Chapter 6

Specific Aim 3: Define a design process integrating dynamic foot morphology data for a novel spacesuit boot

Previously designed planetary spacesuit boots have modified terrestrial hiking boots by integrated a pressure bladder, to allow for interfacing with a pressurized spacesuit. These boots were designed through iteration and subjective feedback from wearers. Upon rigorous performance evaluation [118, 47], though, these designs to date have failed to solve the heel-lift problem, necessitating a new approach to boot design.

The design for any new spacesuit component should aim to match the required operator motions for the intended actions, and be sized for the intended population. This allows for the component to provide proper fit and mobility to the wearer. Designing such a component, however, requires an understanding of body segment size and mobility. Combining the novel dynamic foot morphology model with known foot shape and mobility characteristics provides the necessary information to better fit the spacesuit boot to the foot. However, there does not exist a defined process to design spacesuit components that integrates both traditional and novel data to achieve this objective. The design process must therefore be modified to integrate all available data to improve spacesuit fit, comfort, and mobility.

This chapter presents a literature review of existing foot shape and mobility data as it relates to spacesuit boot design. The data is then integrated into a design framework, which is then used to design a novel spacesuit boot with improved fit, comfort, and mobility. Design justifications for components of the novel spacesuit boot design are outlined. The construction of a prototype based on the novel spacesuit boot design and a spacesuit boot design based on existing efforts are described.

6.1 Existing Knowledge on Foot Shape Mobility

The foot's static shape distribution and mobility have been well characterized through previous analyses [43, 87, 140, 143]. The following sections describe each of these specific foot measures and provide their population-derived nominal values. Figure 6.1 highlights these foot-specific measures.

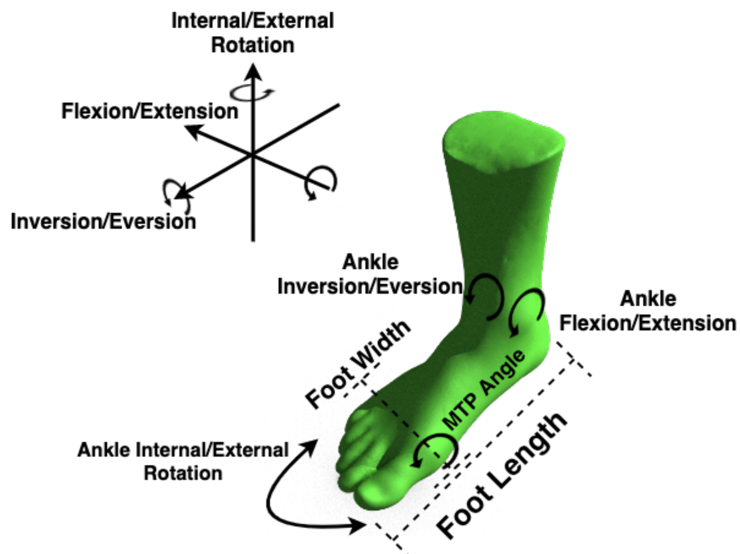

Figure 6.1: Foot-specific measures which directly affect mobility and comfort

6.1.1 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 [54]. Three of these measures are directly related to fit and mobility. Foot length and foot width define the outer bounds of the foot shape. Length is the primary measure used when purchasing shoes, followed by shoe width [85]. In the US sizing system, each half-size corresponds to a 4.23 cm step. Since females generally feature smaller length feet than males, female shoe size is typically 1.5 US shoe sizes more than an equivalent male size

[85]. Figure 6.2 shows that this offset does not sufficiently align the female population to the male population for shoe length. Shoe width sizes are graded with letters (“AA” to “EE”) in the US, offset from a normal “D” in steps of 6.35 mm; a “C” is 6.35mm narrower while a “E” is 6.35mm wider [85]. Shoe width sizes also scale with length; as a longer foot is typically wider [70]. Figure 6.2 shows that the distribution of widths for women is wider than that for men, suggesting that having a common step for both men and women may result in more women not being accommodated in shoe-width. Therefore, when designing a shoe, it is important to consider the target audience’s foot anthropometry outside of the shoe sizing standard and use foot measurements when available.

Arch length denotes the location of the metatarsophalangeal (MTP) joints on the foot. Since power is transmitted through the MTP joints, the 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 6.2 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.

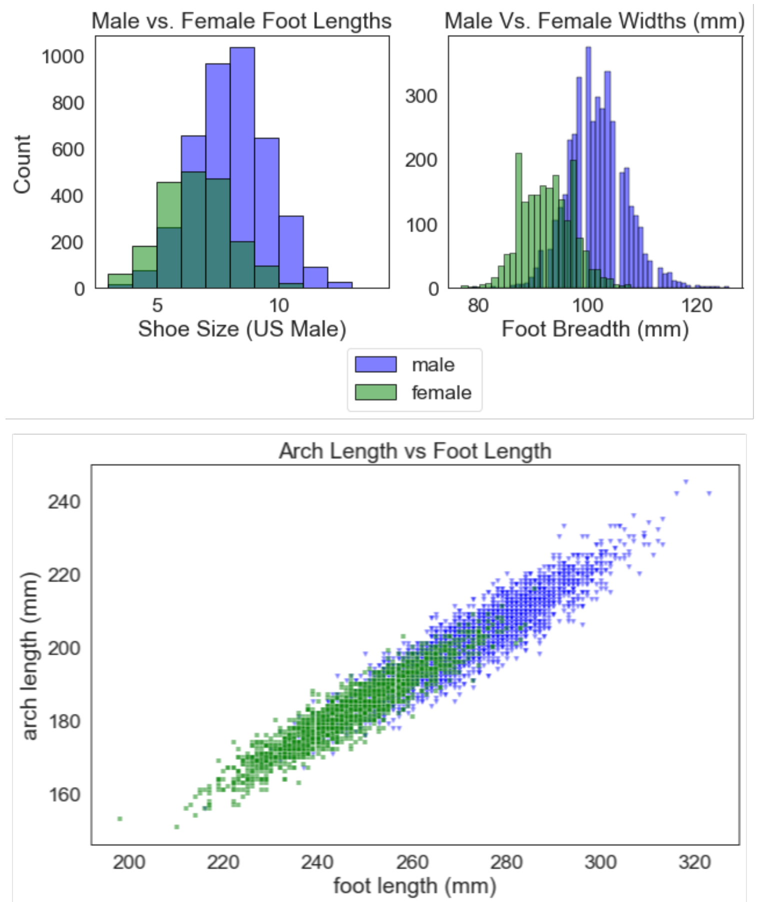

Figure 6.2: (Top-right) Inequality in distribution of equivalent shoe size between male and female. (Top-left) Distribution of male and female foot widths. (Left) relationship between foot length and arch length; visualizations developed from the ANSUR II Dataset

6.1.2 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 initiate a step. Intrinsic foot muscles help stiffen the foot to assist the push-off from the ankle against the ground [43]. The MTP joint not only exhibits flexion in the sagittal plane, but provides the necessary stiffness to allow for the ankle power to translate into push off [128]. Ankle joint rotation may also help balance and stability during gait, particularly on slopes [143]. 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. [140] found that during gait on uneven surfaces, the ankle does not flex past $\pm$ 20 degrees. Wannop et al. [143] 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. The MTP joint has been shown to flex between 70-90 degrees during gait [87]. There is very little ability of the MTP joint to extend or move in the frontal or transverse plane [87]; therefore these motions may want to be limited in the boot's design to prevent injury.

The ankle joint exhibits most of its movement in the sagittal plane. However, the ankle joint can perform inversion/eversion in the frontal plane and internal/external rotation in the transverse plane. Wannop et al. [143] 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. 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 [103]. However, any external force can destabilize the ankle, as commonly seen in basketball or hiking [19]. 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 [143, 52]. Wannop et al. [143] found the ankle internally/externally rotates +15/-20 degrees on a slope.

6.2 Biomechanical Boot Design Framework

The proposed design framework will link traditional linear foot measurements described in the previous section and the dynamic foot shape model (sec. 5) to specific footwear design variables, allowing for the design of a spacesuit boot with an emphasis on improving fit, comfort, and mobility. Note, the framework assumes 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.

The framework incorporates two types of design variables,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. Angular and morphology measurements can inform footwear design for population measurements. These measurements aim to accommodate the shape of the foot, as well as its mobility for the intended activity.

Individual design variables are used to size specific elements which are scaled between sets of boots to fit inter-individual differences. These variables rely on linear measurements of the intended wearer's foots. Individual design variables drive the selection of a shoe size which fits the individual's foot anthropometry.

Figure 6.3 shows how each of these measures is mapped to footwear design variables. In the following sections, the design requirements specific to a planetary spacesuit boot are outlined.

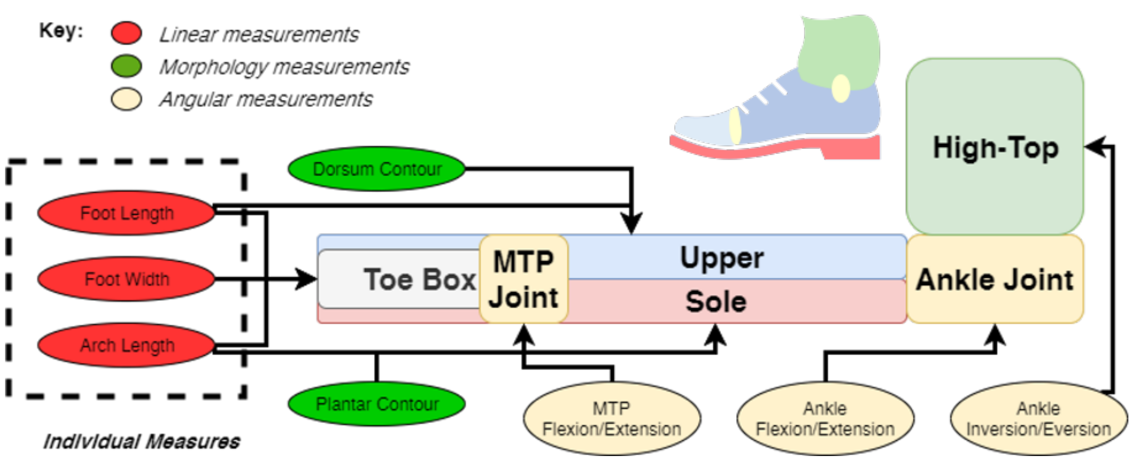

Figure 6.3: Overview and classification of measurements to footwear design variables with representative shoe

6.2.1 Mobility

Footwear is flexible at the MTP and ankle joints to allow for effective push-off during gait. Terrestrial footwear normally derives 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 [62]. fig. 6.4 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.

