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# Space Suit Boot Architecture:

# Analysis and Research for Foot and Ankle Protection

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**This paper presents results from the Space Suit Boot Research and Design for 3D Printing study for the University of North Dakota space suit project. The approach was to examine reports on astronaut injuries during extravehicular activity (EVA) with focusing on foot and ankle injuries. The study surveys modern shoe and boot designs to address the design of the inner boot, outer boot, and overboot to protects the foot and ankle from the biomechanics and kinematics of walking in a 150 kg suit and PLSS. The study concludes with a CT-scan of a candidate Nordic ski boot design that protects the ankle.**

**FIG. 1. Photo of boot print on the Apollo 11 mission to the Moon. Credit: Neal Armstrong.**

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## I Nomenclature

| | | |
|---|---|---|
| *ASTM* | = | American Society for Testing Materials |
| *CSA* | = | Canadian Safety Association |
| CH&P | = | Crew Health and Performance |
| $\Delta T$ | = | "Delta T": Difference in temperature. |
| *EMU* | = | EVA mobility unit (a NASA acronym within an acronym). |
| *EVA* | = | Ethylene Vinyl Acetate. A cushioning material used for insoles in shoes. |
| *EVA* | = | Extravehicular Activity. |
| *EWT* | = | Emergency Walkback Test |
| *HITL* | = | Human in the loop |
| *HRP* | = | Human Research Program |
| *IAC* | = | International Astronautical Congress |
| *ICES* | = | International Conference on Environmental Systems |
| *Inner Boot* | = | A boot that mediates between the foot and the outer structural boot to protect the foot from rubbing and provide support. |
| *Instep* | = | Arched middle portion of the human foot, especially the upper (dorsal) aspect. |
| *ISS* | = | International Space Station |
| *LCG* | = | Liquid cooling garment that cools the astronaut in the spacesuit |
| *LCVG* | = | Liquid cooling and ventilating garment that cools the astronaut and circulates the air inside the spacesuit. |
| *Metatarsals* | = | Long bones of the mid-foot proximal to the toes (phalanges). |
| *NASA* | = | National Aeronautics and Space Administration |
| *NBL* | = | Neutral Buoyancy Lab at Johnson Space Center |
| *Outer Boot* | = | The part of the structural pressure vessel that closes the space suit atmosphere. |
| *Overboot* | = | A protective cover over the outer boot that protects against abrasion, dust, and regolith effects; it also provides thermal insulation and traction. |
| *Phalanges* | = | Bones of the toes. |
| *Plantar Flexion* | = | Downward motion of the ankle joint that propels the body forward. |
| *PSR* | = | Permanently shadowed region of the Moon, typically close to the South Pole. |
| *SMT* | = | System Maturation Team |
| *Sprain* | = | An injury to the ligaments holding a joint together. |
| *Strain* | = | An injury to the muscle tissue itself. |
| *Tarsals* | = t | A series of bones in the foot, located at the root of the foot or "instep". The tarsals consist of the hind and mid-foot and include the calcaneus, talus, navicular, cuboid, and the three cuneiform bones. |
| *TBD* | = | To be determined |
| *TMG* | = | Thermal-Micrometeoroid Garment |
| *UND* | = | University of North Dakota in Grand Forks. |
| *xEMU* | = | Exploration EMU, the suit development project for the Artemis Lunar Program. |

## II. Introduction

One of the least known aspects of EVA operations is the substantial rate of injuries to the astronauts caused by poor design and misfit of the space suit. The incidence of foot and ankle injuries runs second only to the incidence of hand injuries caused by the need to manipulate the pneumatic glove from the inside. This study reviews the record of the injuries that occur inside the space suit boot and their causes. It explores design solutions to prevent and mitigate them.

### A. The Design Challenge

The primary challenge for design of a new space suit boot is to make as compliant as possible with the natural biomechanics and structure of the ankle and foot. It should offer excellent structural support while being flexible enough so that the astronaut can kneel down while flexing the ankle and metatarsals and also extending the foot when necessary. The boot, like the rest of the spacesuit ensemble must be strong enough to hold the atmospheric pressure inside the suit under all anticipated load cases. The boot must also mediate the thermal difference between the suit interior and the extremes of hot and cold in the Moon environment while protecting against damage from the regolith. Like all habitable space architecture, a spacesuit is pneumatic. Pressurizing a suit and all its parts—even an all "soft" fabric suit with an internal bladder—makes it very stiff, which constrains astronaut movement, including foot flexion and extension.

Previous EVA boot designs produced almost completely rigid boots designed for microgravity conditions with attachment to foot restraints. This rigidity restricted full use of the natural extension and flexion of the ankle, foot, and leg. Performing EVAs in a very stiff pneumatic envelope greatly inhibited the free body motion of the Apollo astronauts on the Moon. The ability to flex and extend the feet and ankles, as well as to bend over and to reach down will be key to the astronauts doing productive work on the Moon or Mars surface. The NDX boots are not intended for microgravity use.

This study addresses these design engineering challenges for a lunar surface boot. It takes the approach of designing the boot ensemble from the foot and ankle outward to the harsh lunar environment. This trajectory of analysis and design means that there are effectively at least five essential elements: socks, the inner boot, the LCG or LCVG (which may be integrated in the inner boot), the outer boot, and the overboot (which may be integrated with the TMG). For the purposes of this study, a pressure bladder is as major source of trouble inflicting pain and injury on the feet but not an essential element. In a hard suit, the exoskeletal primary structure holds the atmosphere as in the AX-series of suits, obviating the need for a pressure bladder and a separate restraint layer (Vykukal, Webbon, 1979; Lowenthal, Vykukal, Mackendrick, Culbertson, 1990; Reinhardt, 1990).

