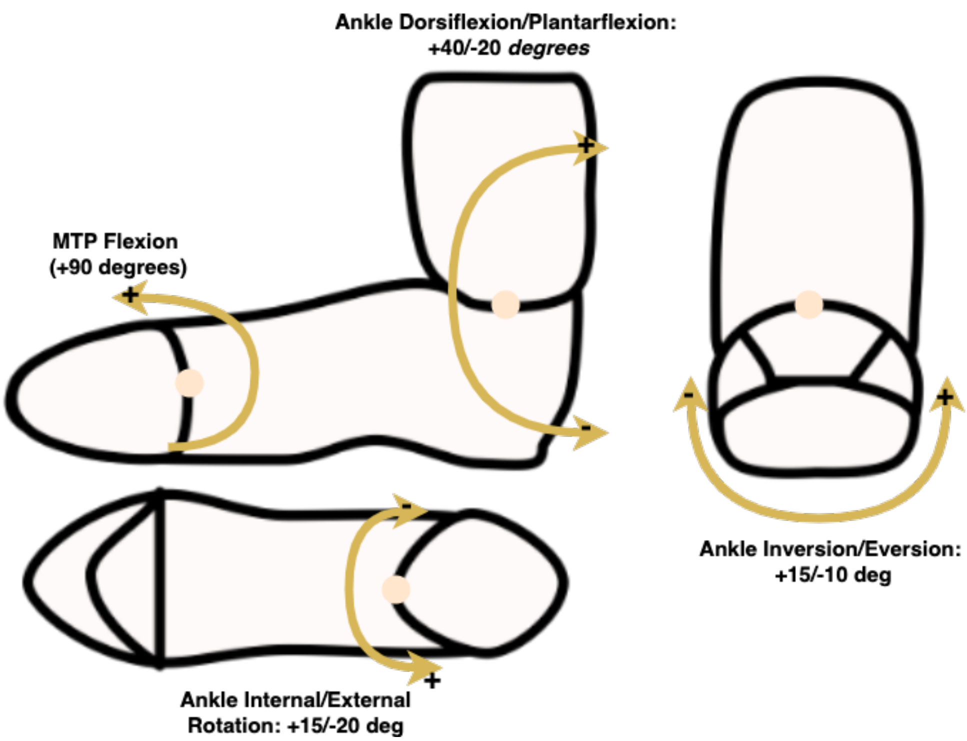

Figure 6. Mobility and flexibility of joints needed in the spacesuit boot (Right boot shown)

The MTP joint should target flexion of +90 degrees and the ankle joint should target dorsiflexion/plantarflexion of +40/-20 degrees. Due to the potential for unstable terrain, a high top style footwear is suggested to stabilize the ankle, similar to a hiking or military style boot. However, it has been shown that a very stiff boot reduces ankle ROM and decreases stability at the knee joint[34], potentially leading to ankle and knee fatigue. By allowing for a internal/external rotation of +15/-20 degrees, and inversion/eversion of +15/-10 degrees, the boot still allows the foot to navigate a sloped and uneven surface without fatigue. The relatively low amount of movement will still allow the ankle to be stabilized and lower the risk of injury.

The only requirements previously stated for boot mobility are in the 2019 NASA SBIR Surface Space Suit Boot Solicitation[43]. The solicitation matches the +40/-20 degrees ankle dorsiflexion/plantarflexion requirement, but presents no requirements for ankle internal/external rotation, inversion/eversion, or MTP joint flexion. The proposed design framework targets higher flexion/extension capability in the ankle joint, as well as specifies extension of the MTP joint, limited ankle internal/external rotation, and limited ankle inversion/eversion.

B. Toe box

The toe box accommodates the foot forward of the MTP joint. The toes provide the contact for power from the MTP and ankle joints to push off the ground during each step. Therefore, the most important feature of the toe box is contact between the toes and the ground during heel-off. As a result, the toe box can feature more space around the top of the toes for comfort[44]. Since the toe box does not need to provide any additional flexibility, it can be constructed with a less flexible, harder, material to allow for adequate support of the boot and foot. In conjunction with the MTP joint, the toe box should also be adjustable such that it can match the arch length of the wearer, allowing for proper fit and indexing of the MTP joint.