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 [19], 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 [97]. 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 to match ankle mobility. The framework also specifies a requirement for extension of the MTP joint, limited ankle internal/external rotation, and limited ankle inversion/eversion.

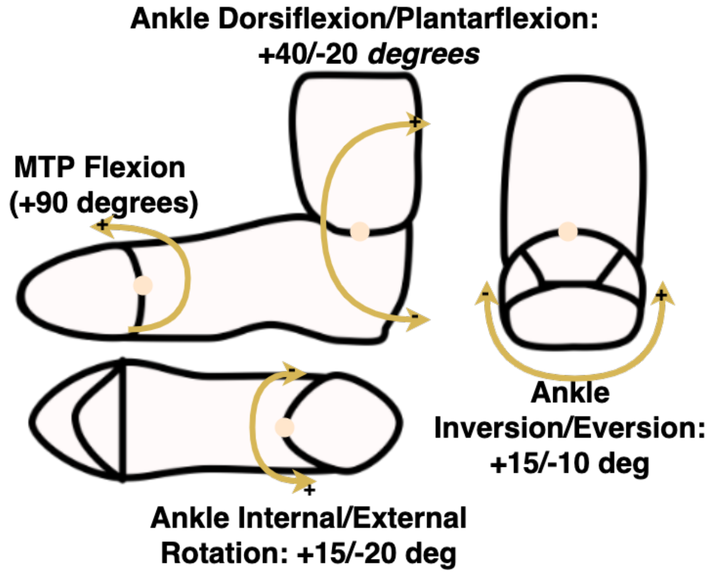

Figure 6.4: Mobility and flexibility of joints needed in the spacesuit boot

6.2.2 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 [84]. Since the toe box does not need to provide any additional flexibility, it can be constructed with a less flexible 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.

6.2.3 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 [44]. 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. The instep height measurement is of particular importance, as it represents the height of the foot from the plantar surface to the dorsal surface just in front of the ankle joint. The instep height measurement was found to have both static and dynamic variability from the dynamic foot shape model in Chapter 5. Therefore, the upper should accommodate this variability to ensure fit can be maintained through the gait cycle for a wide range of static instep heights.

Lacing or other closure mechanisms can assist the upper in conforming to and capturing the foot (sec. 5). Closure mechanisms allow for customization by the individual wearing the boot, so each wearer can adjust the boot to their preferred fit. Conforming the upper to the foot will also eliminate any empty space between the foot and above the dorsum, reducing the chance of heel-lift since the foot will no longer be allowed to move within the boot. In addition, this reduces the chance of contact injuries from rubbing between the foot and boot.

The upper and lacing 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 will need to be designed in conjunction with pressure bladder, as the pressure bladder will need to deform in a structured matter when the laces are tightened. The boot can then loosen and allow the foot to be removed.

The upper's location between the MTP and ankle joint, and its requirement to conform to the shape of the foot, may 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.

6.2.4 Sole

The sole in a traditional boot provides traction, support, and protection to the wearer. The sole needs some thickness to accommodate 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. [39] 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. 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. The arch length measurement can be used to ensure the MTP joint of a wearer is properly indexed to the sole's flexibility, allowing the MTP joint to act as intended (fig. 6.5).

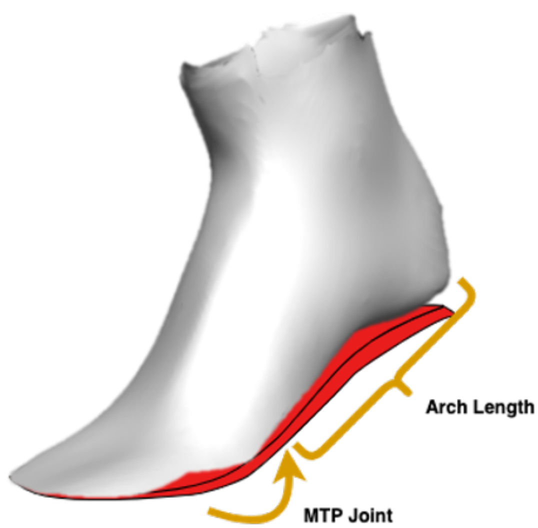

Figure 6.5: Desired sole flexibility (red) needs to be properly indexed to the MTP joint, which can be located by the arch length measurement

6.3 Novel Planetary Spacesuit Boot Design

The biomechanical design framework was used to inform the design of a novel planetary spacesuit boot with improved fit and comfort compared to current prototypes. This work's main goal was to reduce the amount of heel-lift in during walking found in current planetary spacesuit boot designs. Therefore, much of the design emphasis focused on providing an upper which was compatible with lacing to accommodate a static and dynamic variability in instep heights, and a heel counter to secure the heel.

The boot is designed to be compatible with gas pressurized spacesuits. When a spacesuit is pressurized, it's pressure bladder expands to a stiff shape with increased volume. The stiff structure must be deformed by the wearer to provide mobility, as described in Chapter 2. In addition, this structure is the closest layer in a spacesuit assembly to the spacesuit operator, and therefore plays an important role in fit and comfort. A spacesuit's pressure bladder is typically paired with a restraint layer to control the expansion of the bladder[62]. However, through discussions with spacesuit engineers, the pressure bladder was found to be the most important layer in providing fit, comfort, and mobility. To enable lacing compatibility, the pressure bladder will need to change volume, allowing it to properly tighten around the wearer's foot. Previous efforts at integrating lacing into the boot only focused on running the lacing through the restraint layer [58], and did not have an accompanying conformal pressure bladder. Therefore, the design of the prototype planetary spacesuit boot was restricted to the pressure bladder layer to focus on developing a conformal pressure bladder.

Some design elements from previous planetary spacesuit boot designs were implemented to meet the biomechanical and anthropometric requirements presented in the framework above. The following sections describe the design decisions made for various parts of the prototype planetary spacesuit boot.

6.3.1 Ankle Convolutes

Current planetary spacesuit prototypes use single-axis convolute assembly with three segments to provide ankle flexion/extension, but not inversion/eversion [118]. A segment consists of a circular piece of fabric; individual segments are assembled with overlap over consecutive segments. While a variety of convolute joint designs are available (see Chapter 5), rolling convolutes were chosen for this boot design after prototyping efforts found these to be the most easily constructed in a laboratory setting. Rolling convolute joints feature a band around each convolute segment, which guide the convolute's rolling and unrolling during motion [62]. When a rolling convolute ankle joint is flexed, one side of the convolute segments roll over each other and collapse, while the convolute segments on the opposite side unroll and expand (fig. 6.6). A longitudinal restraint strap is attached to the convolute segments to ensure that the convolutes do not unfold completely from pressurization (fig. 6.6). The rolling convolute joint also does not require a restraint layer to function, allowing it to be integrated within the scope of this design. It was decided to retain the number of convolutes from the planetary spacesuit prototypes, but recalculate the sizing and placement of the convolute segments to meet the requirements from the biomechanical boot design framework.

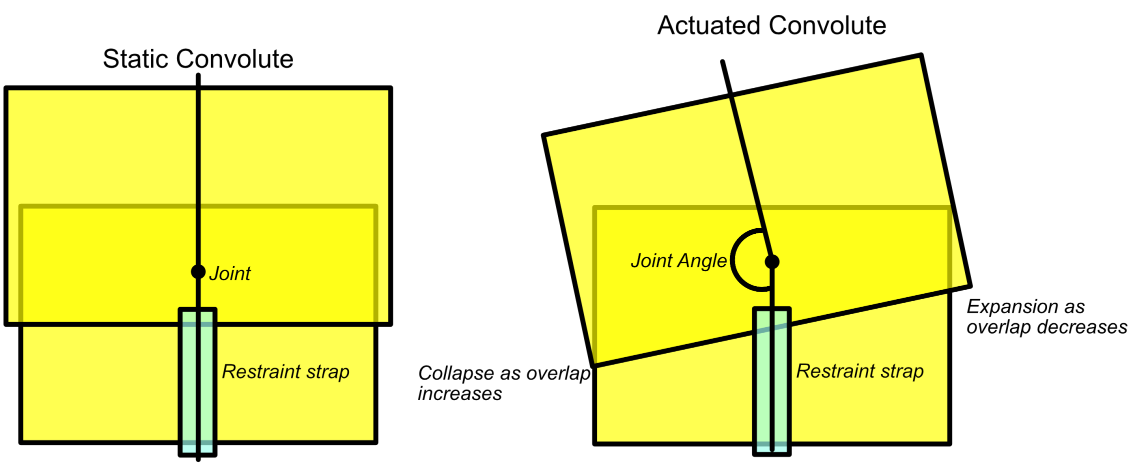

Figure 6.6: Actuation of a convolute joint. The upper convolute segment overlaps the lower convolute segment by a fixed amount, held static at the center by the restraint strap. When the joint is bent, the upper convolute segment rotates around the lower convolute segment. One side of the upper segment rolls over the lower segment, increasing its overlap. The opposite side unrolls from the lower segment, reducing its overlap.

Range-of-mobility for a convolute assembly is limited by the number of convolute segments, height of each convolute segment, and the overlap between each segment. When a convolute assembly is fully actuated, its segments are fully collapsed on one side, and fully extended on the other side. This can be simplified into a triangle, to show the extent to which the convolute assembly is bent (fig. 6.7). The width of this triangle represents the diameter of the convolute assembly. The width and hypotenuse of the triangle are equal as the diameter of assembly is constant for each segment. The height of this triangle is the total actuated height of the convolute assembly when it is fully expanded on one side, and collapsed on the opposite side. A convolute assembly's expanding side can only unroll until it is no longer overlapping the preceding segment (fig. 6.6). Similarly, the collapsing side of the assembly can only roll until each segment reaches the bottom of the succeeding segment. The vertex connecting the base and hypotenuse of the simplified triangle represents the collapsing side of the assembly. The simplified triangle's height represents the expansion of the assembly; as the convolute assembly has a resting height when it is not actuated, the triangle's height only represents the total overlap between all segments.