### B. Methodology

What appears outwardly as a simple design project turns out to be a highly complex and difficult design and engineering problem. When we first proposed this space suit boot project, our idea was to make a quick study of shoe and boot design and then begin designing a better space suit boot. However, we soon realized that we did not know nearly enough about the problems of space suit boots. No one did, it seemed, given the lack of published material on this topic. In this condition of irresolution, we confronted a choice of trying to become expert at boot design or to study the immense variety of shoes and boots that might be relevant to space suit boots.

Because these problems involve documented injuries, we shifted our focus to understanding and addressing the injury problems. The community of researchers and designers concerned with space suit injuries is small — at least the ones who publish about it. What makes that literature more difficult to follow is that they frequently quote each other, which tends to make the community seem even smaller. Once we obtained at least a partial handle on the injury problems, we saw that we could not originate design solutions from thin air. So, we began to seek solutions among the vast repertoire of design ideas and innovations in the footwear industry.

Since the driving purpose of this study is to support the 3D-Printed Space Suit (NDX) at the University of North Dakota, it takes a fresh look at the needs, requirements, and capabilities to develop new boot designs. So, this study ***starts from first principles*** to comprehend the challenges of space suit boot design. It is unconstrained by NASA legacy suit designs and whatever new suit designs are in process at various companies. That said, we hope that NASA's new suit contractors take to heart the literature we will cite: articles, conference papers, Evidence Book Reports, etc., that discuss astronaut injuries caused by poor suit design, poor suit fit or both. At the same time, we are cognizant of all the NASA EVA guidelines we could find, but there is so little material on the boot that it is further unconstrained.

A ***methodological precept*** of this approach in a condition of ambiguity, irresolution, and uncertainty regards any design solution as a potential *hypothesis about what the problem is*. In nearly all cases of scrutinizing the options, the design option — whether it is specific to EVA boots or from a commercial off-the-shelf product — is a partial hypothesis or rather a hypothesis about part of the design problem.

The ***analytical*** approach is unconstrained by previous precedents for suit design and fabrication as well as current suits under development. Instead, it looks at the causes of injuries and factors them into the design logic trees and from there to reviewing state of the art design in the shoe and boot industry that may prove relevant to space suit boots.

The ***research*** approach is to study the wide variety of athletic shoes, hiking boots, sports boots, and work shoes and boots. This survey searched for important innovations that may improve the three boot elements: the inner boot, the outer boot, and the overboot. This purpose involves ***demonstrating*** the methods of analysis as much as applying them.

## III. 3D-Printing the NDX Space Suit

**Fig. 2. First 3D-printed parts of NDX-3 Prototype ready for assembly.**

The manufacturing methods and technology of space suits have not changed significantly since the Extravehicular Mobility Unit (EMU) was adopted at the beginning of the Space Shuttle era (late 1970s). Conventional construction techniques require specialized equipment as well as significant human-hours of extremely skilled workers to make a space suit. As humanity expands beyond Low Earth Orbit (LEO), the capability to manufacture space suits in-situ will be needed. To begin to address these issues the Human Spaceflight Laboratory at the University of North Dakota (UND) is developing several prototypes of additively manufactured space suits, thanks to a NASA grant.

As this space suit should potentially serve for planetary surface operations (Moon, Mars), the design of the proper footwear for the astronauts is of paramount importance.

The Space Suit Boots project is a work package that is part of the program called Development of an Advanced Planetary Mobility Spacesuit using Advanced Additive Manufacturing Design and Techniques (a NASA-funded grant) at the University of North Dakota (UND). The project team has made substantial progress on developing additive-manufactured suit versions, which currently is refining the concept with the NDX-3 and NDX-4. The UND team has been using 3D-printing to manufacture these suits. The component parts, arms, legs, and helmet appear in FIGURE 2.

### A. Objectives

The objectives for this Space Suit program are:

1) To develop a new suit manufacturing technology that uses reliable and repeatable fabrication techniques that are not dependent upon the exotic skills of conventional space suit seamstresses and technicians.
2) To develop a suit that will be low-cost to fabricate, repair, and adjust for crew members of widely varying sizes (See TABLE 1) from 1$^{st}$ percentile female to 99$^{th}$ percentile male.
3) To develop a suit that can be manufactured in space, including planetary surfaces, to ensure that the space suit assets can be adjusted through new additional sizing rings and other parts to fit the astronauts.
4) The space suit boot is a critical component of this additive-manufactured suit program.

### B. Equipment and Materials

To make components of the suit, several 3D printers are being used. All the printers being used are Fused Depositing Modeling (FDM) machines and of commercial type, with specific modifications made for the specific thermoplastic used. For smaller diameters a modified-Raise 3D Pro3 was used. For large diameters, a MODIX Big-60 V4 is being used.

FDM printers work by feeding a thermoplastic filament through an extruder that melts the plastic. The molten plastic is then extruded in a preprogrammed pattern to create a layer of a part such as shown in Fig. 3. Once a complete layer is finished the printer proceeds to print the next layer. Through this process, a part is made layer by layer. The innovation in this project consists in the printing of flexible filaments, instead of rigid ones, which allows for the manufacturing of suit bladders, capable of withstanding pressurization.

During the course of this research a question emerged about whether we can find a single 3D printable plastic material that is flexible enough to respond to foot and ankle biomechanics and meet the full temperature range 140 C down to about -200 C. The challenge is that we learned through thermal-vacuum testing that the plastic material we have been using to fabricate the suit parts begins to delaminate at about -60 C. The thicker the material, the colder it can go before delaminating. However, simply making the suit parts thicker is not a solution because it adds mass — too much mass and there is no indication that will take the material down to -200 C.