C. Upper

The dorsum of the foot is covered by a shoe upper. The shape of the upper needs to conform to the shape of the dorsum to allow for proper driving of the shoe during any activity[45]. Foot shape data taken from a large population will be useful in defining an ideal upper shape that fits a range of persons. The boot upper will also have to conform to the foot shape without causing discomfort during movement. Dynamic foot shape data can quantify how dorsum shape is changing throughout the gait cycle, allowing for the upper to accommodate any expansion or contraction of the dorsum shape for optimal comfort and support. Our ongoing research will develop a statistical model showing how dynamic foot shape changes with foot length and width, which will then drive the design of an upper which can be easily scaled to different shoe sizes.

The upper's location between the MTP and ankle joint, and its requirement to conform to the shape of the foot, drive the selection of a softer, flexible fabric being used to meet these requirements. This presents a challenge with designing the pressure bladder, as the pressure bladder is inherently stiff under pressure. Therefore, a soft inner layer above the dorsum may be used which allows the stiff pressurized bladder to conform to the individual's dorsum. Since the dorsum still transmits power to push the shoe off the ground, the soft layer still needs to have enough structure to transmit this power. If too soft, the layer will simply act as empty space and the shoe will not respond to ankle flexion during heel-off, potentially resulting in heel-lift. Lacing or other closure mechanisms would futher allow the shoe upper to conform to the dorsum and capture the foot. Furthermore, the closure mechanism should be customizable by the individual wearing the boot, so each wearer can adjust to where they feel is comfortable. Conforming the upper to the dorsum will also minimize contact injuries between the wearer and boot.

The upper will also play a role in donning and doffing of the spacesuit boot. Traditional boots feature laces along the upper which secure the foot inside the boot during activity, but loosen to allow the foot to slip into and out of the boot. The closure can be designed in conjunction with a single structured fold in the pressure bladder to allow the pressure bladder to change shape and allow the foot to be released from the boot. Figure 7 shows a possible configuration of the upper using laces which conforms to the shape of the foot while still allowing for donning and doffing.

D. Sole

The sole in a traditional boot provides traction, support, and protection to the wearer. The sole needs some thickness to accomodate tread for grip on uneven surfaces. In general, the thicker a sole, the stiffer it becomes. As a stiff sole resists bending, it might fight against the motion of the foot and shoe during heel-off. Therefore, the sole needs to be flexible during heel-off without imparting additional forces on the shoe and upper. Dobson et al (2019) found that having a fully flexible sole in coal miner's boots inhibited the natural roll-off of the foot during gait, resulting in less comfort[46]. However, it was not verified if the boot's flexibility at the MTP joint aligned well with the MTP joint, since sole flexibility was done simply by cutting into the sole near the MTP joints. Therefore, it will be imperative to ensure that any flexibility at the MTP joint is either perfectly aligned with the foot, or the flexibility does not inhibit the natural roll off of the foot. Dynamic foot shape data can provide a base contour for the sole to be able to bend at the MTP joint during heel-off, as shown in Figure 8. The sole should have higher flexibility near the MTP joints; doing so will allow the sole curvature to match the foot's plantar curvature during gait. In addition, population measures of arch length can help characterize the location of the MTP joint along the foot, ensuring that the MTP joint is properly indexed by the sole.

E. Fleet Sizing

The sole and upper have been outlined as being designed from static and dynamic foot morphology. However, it is unfeasible to create custom boots for every future crewmember; a number of sizes which optimally fit the majority of the population will need be definied for the astronaut population. This process is known is fleet sizing. The statistical models developed from static and dynamic foot shape data can play an important role in testing the potential fleet sizing aspect of spacesuit boot design.

The presented framework allows individual measures, such as foot length, width, and arch length, to scale a baseline design to fit a new crewmember. This is similar to current footwear sizing systems, where foot length and foot width are used as the primary sizing elements[36]. The framework identifies the indexing of the MTP and ankle joints to be important in ensuring proper motion, which indicates that the arch length is more important than overall foot length for sizing. Therefore, arch length and foot width should be the primary factor in selecting a proper boot size for a crewmember to ensure proper joint indexing. Anthropometric population survey data can help select arch length/foot width combinations for the most frequently expected sizes.