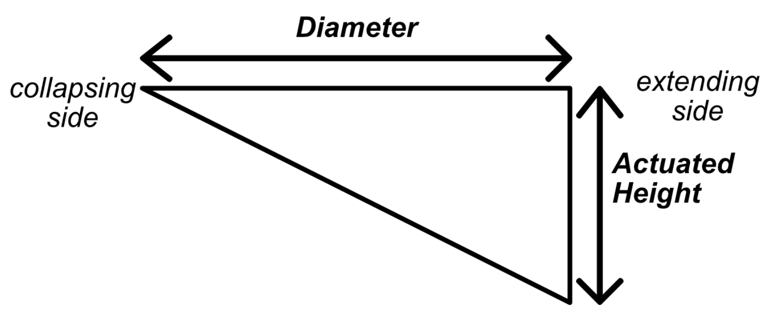

Figure 6.7: Simplified triangle representing a convolute assembly. The left side of the triangle represents the collapsing side of the convolute assembly, while the right side represents the expanding side of the convolute assembly.

The total overlap of the convolute segments can therefore be determined by the diameter of the convolute assembly and the desired range-of-motion (ROM) from this triangle:

$$overlap_{total} = diameter * tan(ROM) \tag{6.1}$$

As unrolling and rolling occur simultaneously for each segment, the placement of a convolute segment should be such that its overlap with preceding and consecutive segments is half the segment height.

To determine the individual convolute segment heights, the total overlap is divided by the number of convolute segments minus one, as the total overlap is distributed across all convolute segments. In addition, the final convolute segment in the assembly does not have a succeeding segment to roll over. Therefore, the height of a convolute segment given a desired range-of-motion (ROM) is:

$$height = 2 * \frac{diameter * tan(ROM)}{n_{segments} - 1} \tag{6.2}$$

Each convolute segment should be placed in the assembly such that it is overlapping the successive segment by one-half of its height.

Circumferential sizing of the ankle convolute assembly was determined by the requirement of the boot to be donned and doffed over the wearer's foot, ankle, and calf. Of these, the heel-ankle circumference was identified as the largest dimension around which the ankle convolute assembly needs be donned/doffed over [54]. The 95% percentile of male heel-ankle circumference, 372 mm, was chosen as the circumference of the ankle convolutes, allowing the convolute assembly to be donned over the foot.

A circumference of 372 mm has a diameter of 184 mm ($\frac{372mm}{\pi}$). As the desired dorsiflexion ROM (40 degrees) is greater than the desired plantarflexion ROM (20 degrees), thus the 40 degree dorsiflexion ROM was used for sizing the convolute. Using equation 6.2, the resulting convolute segment height is 100 mm.

A longitudinal restraint strap is needed to ensure the convolutes do not fully expand during pressurization, and to balance the expansion and contraction of the convolutes during joint actuation. This restraint strap fixes the overlap of the convolute segments at the medial and lateral extents of the joint, allowing the assembly to provide plantar and dorsiflexion. The restraint strap should therefore be 200 mm in height, the height of all but one of the convolute segments.

The ankle joint convolute assembly should also be able to be actuated by the operator's ankle joint, whose joint center is at the malleolus. The ankle convolute segments in current planetary spacesuit boots are placed above the instep region, as their vertical height needs to be accommodated The joint center of the convolute system is at the center of the middle convolute segment. For an ankle joint, this places the joint center well above the malleolus. Therefore, the operator's ankle joint is not indexed properly within the spacesuit boot. Placing the convolute segments at an angle with respect to the plantar-plane of the foot allows the joint segment to be shifted downward (fig. 6.8). A 25-degree tilt was applied to the convolute segments to lower the joint center such that it is closer to the malleolus, improving the indexing of the operator's ankle joint inside the boot.

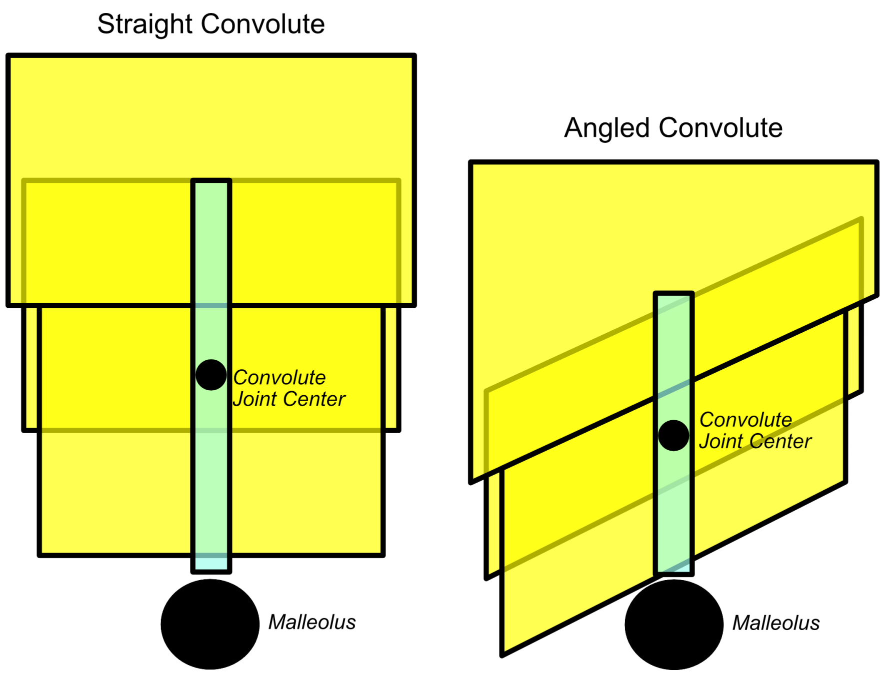

Figure 6.8: Angling the convolutes with respect to the plantar surface allows the joint center of the convolutes to sit much closer to the malleolus, which is the joint center of the ankle.

6.3.2 Upper and Toe Box

The upper of the planetary spacesuit boot prototype should allow the foot to drive the motion of the shoe while providing proper fit and comfort, while the toe-box simply accommodates the toes. A last needed to be selected to provide a baseline design for the upper and toe-box. A last is characterized by its heel-to-toe drop and toe-spring, two sole design features which are very specific to the application of the shoe. As a planetary spacesuit boot is tasked with allowing an astronaut to work and ambulate comfortably across a rough and unknown terrain, parameters from a hiking boot were used to select a last. A male size-9 hiking last was provided for this project from the University of Oregon Sports Product Design Program. This last features a minimal heel-to-toe drop and a toe-spring of 15 degrees. The last features a roomy toe box, where the toe-box is larger than the volume of the toes, for comfort. The last was widened at the ankle to interface to a circumference of 372mm, the same dimension as the ankle convolutes. This allows the ankle convolute assembly to be attached to the upper. The original last and the widening modification are shown in figure 6.9.

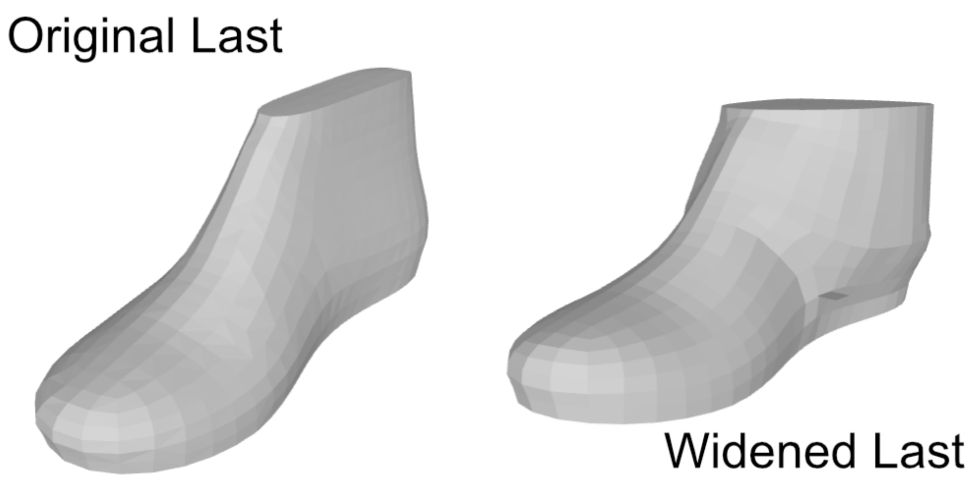

Figure 6.9: Modification of the last to have a wider ankle to accommodate the ankle convolute assembly.

The standard method to generate flat patterns from a last is to place masking tape on the last, cut along seam lines, and flatten the masking tape patterns [93]. The last for this design was 3D printed with ABS. Seam lines for this last's patterns are shown in figure 6.10 . These seams were chosen to ensure the patterns are as flat as possible to minimize folds and creases in the pressure bladder design. As a result, separate patterns were generated for the sole and toe box, and the upper was split into multiple patterns.

The seam which runs along the foot's length across the upper was used to incorporate lacing into the boot.