**Fig. 3. NDX space suit limb section in the 3D-printer.**

This question is still under investigation, but it raises the possibility that we cannot build a flexible space suit boot given current plastic additive manufacturing capabilities and materials. If this limitation turns out to be the case, then we need to consider several other options. These options include:

1) Designing and building a rigid boot that meets all of the other requirements and success criteria.
2) Employing advanced metal alloys with much lower temperature range that are also suitable for 3D-printing.

The realization about the limitations of a flexible boot due to the material vulnerabilities led us to create the two categories under which to study the outer boot: flexible and rigid.

### C. Progress

At this time two pressurizable concept demonstrators, the NDX-3 and NDX-4 have been built and are being subject to mobility testing. Two parts of the NDX suits were held in abeyance while awaiting the research in this paper. For these concept demonstrators, only notional boots and gloves were used (as placeholder pieces of the suit). The result of the present study will dictate a new boot design based on the final findings.

FIGURE 4 shows the NDX-4 (a rear-entry suit) suit fully assembled for the first time and being prepared for human in the loop (HITL) testing. The main focus of the initial testing is mobility while pressurized to replicate the resistance to movement of a suit in the vacuum of space.

FIGURE 5 shows the NDX-3 (waist-entry suit) with a human test subject inside. In this view, the suit is not pressurized as the test shown is to verify form and fit for the test subject.

### D. Results

At this point our team has designed, manufactured, and preliminary testing most of the components of the two initial suits, a waist entry (NDX-3) and a rear entry (NDX-4) All parts, except boots, have been individually pressure tested, and limited Human In the Loop (HITL) testing has been performed.

During testing, we were able to determine that 3D printing joints are able to sustain pressurization and do not present differences under torque testing, when compared with traditional space suit joints, like the ones in the EMU. It is still to be determined if durability can be compared with traditional joints during extensive wear, in particular for the bladder layer, but one of our current studies is looking at that.

### E. What comes next?

A design of a pressurized boot assembly for the NDX-3 and NDX-4 concept demonstrators is in the works, based on the results of the present study.


**Fig. 4. NDX-4 suit with a rear-entry hatch ready for Human in the Loop (HITL) testing at the Human Spaceflight Lab.**

**Fig. 5. NDX-3 suit with a waist entry coupling undergoing initial HITL testing.**

## IV. The Apollo Precedents

Although we are not beholden to the Apollo EVA precedents (or Shuttle/ISS EMU), it is valuable to review them to characterize an important point of departure. The Apollo lunar surface suits included an Outer Boot that was part of the restraint layer. Inside the suit was the pressure bladder that held the atmosphere while being held in shape by the fabric and rigid boot restraint layer. The Overboots went on over the Outer Boots and served as the physical contact with the lunar surface. Instead of an “inner boot” the crewmember donned the pressure bladder which acted as a kind of full-body stocking. The astronaut wore the liquid cooling garment (LCG) inside the pressure bladder. Fig. 6 shows a display of most parts of the Apollo lunar surface suit, with the pressure bladder notably absent.

The Apollo lunar surface suits’ outer boot constituted part of the restraint layer. The restraint layer ***restrains*** the inflation of the pressure bladder to give it as constant a shape and as constant a volume as possible. In this way, the suit can hopefully maintain a steady level of resistance to astronaut motions such as joint torque, hand manipulation, and general limitation of the ergonomic envelope. The Apollo outer boots were part of the restraint layer, as are the Shuttle/ISS EMU boots. The overboots were not part of the pneumatic suit architecture; they went over the outer boots as the contact layer with the regolith.