Arch length and foot width, along with additional subject anthropmetrics like height and weight, can morph a statistical shape model to represent the foot shape of the crewmember. Similarly, a number of digital shoe models can be generated by scaling across the population's foot width and arch length measures. Monte-Carlo simulations can test the interaction between the scaled digital shoe models and parametric foot shape model, and help scale the overall boot size per arch length and foot length[47]. This creates a set of scaled boot models for each arch length/foot width size found in the population, and accounts for changes in foot shape that are related to changes in arch length and foot width. Interactions which are greater than the current US shoe sizing systems step increases of 1/6 in (4.23mm) for length, and 3/16 in (4.76mm) may warrant a looser boot shape, while empty space below these values would warrant a tighter boot shape[36]. Padding and inserts can also be used in boundary-cases to ensure the foot stays indexed even in a larger shoe.

However, simulations cannot fully account for individual preference of fit. Simulations will need to

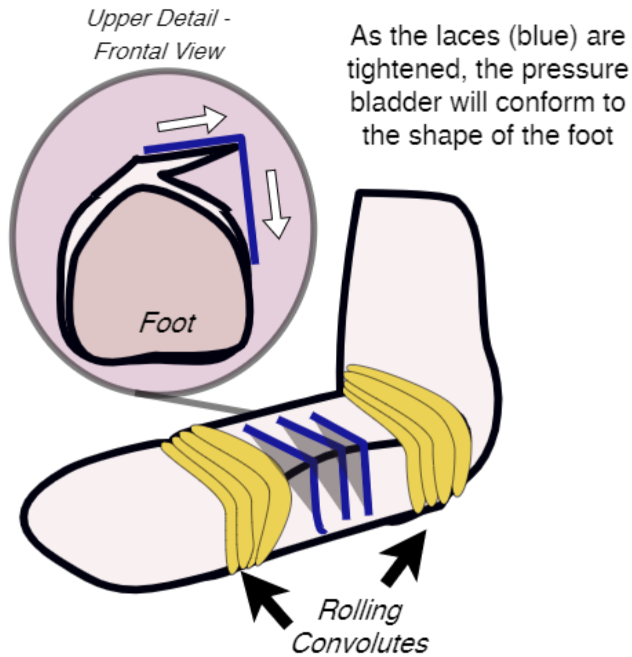

Figure 7: Conceptual design of a boot's upper configuration with pressure bladder

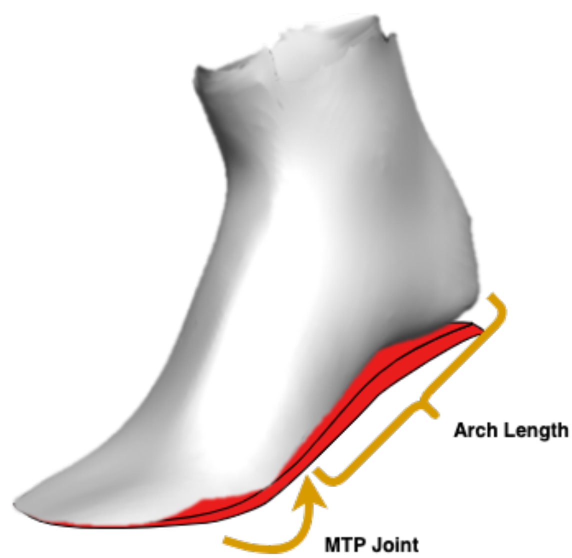

Figure 8: Desired sole flexibility (red) matched with plantar foot contour at MTP joint

be tested with objective suit fit metrics to ensure they are accepted by the crewmembers. This is especially important for when padding and inserts are used, as they are known to affect fit perception and performance[20].