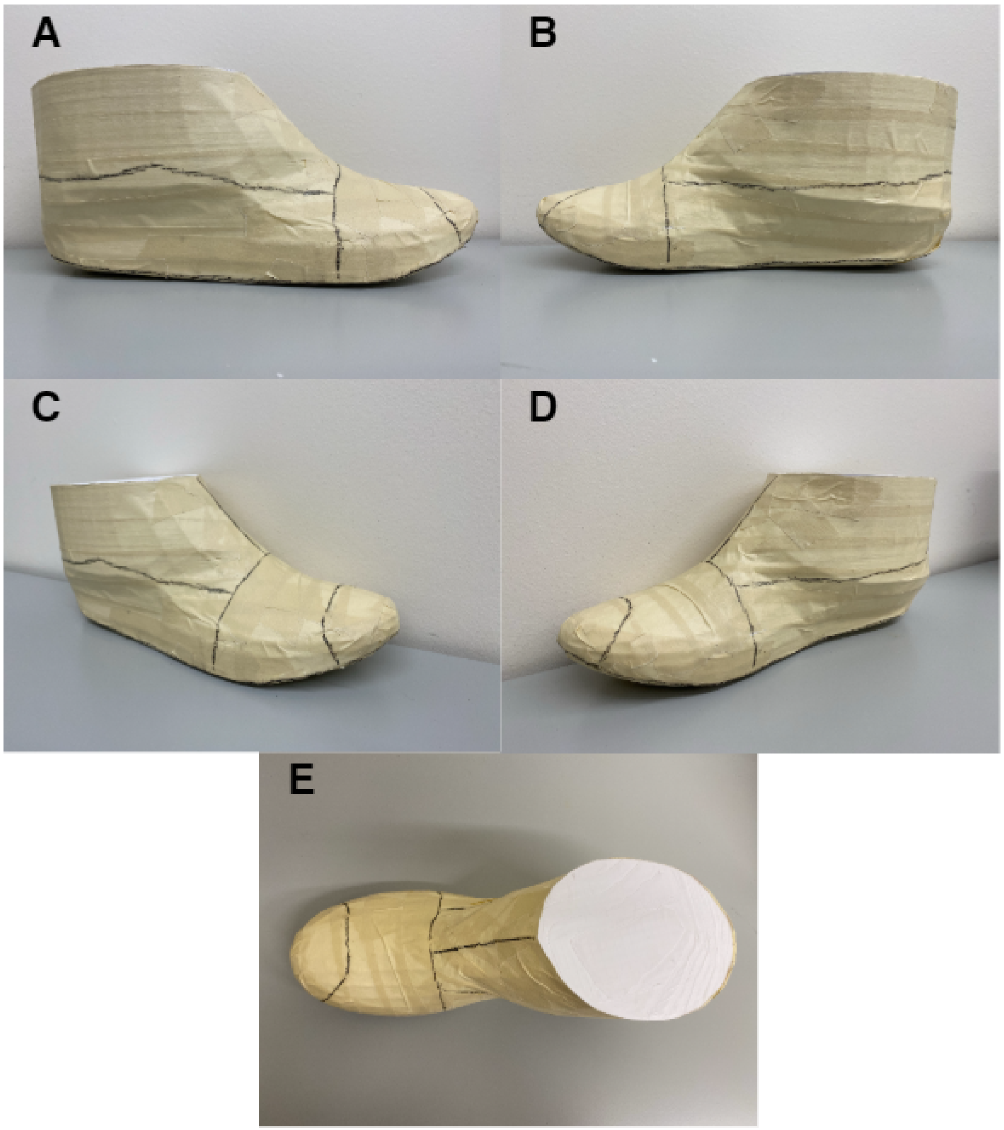

Figure 6.10: Seam lines on taped last. The lateral (A), medial (B), lateral profile (C), medial profile (D), and top-down (E) views are presented

6.3.3 Instep Lacing

A rolling convolute was used to make a conformal pressure bladder which accommodates the lacing, and changes its volume as the lacing is tightened. This convolute allow for deformation of the pressure bladder without resulting in folds, which have been shown to cause discomfort [31], and may be unpredictable in their deformation. As the lacing is tightened, the convolute contracts in a prescribed fashion and decreases the distance between the plantar and dorsal surface of the shoe's interior, resulting in a tighter fit. When the lacing is loosened, the convolute is expanded and the volume is increased, resulting in a looser fit.

Initial designs of the lacing convolute had the convolute placed around the entire foot fig. 6.11. Thus, when the convolute is contracted, the distance between the plantar and dorsal surface decreases uniformly across the length of the foot. However, findings from the dynamic foot shape model (see Chapter 5) found that instep height variability mostly occurs towards the ankle joint. Therefore, the lacing convolute design was modified to pivot at the MTP joint. The lacing convolute is designed into the seam between the inferior and superior upper patterns. The overlap for the lacing convolute was designed with a varying height across the length of the upper patterns, as opposed to the constant height of the overlap used for the ankle convolutes. The overlap is 1 cm at the toe-box, and 5 cm near the heel, allowing for the pivot at the MTP joint.

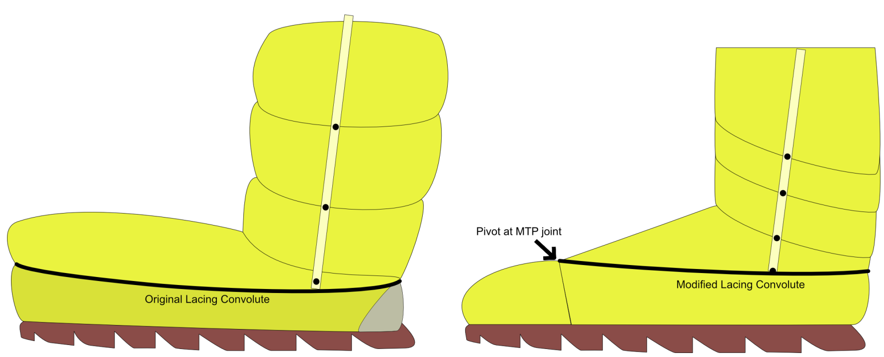

Figure 6.11: Evolution of lacing convolute design. Originally, the lacing convolute ran the length of the boot (left). The lacing convolute was then iterated to pivot at the MTP joint, and provide greater capture closer to the heel

The convolute is paired with a lacing system to allow the wearer to adjust the fit of the upper to their desired tightness (fig. 6.14). In a spacesuit boot, the lacing will need to withstand the pressure forces; the pressure forces will want to expand the boot and loosen the lacing. A BOA lacing system (BOA, Denver CO) was chosen for its strength and fine adjustment, and was provided by BOA. The BOA H4 system consists of a dial, a steel lace, tubing, and low-friction guides; this is the strongest system provided by BOA. The guides are attached in an alternating pattern between the top and bottom layers of the convolute. The lace is run from the dial, through the tubing on the medial side, through the guides, and back through the tubing on the lateral side to the dial. As the dial is tightened, the lacing length is decreased, bringing the guides closer together and contracting the convolute. The lace length is kept constant through the tubing, which fixes the length between the dial and the guides. This is necessary to ensure that no tightening is occurring near the ankle convolute assembly, which would prevent the ankle convolutes from working. Once the lace is tightened to the desired level, the dial can be locked; this prevents the lace from lengthening or shortening.

All lacing adjustment is done when the boot is unpressurized. Adjusting the lacing when the boot is pressurized will require additional effort to compress the air inside the boot. Therefore, adjustment of the boot in an operational setting will require the user to de-pressurize the spacesuit, which precludes adjustment from occurring during an EVA. Therefore, it will be important for users of this system to spend time during training to find their ideal fit prior to performing an EVA.

The placement of the dial was chosen to provide dynamic tightening (fig. 6.14). The dial is placed on the front of the convolute assembly. The tubing is run on the distal side of the convolute assembly. Therefore, when the ankle is plantarflexed, such as during heel-off, the distance that the lace travels increases. Since the lace length is locked, the guides must move closer together to accommodate the lace travel length; this therefore rolls the convolute and tightens the fit. The dynamic tightening accommodates the drop in instep height characterized in the dynamic foot shape model (Chapter 5), ensuring that fit is maintained throughout the gait cycle.

6.3.4 Heel Counter

The heel counter is used in footwear to provide a stiffer rear foot support [137], which may prevent the rear of the shoe from deforming and allowing the heel to lift out of the shoe. The placement of the rearmost BOA dial (fig. 6.14) acts as a heel counter, as it is designed to sit above the heel.

An additional heel counter was designed based on the dynamic foot morphology model (Chapter 5). The selected last had a similar shape as seen in the foot model, and was used as a mold for the heel counter. Clay was molded to the heel of the last to provide a template for the heel counter shape. The thickness of the polymer heel counter was determined through iterative testing; polymer thickness was increased until it interfered with donning and doffing. The heel counter is designed to be placed underneath the lacing convolute, as to not interfere with its operation.

Figure 6.12: Image of additional heel counter which was placed inside the boot

6.3.5 Sole

The sole of the boot provides support, traction, and protection to the wearer. As the novel spacesuit boot will only be constructed for laboratory testing, a simple sole was constructed to represent the height that a manufactured sole would have. A sole was designed by our collaborators at the University of Oregon Sports Product Design Program to fit the last used for the novel spacesuit boot design. A 3D model of the sole is shown in fig. 6.13.

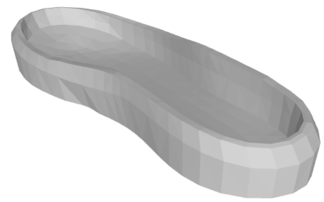

Figure 6.13: 3D view of the sole generated from the last.

6.3.6 Summary

The novel spacesuit boot's design summarized in figure 6.14. The various design elements work together to provide adjustability for the wearer through lacing, and secure the heel in place through the lacing and heel counter.

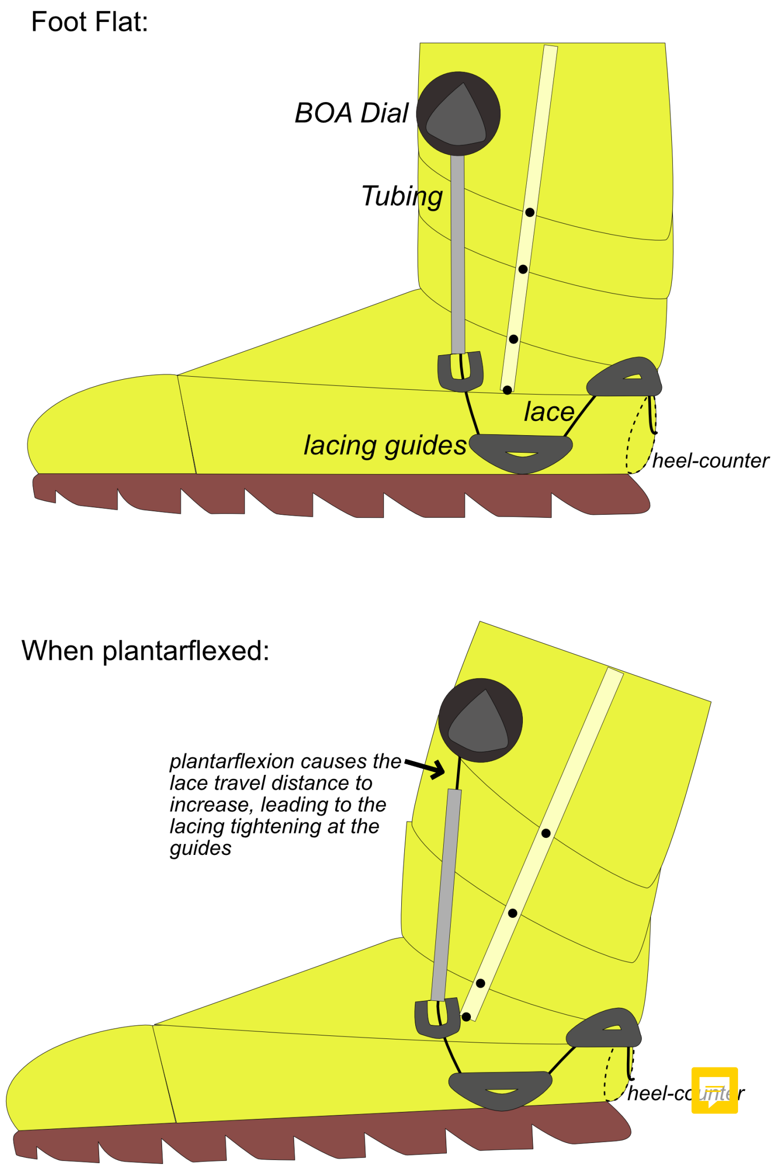

Figure 6.14: Overview of the novel spacesuit boot. Only the medial side is shown, but the lacing is mirrored on the lateral side. The heel counter's location is shown as a dotted line as it is internal to the pressure bladder. When plantarflexed, the distance the lace has to travel is increased and is shown by the arrow. Therefore, the lacing near the guides further tightens.