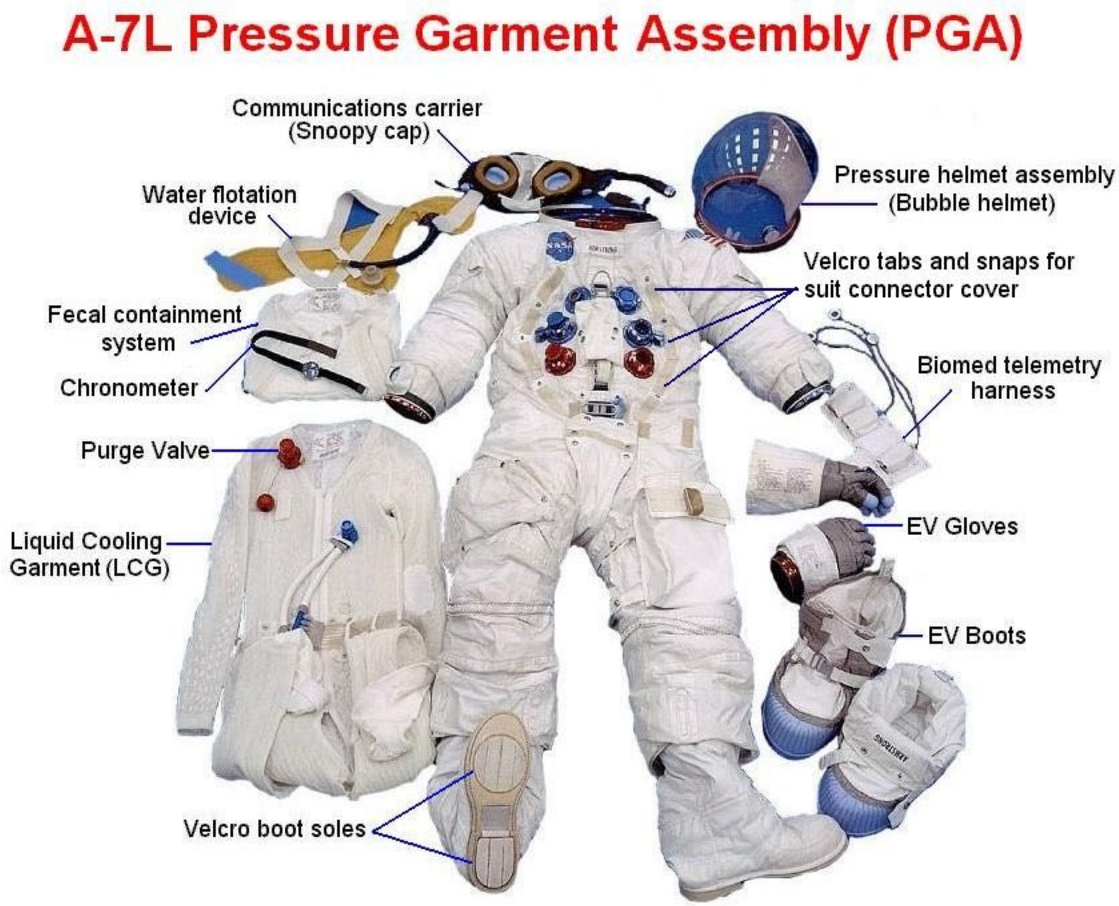


**Fig. 6. The Apollo Lunar Surface Suit Disassembled. Note the Outer Boots attached to the fabric of the restraint layer. The Overboots attach to the Outer Boots via the "Velcro boot soles." The "EV Boots in the lower right corner are actually the Overboots. The pressure bladder is absent from this photo.**

The NASA EVA Evidence Book (Chapell et al, 2017, p. 1) describes the Apollo suits and their shortcomings with general suggestions for improvement:

> The Apollo astronauts completed EVA tasks in suits that were designed for their short duration lunar missions, although suit mobility problems were evident. The more frequent EVAs and more varied EVA tasks that are anticipated during the future longer-duration exploration missions will require EVA suits and systems that are better oriented to human health and performance than those used during the Apollo Program. Many of the problems that were encountered with the Apollo EVA suits (e.g., limited mobility and dexterity, high and aft center of gravity, and other features requiring significant crew compensation) will need to be corrected or mitigated to optimize EVA objectives of exploration missions.

Figs. 7a and 7b show the "astronaut underwear." Fig. 7a shows from the front the LCG/LCVG in white or silver, then the pressure bladder that goes over the LCG/LCVG, and finally the outer garment consisting of the restraint layer and the Thermal-Micrometeoroid Garment (TMG) that covers all the rest. Fig. 7b shows a detail of the LCG/LCVG. Note how the legs extend down toward the ankles but stop above the "ankle bones." The LCG/LCVG is held in place by stirrup straps that go around the feet, which are not to be confused with the cooling portion of the LCG/LCVG itself.

Fig. 8 presents a cutaway view of the 16-layer traditional space suit lay-up. Please note the LCG/LCVG on the inside, covered by the pressure bladder which the Dacron restraint layer covers in turn.

Fig. 7a. Layering of a space suit. Note the Pressure Bladder layer in orange and how it encloses the feet. The bladder goes on over the LCG/LCVG. Courtesy of JAXA.


Fig. 7b. Liquid Cooling Garment/Liquid Cooling and Ventilation Garment (LCG/LCVG) front and back views. Note how the cooling portion of the LCG/LCVG runs down the leg and stops above the ankle. Courtesy of NASA.

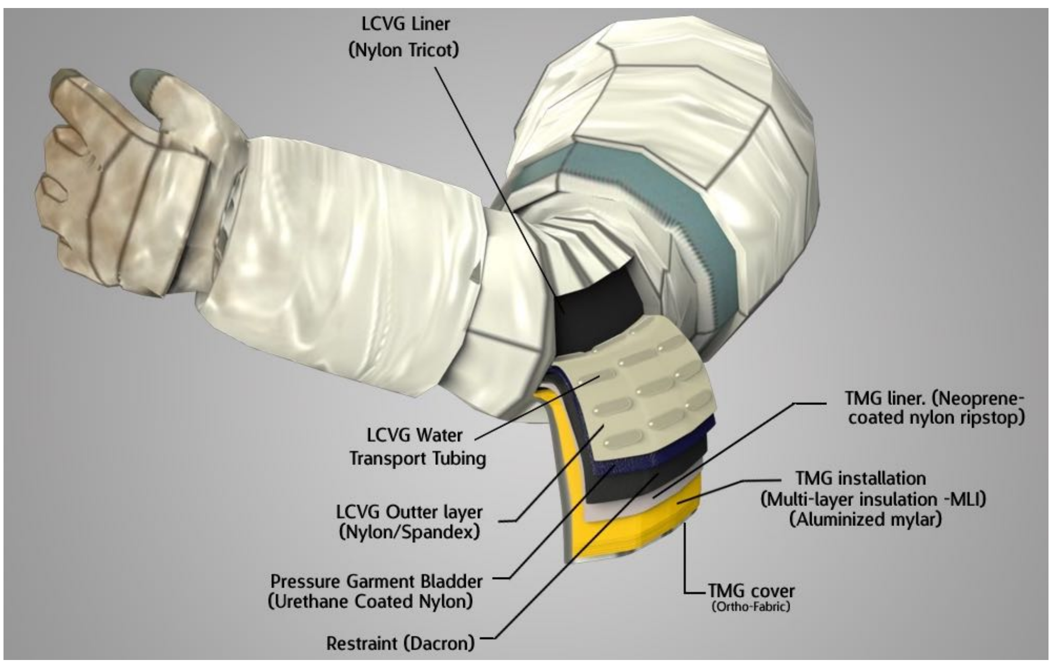


**Fig. 8. Cut-away view of Conventional Space Suit Layering. Courtesy of ILC Dover.**

The 2021 Evidence Report (Dunn, Benson, Norcross, Newby, p. 7) recounts the Apollo mobility limitations and their possible connection to the constraints built into the rigid boot and suit design:

> Normal human locomotion includes flexion at the hip, knee, and ankle, but the Apollo A7LB (lunar surface EVA suit) had limited ability to bend the suit at the hip and rotate within the suit. This likely contributed to the loping and hopping style gait, which relied much more on knee and ankle range of motion.