V. Prototyping and Validation Plan

The resulting boot design from this framework and corresponding computational analysis will serve as a starting point for iteration of a spacesuit boot prototype. In initial efforts, existing off-the-shelf shoe components will be used and modified to reduce complexity. The pressure bladder will be constructed from a heat-sealable nylon fabric (Seattle Fabrics, Seattle USA), and reinforced with stitches. The pressure bladder will be fixed to the inside of the shoe using a series of tabs, ensuring that it is always indexed properly inside the foot. The rolling convolute and toroidal joints will be designed with well-established methods[42]. The soft upper layer will require a materials analysis to find a material flexible enough to conform to the dorsum, while still effectively transmitting ankle power. For ease of construction, prototypes will be constructed in a men's shoe size 11 for iteration (the shoe size of the first author).

Testing will occur with the prototypes thoughout development. Prototypes will be bench tested to ensure they hold upto 16 psi of pressure during flexion and extension of joints[43]. Once the design is satisfactory, prototypes will undergo a series of human subject testing for design evaluation. Subjects will be recruited and selected based on their ability to fit the prototype sizes manufactured. Subjects will conduct unpressurized donning and doffing tests to ensure the boot can functionally be worn.

An existing glovebox apparatus will be modified with a solid leg component to do pressurized human-in-the-loop testing of the boot. While this will now allow for full gait replication, subjects will still perform representative motions to assess mobility and comfort of the boot. Subjects will be asked to perform flexion of the MTP joint, and flexion/extension of the ankle joint. Kinematics can be collected to assess subject mobility in the new spacesuit boot. In addition, a combination of a subjective surveys[10], kinematic mismatch between the foot and boot[20], pressure-sensitive insoles[46] can provide information about subject-specific relative comfort and performance. These metrics can be compared against the subject's actual foot shape to explore the effects of fit on performance and comfort. As available, data will be compared against existing spacesuit boot design prototypes developed by our collaborators.

VI. Discussion

This analysis outlined a framework for designing a new spacesuit boot with an emphasis on fit and mobility during gait. The framework aims to reduce the risk of spacesuit boot injury by developing a process to design a spacesuit boot. It is expected that focusing a design on fit and mobility will reduce the occurrence of heel-slip and contact injuries.

Novel new foot measurements, such as dynamic foot morphology, are outlined and integrated into this framework. This motivates current efforts in dynamic foot morphology quantification and provides a direct path for such data to be used in an engineering context. Population-specific measurements are used to design the shoe to dynamically fit any human foot throughout the gait motion, while individual-specific variables are used to design sizing elements of the shoe. This framework therefore serves as bounding requirements to ensure future spacesuit footwear does not inhibit natural foot motion or cause discomfort due to incompatibilities between foot and shoe shape. The only previously bounding requirement, the 2019 NASA SBIR solicitation for a new surface space suit boot, had only one requirement for ankle flexion/extension, which was validated in this paper. There were no requirements other ankle motions or MTP join motions, and no requirement for proper static and dynamic fit to the wearer's foot. This paper provides a series of requirements based from previous biomechanics studies on foot motion while walking and hiking to provide proper fit and mobility through the spacesuit boot design.

While this framework outlines an ideal spacesuit boot design, it does not demonstrate its feasibility or effectiveness. Prototypes need to be constructed and tested to validate and iterate on this framework. In addition, prototypes will need to be constructed and tested on a range of subjects to ensure design is scaleable across common shoe sizes.

The testing plan outlined in this analysis will provide preliminary data on comfort and mobility of the spacesuit boot. However, the tests are being conducted in a controlled environment not fully representative of the gait motions experienced in a spacesuit. The designs would ideally be validated in a full spacesuit assembly, pending availability and cost. Full spacesuit testing with this new design vs previous designs will fully ensure that this framework indeed produces a more comfortable boot design.

Fit and mobility are not the only concerns with the current boot design. Thermal regulation will also need to be incorporated into the boot design to ensure safe operation in very cold EVA environments, such as permanently shadowed regions, is possible. In addition, other protective layers found in the spacesuit will need to be added to the outside of the boot without reducing its flexibility and comfort. This will be an area of future work which will expand upon this framework.

The framework provided by this paper will be utilized to design a planetary spacesuit boot which has the proper fit and mobility to reduce astronaut injury risk. Once designed and constructed, validation testing will test the efficacy of this framework and provide details to further iterate on. The design can serve as the basis for other required planetary boot technology, such as heating elements and protective layers.

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