6.4 Novel Planetary Spacesuit Boot Construction

Much effort was required to translate the novel planetary spacesuit boot design into a functional prototype, as shown in figure 6.15. The following sections outline the manufacturing process for constructing the boot prototype.

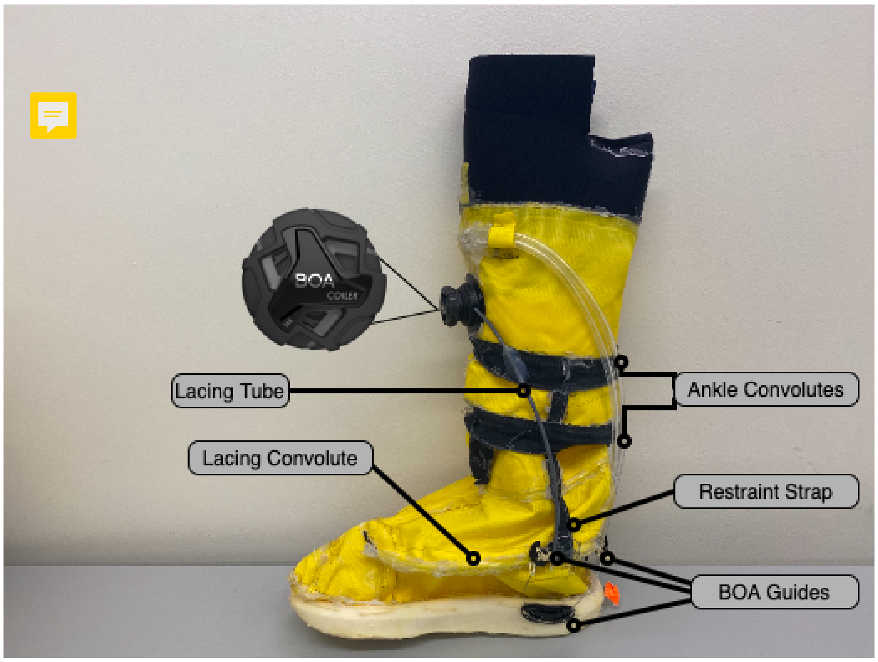

Figure 6.15: Prototype planetary spacesuit boot constructed with BOA lacing, ankle rolling convolutes, and a heel counter. The heel counter is not visible as it is inside the pressure bladder

A heat-sealable urethane coated nylon (Seattle Fabrics, Seattle WA) was used as the material for the pressure bladder [62]. Discussions with spacesuit engineers suggested 400 Denier nylon for its strength. The material can be made air-tight by heat-sealing with a mini-iron (Clover Needlecraft, Los Angeles CA) which can reach a maximum of 580 degrees Fahrenheit.

Numerous coupons were made to test how long heat was required to achieve a strong seal between the nylon fabric. These coupons had heat applied at 390 degrees Fahrenheit in intervals of 5 sec up to 30 seconds. The coupons were the tested on an Instron machine using an ASTM D5034-19 fabric tensile test method. It was found that the coupons with 20 seconds of heat application and up failed at the nylon interface, and not just at the urethane, suggesting a strong bond had been achieved between the fabric.

As only one side of the material is coated in urethane, and the urethane can only be bonded to another layer of urethane, care must be taken in the patterning to ensure that each panel is sealable. It was decided that the urethane-coated side of the patterns will be facing towards the foot, as it is done in current spacesuit construction. Panels were sealed together with another strip of pressure bladder material (fig. 6.16). This technique was applied to each section of the pressure bladder, with specific details regarding construction below.

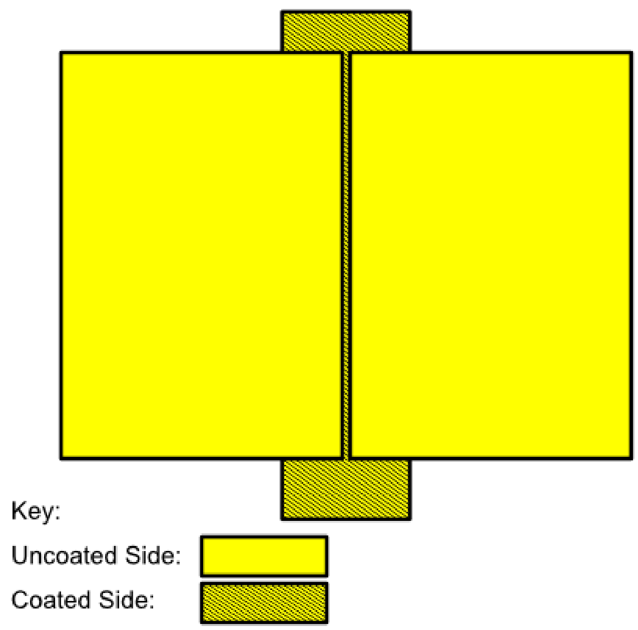

Figure 6.16: Two pressure bladder patterns (left, right) are connected by a single strip of material (middle) at the team. This strip is heat-sealed to both patterns, creating an air-tight seam.

6.4.1 Ankle Convolute Construction

Ankle convolute construction starts with a flat panel for each convolute segment, as summarized in figure 6.17. The convolute assembly was constructed by folding over the top of the convolute segments for the two convolute segments by one-half of the convolute segment's height to achieve the desired segment height. Then, the bottom of the preceding convolute segment is sewn to the folded-over top of the succeeding convolute segment using a straight stitch at 1.0 mm pitch, at both the overlap itself and 1 cm above the overlap. The stitches are then heat-sealed. This process is repeated for the next convolute segment.

A restraint strap is constructed from a 3/4" in canvas fabric which is folded in half and stitched on one side. Two restraint straps are used for each convolute assembly, and are placed at 25% and 75% of the flat panel convolute assembly's width. This results in the restraint straps lying on the medial and lateral neutral axes of the convolute assembly once it is folded into a cylinder. As a result, these restraint straps will be on the medial and lateral side when the convolutes are fully assembled. The restraint straps are stitched to the junctions in two locations between convolute segments by using a straight stitch at the overlap and 1cm above the overlap.

Once all three convolute segments and the restraint straps are attached, the two ends of the segments are brought together to make the flat panel into a circular convolute assembly. A strip of urethane-coated nylon is then used to seal the seam on the inside. 3D printer filament is used for the bands of the rolling convolute. The filament is inserted into the gap between the stitching at the convolute segment junctions. The filament is trimmed to length at the seam. A 1.5cm strip of canvas material is glued to the bottom of each convolute segment to ensure that the convolute's overlap actuates properly. Without this canvas strip, the succeeding convolute segment was found to expand under pressurization and prevent the preceding convolute segment from rolling over it. The ankle convolute assembly is now ready to be attached to the upper.

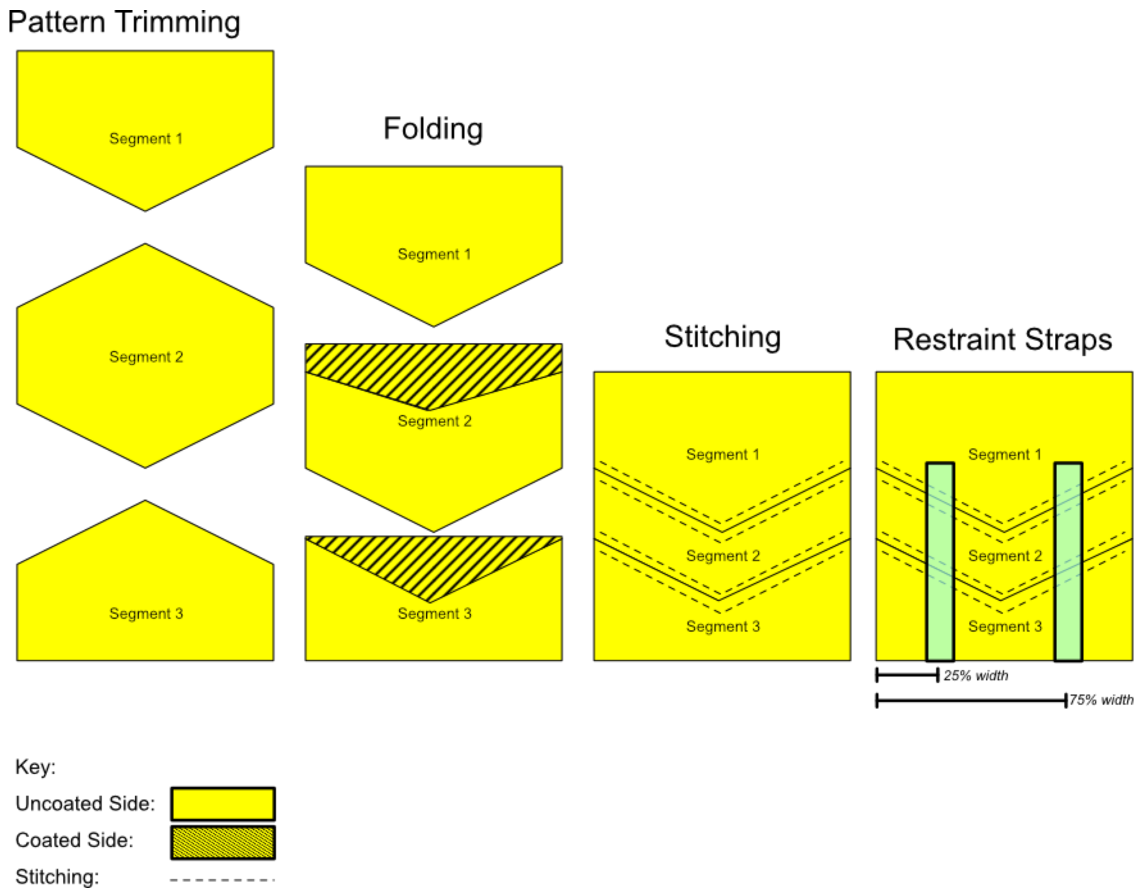

Figure 6.17: Ankle convolute flat pattern construction.