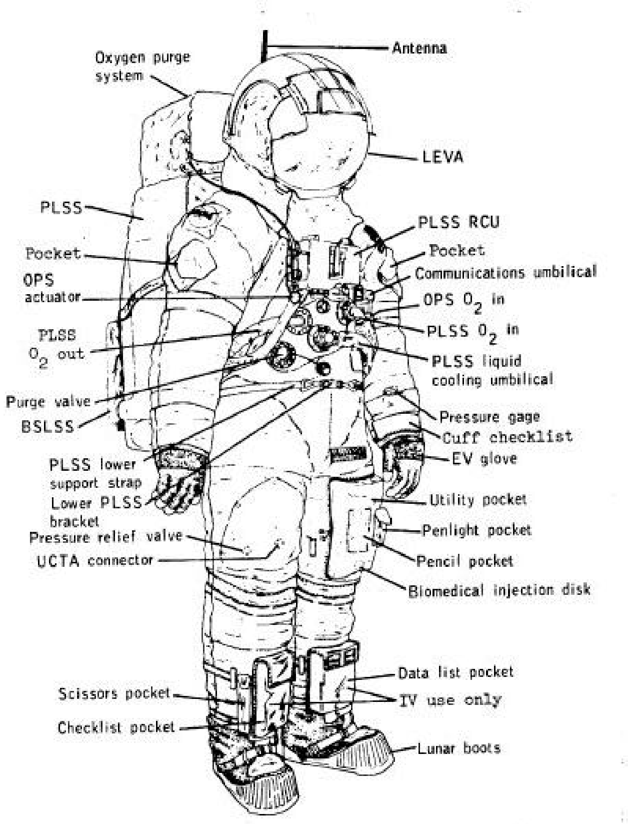


**Fig. 9. Apollo Lunar Surface Suit diagram, Credit: NASA.**

**Fig. 10. Buzz Aldrin's lunar space suit boot at Tranquility Base. Credit: Neil Armstrong.**

Fig. 9 shows a diagram of the Apollo suit. The lunar boots appear with the overboots on top of the outer boot. Fig. 10 shows a closeup of Buzz Aldrin's overboot.[4]

## V. 3D Printed Space Suit Requirements and Success Criteria

This section presents our requirements and success criteria. The requirements include documents from NASA and parameters for the 3D printed space suit from the Space Studies Department at the University of North Dakota. This North Dakota team also developed our own success criteria for each of the three key boot elements.

### A. NASA Requirements

That said, NASA has promulgated requirements for the Artemis program lunar space suits and their boots. Fester and McFarland (2022, p. 2) cite the "major" NASA requirements for lunar spacesuits in TABLE 1.

One area where we remain to be convinced is the lunar thermal extremes that neither NASA nor anyone else has solved or even defined adequately the surface thermal environment problem for spacesuit boots. The issue is whether the same boot design can serve both in the lunar noon and in the lunar night, and more specifically in the permanently shadowed regions of the South Pole. This huge temperature range will challenge nearly all plastic and rubber-like materials not to melt from the extreme heat or to fracture from the extreme cold. The boot stands out as a particular nexus of these challenges. In addition to exposure the extreme ambient temperature swings of the surface, the boot is in contact with the surface itself, therefore subject to conductive heat transfer.

Fester and McFarland (2022, p. 4) advocate the need for two major trade studies:

[4] The way we know it was Aldrin's boot is that Neal Armstrong held the camera their entire single EVA on the Moon.

1) Overboot for contact with the surface [as was used during the Apollo lunar EVAs] versus a single boot architecture.

2) Active heating versus passive insulation

In item one, they refer to a single boot doing double duty as an Outer Boot in the restraint layer and also as the Overboot, making contact with the regolith. This proposal is unlike the Apollo Outer Boot that in effect (from today's perspective) did double duty as an Outer Boot and as an Inner Boot. In item two, they refer to the issue of whether it is necessary to heat the boot to protect the foot in the Permanently Shadowed Regions (PSRs) or whether passive insulation would suffice to retain body heat.

| **TABLE 1. NASA xEMU Lunar Boots Driving Requirements** | |
|---|---|
| **Requirement** | **Specification Summary** |
| **Anthropometric Range** | 1st percentile female to 99th percentile male<br>Foot Length: 12.6 – 30.5 cm (8.5 – 12.0 inches)<br>Foot Breadth: 7.9 – 11.4 cm (3.1 – 4.5 inches) |
| **Indexing** | Prevent unintended relative motion between the feet and the boot [and between the foot and the ankle]*. |
| **PSR Limiting Exposure Time** | "Two hours of operation in a PSR" (permanently shadowed region) with surface temperatures at -225 C (18 K, -373°F) |
| **Equatorial Lunar Noon Limiting Exposure Time** | No Specification for 140 C (383 K, 284° F)* |
| **Lunar Dust Protection** | "Preclude dust entrapment, mitigate abrasion, protect mechanism." No [current]* specification for electrostatic dust attraction.[5] |
| *Added by Author: The current Artemis program addresses only the coldest zones on the Moon at the South Pole. It does not consider the equatorial hot zone. | |

The authors of the papers reviewed for this study all seem to assume that they can handle the cold extremes with either passive thermal insulation, active heating, or both. That may be true. However, none have written incisively about managing the extreme heat of the equatorial noon. The sole of the overboot will be in contact with the hot surface. It is possible that a set of thermal insulation materials may protect the boot and foot from conductive heat gain. However, the surface regolith will also be reradiating infrared energy that will hit the sides of the boot at very short distances. The current xEMU stops the LCVG short of the boot top. The xEMU boot design parameters do not appear to show evidence of considering managing this double radiative heat gain. With all the best insulation in the world, the foot might still need cooling.