6.4.2 Upper and Toe-Box Construction

Patterns for the upper and toe box expected to interface with the pattern for the sole are extended by 1 cm to provide a seam to attach to the sole (fig. 6.18). This avoids having to use a strip of urethane coated nylon on the interior of these seams, which is at a sharp angle and proved difficult to manufacture.

The patterns for the toe box are simply assembled and sealed together by using strips of urethane-coated nylon at the seams. Construction of the upper needs to account for the instep lacing feature. The inferior upper pattern is extended by the dimensions of the overlap needed for the instep lacing. The top of the overlap is folded over and the superior upper pattern is stitched to the fold. This is done for both the lateral and medial upper patterns. The lateral and medial upper patterns are attached at the heel with a strip of urethane coated nylon. Then, 3D printer filament is inserted into the gap between the stitches to provide structure to the convolute.

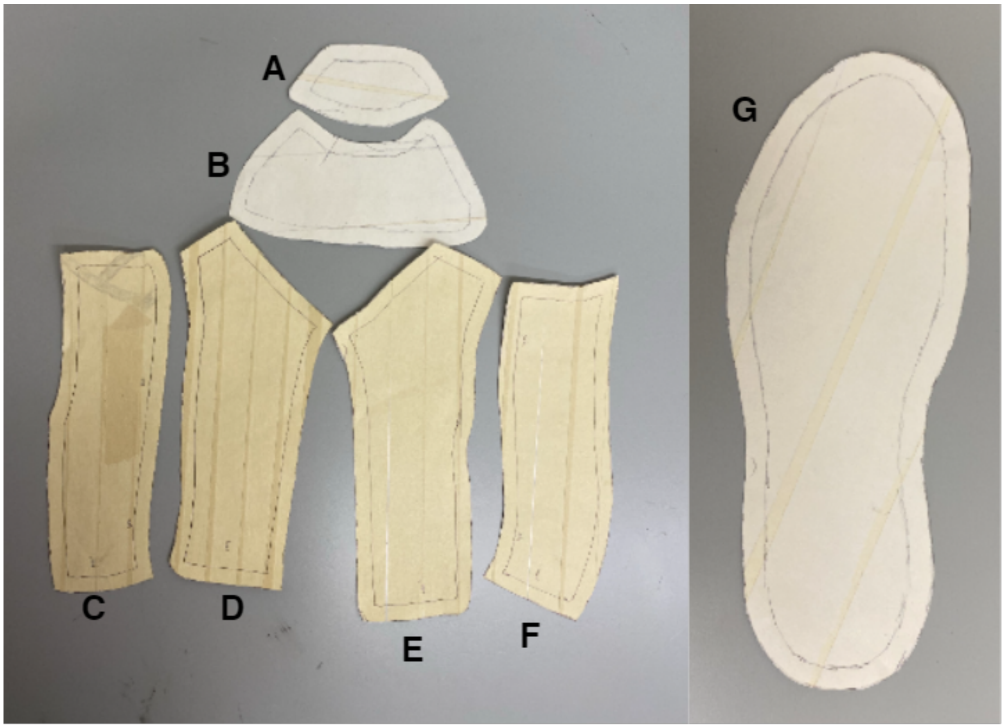

Figure 6.18: Patterns for the upper, toe-box, and sole. These patterns are cut from the last taping process, and flattened onto a piece of paper. New patterns are then traced around the flattened tape patterns, and used to make the respective panels. A 1cm seam is added around each pattern to provide flexibility in manufacturing. Patterns were generated for the forward (A) and rear (B) toe-box, inferior (C) and superior (D) medial upper, inferior (F) and superior (E) lateral upper, and the sole (G).

6.4.3 Sole Construction

Ethylene-Vinyl Acetate foam is a common material used for sole construction in sneakers and daily shoes. Collaborators at the University of Oregon Sports Product Design Program informed us that their prototyping process for most footwear involved using Smooth-On Flex Form-it 17 (Smooth-On, Macungie PA) expanding foam, which provides a similar bounce and deflection as Ethylene-Vinyl Acetate foam.

A mold for the sole was designed to allow for casting from the expanding foam. The sole was provided as a 3D mesh file (fig. 6.13). A negative of the sole was created using the Blender software, where a rectangular box mesh which was bigger than the sole was placed over it and the difference between the two meshes was taken. A seam was added to this box so that it can be separated into two halve. Three holes were placed in the top half of the box above the centerline of the sole negative, allowing for the foam to be poured in before it cures. In addition, four holes were placed at the corners of the box, allowing the box to be clamped together with bolts and thus sealing the mold. This mold was then 3D-printed out of PLA material, and is shown in fig. 6.19.

Figure 6.19: Two halves of the mold used to cast the sole.

Ease Release 2831 (Smooth-On, Macungie PA) was applied to the 3D mold. The expanding foam was mixed, poured into the mold, and allowed to fully cure as per the manufacturer's instructions. The mold was then unclamped, and the sole was peeled out of the mold. Any flash, excess material from the molding process, was then cut off with a knife.

The pressure bladder is attached to the sole through a welting process. The seam from the attachment of the pressure bladder's upper and sole patterns is sewn to the sole. This process is reinforced with hot glue.

6.4.4 BOA Lacing Integration

The BOA lacing guides are secured to the pressure bladder and sole through stitching. The guides are first perforated with four holes, and then hand stitched to the pressure bladder and sole. The BOA lacing dial is glued to the top of the upper most convolute segment. The lace tubing is press-fit into the dial and the first set of guides. The lace tubing is also glued to the canvas straps at the bottom of upper-most convolute segment to ensure it stays secure.

6.4.5 Heel Counter

The heel counter made by casting a thin (3 mm) layer of Elite Double 16 dental polymer (Zhermack SpA, Badia Polesine (RO), Italy). This layer was trimmed to size to fit on the interior of the boot beneath the lacing convolute. The heel counter was secured to the interior of the boot with hot glue and tape.

6.4.6 Pressure Sealing

While the urethane-coated nylon has an air-tight seam when heat-sealed properly, manufacturing tolerances and wear from use of the boot were found to create leak paths in the prototype spacesuit boot's pressure bladder. It was found that hot glue was an adequate sealant for the pressures used in testing. Therefore, a thin layer of hot glue was applied to all seams in the pressure bladder.

6.5 Classic Spacesuit Boot Design and Construction

To evaluate the design of the proposed novel spacesuit boot, a comparison "classic" spacesuit boot was fabricated, based on current designs to the extent possible (fig. 6.20). Similar construction techniques were used as the prototype planetary spacesuit boot: the same sole was used for both boots, and the upper for both boots was designed around the same last. The convolutes for the classic spacesuit boot were constructed with the same height, and overlap, but the convolutes were left flat to the foot's plantar surface, as they are in current planetary spacesuit boot prototypes [118]. In addition, the restraint strap was secured to the sole in the absence of the lacing convolute. The upper for the classic spacesuit boot does not have any lacing; the superior and anterior upper patterns were sealed at the seam separating them. This ensure that the two boots are identical except for the three novel features in the prototype boot: angled ankle convolutes, lacing, and a heel counter.

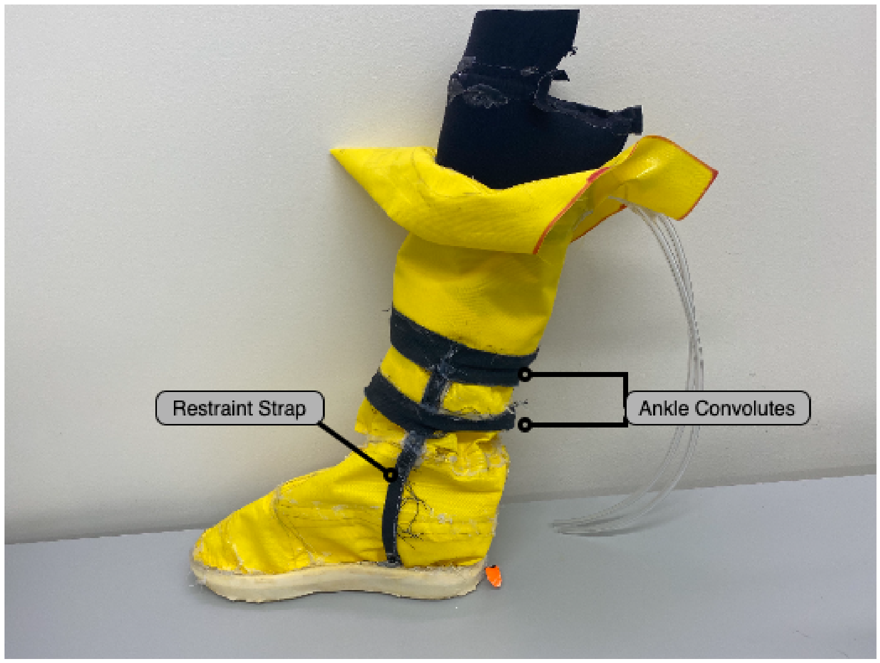

Figure 6.20: Classic spacesuit boot which was constructed with similar techniques as the prototype spacesuit boot, but without lacing, or a heel-counter.

6.6 Summary

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-lift and contact injuries.

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 spacesuit boot, had only one requirement for ankle flexion/extension. This work provides a series of requirements based from previous biomechanics studies on foot motion while walking and hiking to expand upon the provided NASA requirements.