### B. North Dakota Requirements, Guidelines, and Success Criteria

In this approach, we are designing the boot from the foot outward. We have four requirements and three guidelines.

#### *1. Requirements*

1. The height of the boot shall be 23.0 cm (9.55 in).
2. The top of the boot shall mate and close a pressure seal to the bottom of the lower leg section. As an example, the NASA xEMU lower leg to boot sealing ring is 5.25 inches (13.335 cm) interior diameter (Fester, McFarland, 2021, p. 7).
3. The size of the Inner Boot (or Outer Boot if it does double duty) shall be US size men's 11, EE wide.
4. The design of the Outer Boot shall be suitable for 3D printing and compatible with the rest of the North Dakota space suit (NDX) project.

[5] NASA does have a requirement to not take more than 50 g of dust into the crew cabin from each EVA, but it does not appear to address the electrostatics in particular.

*2. Guidelines*

1. The analysis and design of the boot shall take into consideration all environments on the Moon, including both the hot equatorial noon and the cold, permanently shadowed regions (PSR) at the South Pole.

2. The analysis and design of the boot does not presuppose the conventional bladder and constraint layer. The NDX-3 and NDX-4 are essentially hard suits, in which the outer shell could at least theoretically serve as the pressure vessel, eliminating the need for an inflatable bladder and an additional restraint layer.

3. The design of the NDX suits does not preclude a thermal, dust, and micrometeoroid garment.

**C. Inner Boot vs Outer Boot vs Overboot**

The complete EVA boot we envision consists of three articles:

- Inner Boot – Protects the foot and ankle and supports them.
- Outer Boot – May be part of the restraint layer for a pressure bladder or the actual pressure vessel.
- Over Boot – Protects the Outer Boot from the lunar surface conditions and environment.

At this stage, the allocation of functions for the 3D-Printed Suit among the three boot elements is still fluid and changeable:

- The internal boot provides support to the foot and ankle and protects them from injury.
- The external boot acts as part of the integrated space suit pressure vessel,
- The overboot provides traction, protection against puncture and abrasion, and thermal insulation, particularly from conductive heat transfer to the ground. The overboot may also incorporate a "gaiter" or outer dust cover.
- The thermal insulation remains an open question: to what extent should the inner boot be insulated against radiant heat transfer or should the outer boot or overboot be insulated?

**C. Success Criteria**

The goal of this task is to make the 3D printed boot responsive to human locomotion and working positions while protecting the astronauts from injury such as sprain, strain, or irritation. Therefore, it will be desirable —if not imperative—to enable the internal and external boots to flex and extend together in concert with the actions of the foot and ankle. The project success criteria that follow stand in addition to the NASA and UND requirements above.

*3. Success criteria for the Inner Boot*

a) The inner boot provides arch, foot, and ankle support to the astronaut.

b) The inner boot is flexible.

c) The inner boot with the astronaut's foot in it fits easily into the outer boot.

d) The inner boot enables the best motions of the foot and ankle biomechanics.

e) The inner boot protects the foot and ankle against excessive pitching, rolling, shearing, and torsion forces.

f) The inner boot is padded with soft material to protect the astronauts from blistering, bruising, chaffing, compression, irritation, and rubbing.

g) The inner boot must fit comfortably but not too tightly within the outer boot.

h) If there is a pressure bladder over which the Inner Boot fits, it must prevent the bladder from creasing, folding, or wrinkling to help protect the foot.

i) The inner boot must not have external protrusions such as lugs, ribbing, or other textures that can abrade or damage the soft inner lining of the outer boot.

j) Option: The Inner Boot may provide an interface to the LCG or LCVG for active cooling and ventilation to cool the feet.

k) The top of the inner boot should be precisely located in relation to the seal between the lower leg and the outer boot top, although where that precise location should be remains TBD.

*4. Success Criteria for the Outer Boot*

a) The outer boot restrains the bladder that holds the atmospheric pressure within the suit and meets all mechanical, safety, and structural requirements of the space suit design.

b) The outer boot accommodates a men's size 11, EE wide inner boot.

c) The outer boot works in concert with the inner boot to afford the best feasible foot and ankle biomechanics.

d) The outer boot handles the major "$\Delta T$," the difference in temperature of the internal atmosphere and the ambient conditions on the lunar surface.

The temperature on the lunar surface can vary from -200 C to +140 C (-328° F to 284° F). This $\Delta T$ consists of two factors: radiation gain and loss from ambient conditions, particularly direct sunlight, and conduction gain and loss from contact with the hot or cold regolith.

The Apollo missions contribute some experience to the Overboot. In particular, Schering et al (2013, p. 18) surmised from Apollo reports that "The boot . . . was slippery on rocks or boulders, [perhaps because] the Regolith had a high coefficient of friction." For this reason, we give attention to the lug soles for improved traction on candidate Overboot features.