These requirements, along with findings from the dynamic foot shape model in Chapter 5, were translated into a prototype spacesuit boot design. This design features a novel lacing feature which accommodates the static and dynamic variability in instep height. In addition, the prototype boot also features a heel counter, which should assist in ensuring the heel does not slip out of the boot during walking. The prototype boot modifies the ankle convolutes found in current planetary spacesuit boots by tilting their plane towards the heel, thus lowering the joint center to be better indexed with the operator's ankle joint.

The prototype boot was constructed using an urethane coated nylon for the pressure bladder. A sole constructed from expanding foam was integrated into the design. Lacing for the prototype boot was provided by BOA.

A classic planetary spacesuit boot was also constructed, but omitted the novel features of the prototype spacesuit boot. No lacing or heel counter was included in the classic spacesuit boot. Ankle convolutes were left parallel to the plantar surface. However, this boot was constructed using the same last, resulting in similarly shaped patterns. In addition, the sole used for this boot is identical. This ensures that the novel features of the prototype spacesuit boot can be compared to the classic spacesuit boot through evaluation, which is described in Chapter 7.

Chapter 7

Specific Aim 4: Evaluate novel planetary spacesuit boot design for fit and comfort

The novel pressurized spacesuit boot prototype developed in Specific Aim 3 was validated for fit and comfort through subject evaluation. Results of the validation can help answer the main hypothesis of this thesis: a spacesuit boot designed with dynamic foot morphology will provide increased compatibility between the spacesuit and operator. In a terrestrial environment not requiring pressurized spacesuits, EVA tasks are best performed with a work boot. Therefore, an unpressurized laced work boot was used as the gold standard to compare the novel spacesuit boot to. As the novel spacesuit boot features lacing, the unpressurized work boot was compared in both laced and unlaced conditions. A classic pressurized spacesuit boot, not featuring any lacing, was used in the evaluations to compare the novel spacesuit prototype to current spacesuit boot technology. This chapter details the methods for the subject evaluation of all four boots, results, and a discussion on the results as related to each boot's performance.

7.1 Pressurization Test Interface

A pressurization interface was constructed to allow a pressurized boot to be worn by a subject during testing. This interface was common between the classic and novel pressurized spacesuit boots. The interface was designed to allow the user to wear a pressurized spacesuit boot without having to wear an entire spacesuit, much like wearing the control work boot. This allows for the performance of the boots to be isolated to the boots themselves, and not to the presence or absence of a spacesuit.

7.1.1 Interface layers

A base layer of neoprene is heat-sealed to the upper-most ankle convolute. This neoprene layer is patterned as a staircase (fig. 7.1), with the dorsal side having a height of 3 cm, and the ventral side having a height of 6 cm. This layer has the same circumference as the The dorsal side of this layer is then heat sealed with neoprene sealing tape. This creates a 6 cm diameter for the wearer to don and doff the boot. While this gap is much smaller than the wearer's anthropometry that needs to pass through it, the stretch characteristics of the neoprene allow for the foot, heel, and calf to pass through. As a result, a tight fit was maintained around the wearer's calf once the boot was fully donned.

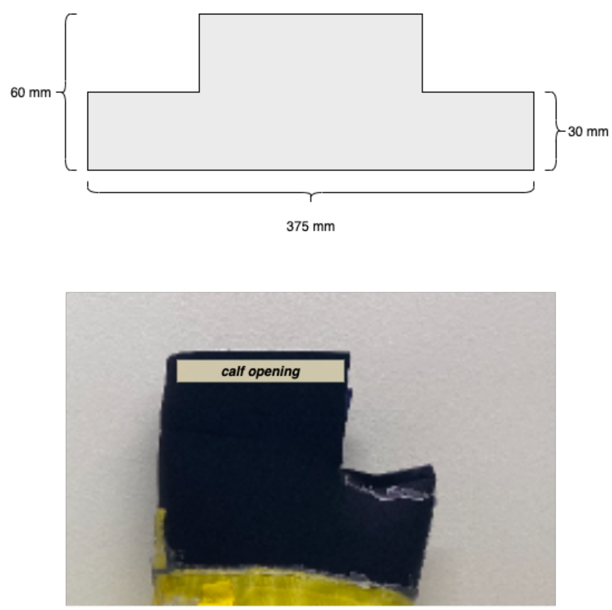

Figure 7.1: Patterning of the base neoprene layer (top) which results in a much smaller opening (bottom, yellow highlight) for the wearer's calf to enter through.

A neoprene and canvas strap was constructed with velcro backings to assist in creating a seal around the neoprene base layer. After the boot is donned, the canvas strap was wrapped over the neoprene layer around the wearer's calf. The strap was then secured to itself using the velcro backing. The canvas material has minimal stretch, ensuring that the lower neoprene layer does not balloon from the internal pressure of the boot. The neoprene strap is then similarly wrapped over the canvas strap. The stretch of the neoprene strap allows it to compress the lower layers around the subject's calf, creating an even tighter fit. Two additional elastic straps with velcro backings were constructed and placed at the top of the lower straps, further sealing the interface between the boot and the wearer. An overview of the straps is provided in figure 7.2.

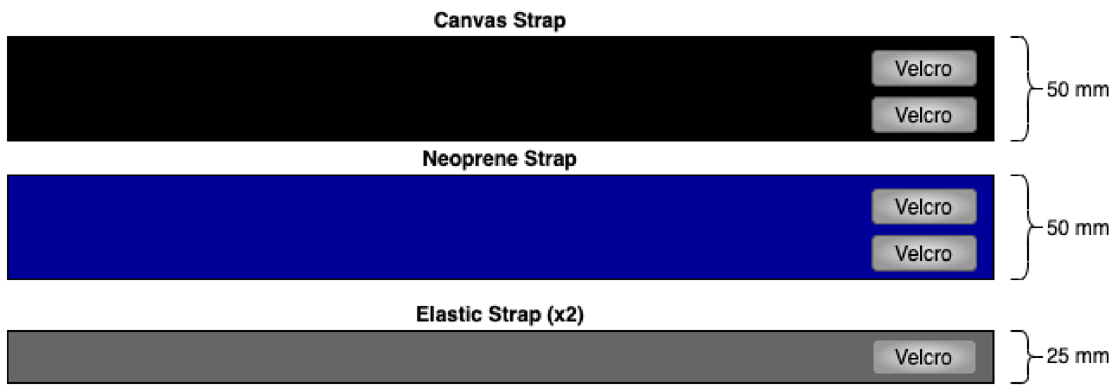

Figure 7.2: Overview of straps used to create a seal around the wearer's ankle.

7.1.2 Air Feed and Monitoring

Two air lines were integrated into the boots just below the neoprene layer; a supply air line to provide pressurized air and a monitoring air line log the boot's interal pressure with a pressure gauge. Masterkleer Soft PVC Tubing (McMaster-Carr, Elmhurst IL), with a inside diameter of 1/8" and an outside diameter of 1/4", was used for the air lines. A vertical slit was cut in the boot 2 cm below the pressurization interface to allow the air lines to enter the boot. The slit was then sealed with hot glue. The air lines were oriented along the circumference of the boot's calf to minimize interference with the ankle convolutes.

The boot's monitoring line was connected to a differential pressure manometer (Amprobe MAN30, Amprobe, Everett WA). This manometer provides a gauge readout of the internal air pressure in the boot. The supply line was connected to the lab's air line, which provides air at

100 psi, with a ball valve. The ball valve was adjusted by the test conductor while monitoring the boot's internal pressure through the manometer.

7.1.3 Interface Performance

The pressurization interface was used on all subjects during boot evaluation. Every subject was able to reach a boot internal pressure of 2.5 psi for both boots. Leakage was still present in the boots due to high tolerances from manufacturing the boots by hand.

The EMU operates at 4.3 psi, and future planetary exploration suit concepts have called for suits to be operated at a higher 8.3 psi to reduce the pre-breathe time required for astronauts prior to getting into the suit [77]. The ACES, which was not designed for EVA operations, operated at 3.5 psi [133]. Higher operational pressures may require increased effort to move suit components.

It was originally desired to reach a pressure of 4.3 psi to replicate the spacesuit pressure in current EVA activities aboard the EMU. While the boots were only able to achieve 2.5 psi, this was still deemed sufficient to proceed with testing as the boot's material was fully expanded to its maximal volume. This allows the boots' mechanisms, such as the rolling convolute ankle joint, to function as they would at a higher pressure. A higher pressure would require additional effort from the subject to move the boot, but would activate the mechanisms in the same fashion. Therefore, it was decided to continue with testing as this would still provide insight into the performance of the boot's mechanisms with regards to subject fit and comfort, but results will need to be taken into context with the lower operating pressure.

7.2 Experimental Design

The goal of this evaluation was to assess fit and comfort of the novel spacesuit boot, as it compared to the classic spacesuit boot, unlaced work boot, and laced work boot. Fit was primarily assessed through heel performance, as reducing heel lift is a primary focus for planetary EVA boot design. Proper dynamic fit will allow for high heel performance, which would improve upon current planetary spacesuit boot efforts. Subjects in this evaluation performed five heel-raises and a short walk for each test boot condition. Quantitative measurements were taken during the heel-raises, and surveys were administered after completing the evaluation for each boot. Therefore, this experiment aimed to answer the following hypotheses:

- The novel spacesuit boot design provides equivalent comfort compared to the laced work boot and improved comfort compared to the unlaced work boot and classic pressurized spacesuit boot
- The novel spacesuit boot design provides equivalent heel performance compared to the laced work boot and improved comfort compared to the unlaced work boot and classic pressurized spacesuit boot

7.3 Methods

7.3.1 Subjects

Five subjects with a self-reported shoe size between 8-10 US Male (9.5-11.5 US Female) were recruited to participate in this evaluation. Participant foot length, foot width, and arch length were measured with a Brannock device when they arrived in the lab. A summary of participant foot anthropometries is provided in table 7.1.

Table 7.1: Summary of subjects' foot measurements

Subject	Foot Length (cm)	Foot Width	Arch Length (cm)	Sex
FQ	25.5	C	26	F
FT	25.5	D	25	F
RM	25.5	C-D	27	M
TF	25.5	D	25	M
TQ	26.5	D	27	M
Average	25.7 ± 0.4		26 ± 1	

7.3.2 Procedures

For each boot condition, subjects donned the test boot on their right foot. The order of the test boots was counterbalanced across all subjects. Subjects were instructed to bring their own low-top sneaker to wear on their left shoe; a low-top sneaker does not limit the amount of heel-rise when compared to a high-top shoe, and therefore serves as a control between all test boot conditions.