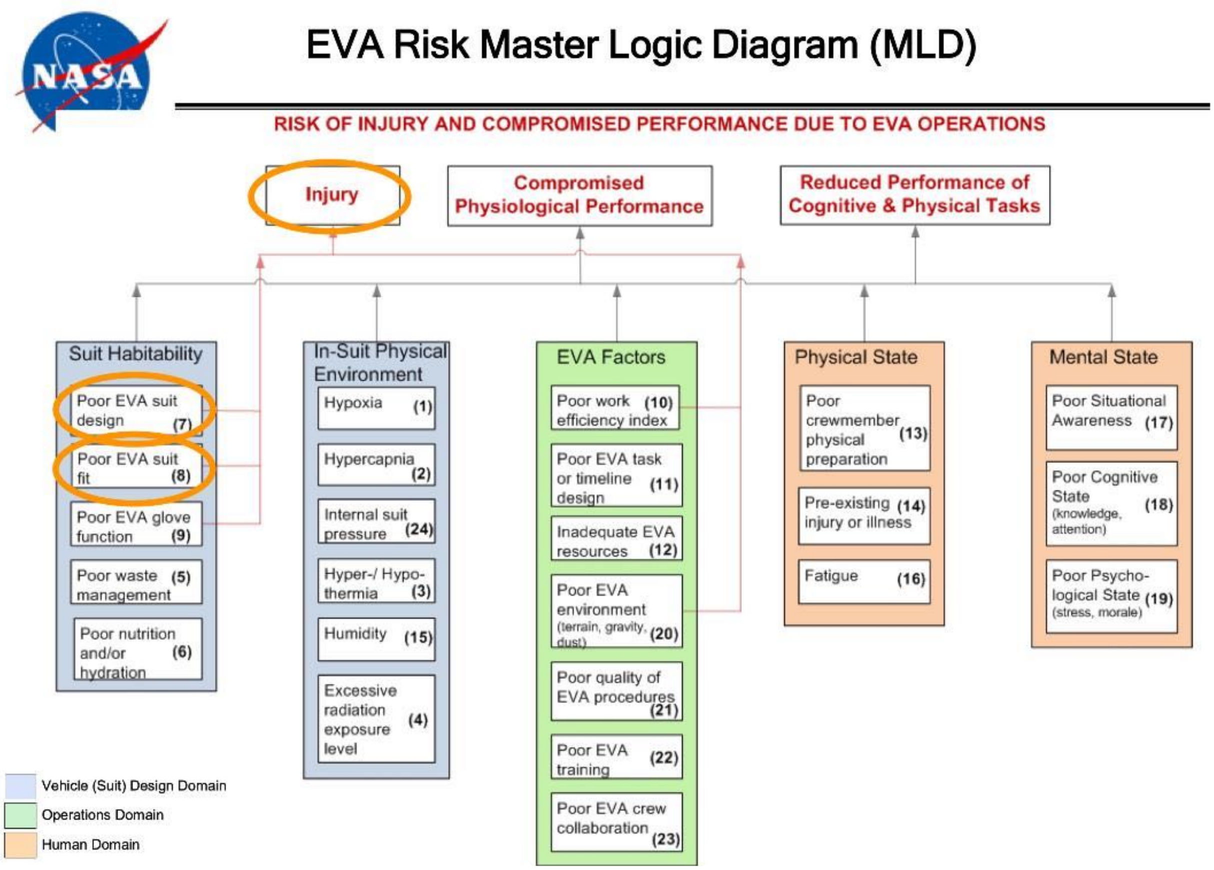


**Fig. 11. EVA Risk Master Logic Diagram. Note the injury-causing factors in the orange ovals. Credit: Michelle Rucker, NASA Johnson Space Center, orange ovals added by the author.**

*5. Success Criteria for the Overboot*

a) The overboot protects against conductive heat gain and loss through the sole of the boot.

b) The overboot protects the outer boot from damage caused by hard and sharp regolith.

c) In concert with a “gaiter” dust cover, the overboot may protect the entire footwear ensemble from dust intrusion.

**The overboot provides traction for walking and working.**

## VI. Foot and Ankle Injuries

NASA is aware of the problem of EVA injuries. As shown in Fig. 11, the NASA EVA Risk Master Logic Diagram (MLD) above connects EVA injuries to two causes: Poor EVA suit design and poor EVA Suit fit. These two orange ovals include poor EVA boot design and poor EVA boot fit as well. The underlying question remains: What are we going to do about it?

In concert with this MLD, NASA also recognizes key knowledge ***gaps*** in its EVA research and development programs and projects in Abercromby et al (2019, p. 4). Abercromby et al identify a great many gaps for the EVA program, but two stand out as being potentially related to foot and ankle injuries within the Crew Health and Performance (CH&P) domain. These gap definitions appear in TABLE 2. They derive from the EVA System Maturation Teams (SMT). At a programmatic level, Abercromby et al (2020) identify the knowledge (and other) “gaps” in the EVA research and development.

**TABLE 2. NASA EVA Knowledge Gaps Related to Potential EVA Injuries**

| EVA SMT Gap Number | CH&P Gap Description |
|---|---|
| EVA-Gap-90 | The effects of EVA suit sizing and fit on crew health, performance, and injury risk are not adequately understood. |
| EVA-Gap-94 | The risk of crew injury due to exploration EVA operations and methods for mitigating that risk are not adequately understood. |

The consideration of these gaps encompasses Chappelle, et al, (2017) notably pp. 19-20 concerning foot injuries during EVA, and also the discussion pp. 21-24 concerning mobility, suit fit, and “alternate technologies.”

At a more general level this task includes consideration of NASA Human Research Program/ Human Research Roadmap’s EVA7 Gap: “How do EVA suit system design parameters affect crew health and performance in exploration environments?”

### E. The Rate of Injuries

General suit design issues also affect the feet, especially where the pressure bladder comes into play. Astronaut Michael Gernhardt et al (2009, p. 347) recount an earlier study of injury symptoms and their occurrence during neutral buoyancy training in the Neutral Buoyancy Lab (NBL) (Strauss, 2004)[6]:

> A study that was conducted from July 2002 to January 2004 identified the frequency and incidence rates of symptoms by general body location and characterized the mechanisms of injury and effective countermeasures (Strauss, 2004). During this study, 86 astronaut-subjects were evaluated in the NBL during 770 suited test sessions. Symptoms were reported by the test subjects in 352, or 45.7%, of the sessions. Of these symptoms, 47% involved hands; 21% involved shoulders; 11% involved feet [for 39 test subject sessions]; . . . While most of the symptoms and injuries sustained during EVA training were “mild, self-limited, and controlled by available countermeasures,” some “represented the potential for significant injury with short and long-term consequences regarding astronaut health and interference with mission objectives.