Subjects started by performing one set of five heel-raises, and were instructed to best synchronize their heel-raises between both feet. They were also instructed to lift each foot independently as high as possible. Subjects were monitored during their performance of the heel-raises, and asked to repeat the heel-rise set if they were not able to maintain balance during the heel-raises, or were not synchronized when initiating the heel-rise. After performing the heel-raises, subjects were then instructed to walk a distance of 4 meters. This distance was limited by the length of supply air line available to pressurize the spacesuit boots.

7.3.3 Quantitative Measures

Each of the test boots had two markers placed on their medial side. The first marker was placed on the sole in-line with where the center of the shank would lie in the boot. The second marker was placed on the sole 10 cm forward of the first marker. Silver retro-reflective tape was used as the markers for the work boot as it provided the greatest contrast against the black sole. Black Duck tape was used for the spacesuit boots for contrast against the white sole. Markers were similarly placed on the subjects' left shoe, choosing a color which provided the greatest contrast against their shoes.

For the heel-raises, subjects were instructed to stand centered between two Intel RealSense D415 cameras. These cameras were used to collect video data of the markers' movement for both the left (control shoe) and right (test shoe) sides fig. 7.3. Kinovea software was used to measure the vertical amount of heel-rise with these markers. For each heel-rise set, the distance between the two markers is used to calibrate the video data from the camera's coordinates to the global coordinates. The horizontal axis was defined as the plane of the floor. The Kinovea software tracked the vertical displacement of the first marker to assess heel-rise magnitude with respect to the floor to measure the heel position over time in the vertical plane.

Figure 7.3: Marker locations for the novel spacesuit boot (A), work boot (B), and a subject's left shoe (C). The novel spacesuit boot and left shoe use black Duck tape for markers on their sole. The work boot uses a silver reflective tape for its markers. The Kinovea software's annotations are shown on each of the image: Marker 1 is tracked to provide heel rise magnitude, and the orange line is used to calibrate the coordinate system.

Findings from Chapter 4 showed that IMUs may not be appropriate for detecting instances of heel-lift and characterizing heel performance. Therefore, a force sensitive resistor (FSR 402, Interlink Electronics, Camarillo CA) was embedded in the sole of the test boots fig. 7.4. The FSR was attached to a Raspberry Pi Pico, which measured the voltage across the sensor with a voltage divider. The FSR was supplied with a 3.3V reference voltage. As a force is applied to the FSR, the resistance of the FSR decreases. To align the sign of the FSR voltage to the sign of the heel rise magnitude, the voltage reading was inverted such that applying force to the FSR decreased the voltage.

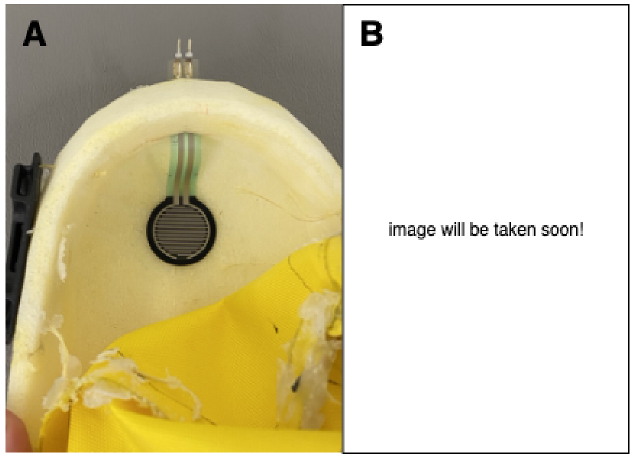

Figure 7.4: Location of the FSR embedded into the sole of the novel spacesuit boot (A) and the work boot (B). The FSR was embedded in the classic spacesuit boot's sole in the same fashion as the novel spacesuit boot

Post-hoc calibration of the FSRs was conducted to characterize the voltage response to force. Calibration was conducted by applying a force from a instrumented force gauge to the sensors, while they were still embedded in the boot. The voltage response of the FSR and the force gauge's output were synced with a custom Python script. Due to sensor breakage, the sensor in the novel spacesuit boot for subjects FT and TF was not calibrated, as it was replaced prior to being used by the other subjects. Calibration results fig. 7.5 showed a similar voltage response for both spacesuit boots, while the work boot's voltage response appears shifted. This may be due to the softer material sole used in the spacesuit boots compared to the work boot. However, for all boots, there is a strong inflection point in the response at 0.5V, where voltages below 0.5V covered a wide range of applied force. Therefore, it was decided to characterize a voltage of 3.3V as "no contact", voltages between 0.5 and 3.3 V as "mild contact", and voltages below 0.5V as "full contact".

A Python script was written to sync the FSR and video data, collecting frames from both cameras and the FSR voltage at the same time. The internal pressure of both spacesuit boots was also logged from the manometer and collected with the FSR and video data, but the reading of the manometer was only updated about once a second. Computational power limited the sample

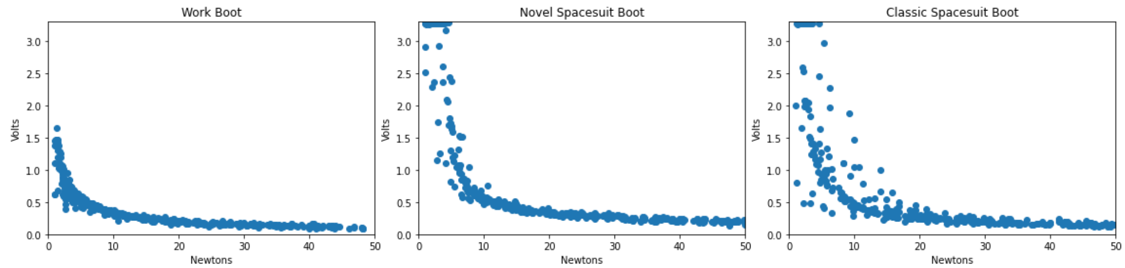

Figure 7.5: Voltage response curves of the FSR to an applied force from a force gauge, for each of the three boots.

rate of the FSR and video data to 14 Hz. While this is much lower than typical biomechanics sample rates, it is still within the frequency content of gait [12].

While video and FSR data was collected during the short walk, this data was not analyzed due to the video's limited field-of-view, thus only capturing one step in each walk.

7.3.4 Survey Measures

After completion of the exercises in each boot, subjects filled out a survey assessing heel performance, discomfort, and exertion. Heel performance was defined as the response of the shoe to the subject's heel. Heel performance was assessed by asking the subject to score the boots' heel performance on a ranking from 1 (low) to 10 (high). Low heel performance was described as analogous to a flip-flop, where the shoe does not lift when the heel is lifted and there is high heel-lift. High heel performance was described as analogous to a well fitted sneaker, where the shoe instantly responds to the subjects heel being lifted and there is minimal to no heel-lift. The Corlett-Bishop Discomfort Scale [35] was used to assess subject discomfort; the survey was modified and limited to 10 areas below the knees of the subject. This survey asks subjects to report their discomfort from a scale of 0 (none) to 10 (extremely high) for each of the areas, shown in figure 7.6. The Rating of Perceived Exertion (RPE) [21] was used to assess how much effort was required to perform the motions. This question asks subjects to report the amount of effort required to perform the heel-rise and walking tasks.

After performing the exercises in all four boots, subjects were then asked to rank the boots from best to worst with respect to overall performance and comfort.

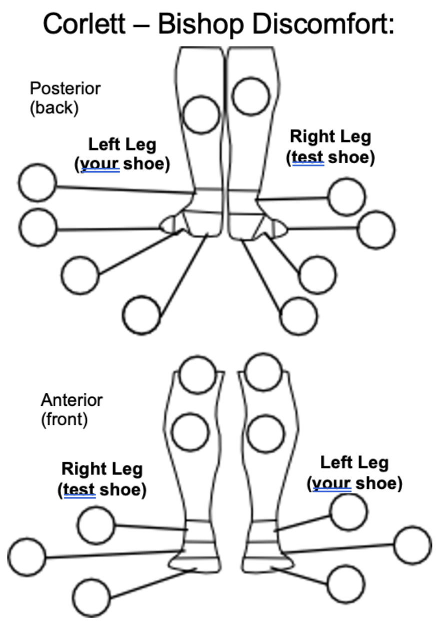

Figure 7.6: Modified Corlett-Bishop Discomfort Scale mapping used for this evaluation, limited to areas below the knee

7.3.5 Quantitative Data Processing

Heel position, as measured by the Kinovea software, was used to identify heel-off initiation time and maximum heel-rise magnitude for both the left (control) and right (test) shoe for each boot condition's heel-rise set. For all sets, the first heel-rise was not analyzed. Python's `scipy.signal.find_peaks` peak detection algorithm was used to identify the peak heel positions for each heel-rise with a width of 5 samples. The left shoe was lifted higher in all heel-raise compared to the right shoe, necessitating differing peak prominence parameters for the peak detection algorithm. A peak prominence of 4 cm was used for the left shoe compared to a peak prominence of 1.5 cm for the right shoe. The heel position at each peak was noted as the maximum heel-rise magnitude for each heel-rise in the set.

Heel-off initiation time was identified by first inverting the heel-position signal and then identifying the signal peaks with the identical parameters for each side as for the maximum heel-rise magnitude analysis. These peaks are the foot-flat phases of the heel-rise motion for each heel-rise. Then, a moving average filter with a window size of 10 samples was applied to the heel position signal. The filtered signal was then integrated to obtain the heel's velocity. Within the foot-flat phases, a threshold of 1 cm/s, decided on after trial and error, was used to identify when a heel-rise was beginning. The point at which the velocity signal crossed 1 cm/s was identified as the heel-off initiation time for that heel-rise.

The FSR voltage was recorded at each heel-off initiation time. The maximum FSR voltage obtained during each heel-rise was obtained by first applying a moving average filter with a window size of 20 samples to the FSR voltage signal. Then, Python's `scipy.signal.find_peaks` algorithm was used to identify peaks with a prominence of 0.5 V and a width of 5 samples. As the FSR signal was quite noisy at its peak, a window of 50% of the peak's width from the peak's highest value was isolated. The average FSR voltage in this window was then noted as the FSR peak voltage for that heel-rise.

7.3.6 Statistical Analysis

7.4 Results

7.5 Discussion

7.6 Summary