Gernhardt (2009, p. 348) also recounts a simulation of a 10 km “Emergency Walkback Test” (EWT) from a disabled rover. The suited subjects walked the 10 km on a level treadmill:

[6] The microgravity environment simulated so well in neutral buoyancy testing is different from lunar 1/6 g, especially regarding motion, rates of motion and the force needed to react. However, it is the best and only data we have of this kind.

During the 10-km EWT, subject discomfort levels were recorded, and a medical monitor examined the subjects for signs of suit-induced trauma at the completion of the test. . . . The knee area and **the feet/toes** were the most frequent sites of discomfort during and after the test. [emphasis added]

The 2021 Evidence Report (Dunn, Benson, Norcross, Newby, emphasis added) states with regard to suit misfit:

(p. 7) Abrasions and contusions, due to rubbing and impact against the soft suit components to move the garment, are less serious injuries that frequently occur at the wrist, arms, knees, and **ankles.**

(p. 11) A suboptimal suit fit can directly cause or contribute to injuries to the occupant through impingement (such as at the shoulder) or contact-related injuries (fingernail loss, knuckle abrasions, **excessive contact at the top of the foot**). [emphasis added]

This finding implicates the possible need to customize and size individual boots for each crew member, which raises questions of cost, inventory, and supply. So, it becomes incumbent upon us to inquire into the causes of these suit conflicts, misfits, and potential remedies to resolve them.

**B. But First, One Big Caveat!**

Anderson, Diaz, et al (2012, Nov, p. 5) state that "Spacesuit injuries are short term, minimal published data for EVA."[7] From this *not-so-subtle warning*, can we infer that the data set for microgravity EVA suit-related injuries is less than complete and so less than reliable? Take for example the conflicting representations in two peer-reviewed or refereed articles.

*1. Foot Injuries but No Ankle Injuries?*

1) Scheuring, Mathers, Jones, and Wear (2009, p. 121) give a summary of the scope of the problem of in-flight EVA injuries up to that date:

Further examination of the 50 injuries that occurred due to the EVA suit is depicted in [Fig. 12 ]. In this analysis, the hand represented the most commonly injured area of the body during EVA, followed by **the foot.** Five other injuries occurred during EVA that were not due to interaction with the suit components. Four of these injuries involved muscular strains while performing EVA activities, and the fourth a hand abrasion immediately following the EVA. EVA-related injury incidence from all sources was 0.05 per hour in 1087.8 h of EVA activity during the space program to date. This equates to an in-flight musculoskeletal injury incidence of 1.21 per day or 0.26 per EVA.

A copy of Scheuring et al's ((2009, p. 119) column chart appears as FIGURE 8. It reports 11-foot injuries and about two leg injuries, but ***no*** ankle injuries.

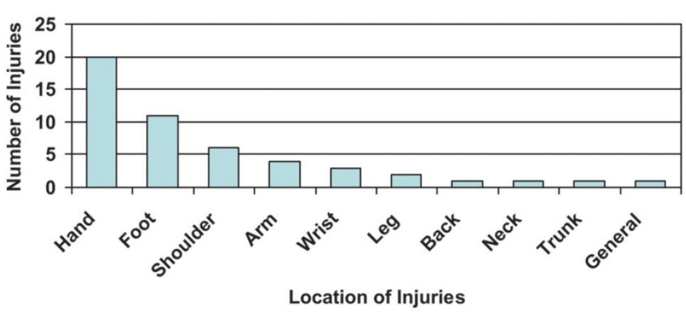


**Fig. 12. Location of in-flight musculoskeletal injuries [up to 2009] in the U.S. space program due to the EVA suit. Courtesy of Richard Scheuring (2009, p. 121).**

*2. Ankle Injuries but No Foot Injuries?*

David, Doarn, Polk and the same Scheuring published an article a decade (2019, p. 257) later in which they report 11 ankle injuries that do not appear in the 2009 column chart and at the same time do not report any foot injuries.

- **Is it possible that all the ankle injuries occurred during that one decade from 2009 to 2019?**
- **And is it equally possible that all the foot injuries occurred before the 2009 article?**
- **On the same page these authors record 94 skin abrasions. Could some of these abrasions have occurred to the astronauts' feet?**

Scheuring et al (2009, p. 118) offer a partial explanation for some intentional omissions from the data set:

[7] However, despite these deficiencies, this reporting is almost the only experimental or empirical data we have.

> Many entries in the pain category were particularly difficult to define. Astronauts often mentioned pain in a particular area of their body without a clear mechanism elucidated. Because a clear mechanism for these conditions could not be ascertained, **they were excluded from reporting in the study**. . . . In addition, in-flight musculoskeletal injuries **were excluded** if they reflected an acute exacerbation of a pre-existing preflight condition. [emphasis added]

Anderson, Diaz (2012, p. 4). et al sum up this situation: "Several studies have quantified and tracked astronaut injury. However, EVA-specific information is limited.

With apologies to Kurt Goedel and his famous incompleteness theorems (Stanford, 2 April 2020), this system of EVA injury data reporting fails as neither complete nor consistent. These omissions strike an ill note comparable to the cardinal sin of tearing pages out of a lab notebook. In light of these systemic contradictions within the EVA injury data, let us make a transition from a quantitative approach to a qualitative one.

**D. Qualitative Approach**

Gernhardt (2009, p. 336) identifies three risks based largely on astronaut experiences and some controlled plus some controlled *and* randomized trials. All turn on the suit design.

- Risks to Crew Performance: EVA Suit Design Parameters
- Risks to Crew Health: EVA Suit Design Parameters
- Risk to Work Efficiency: EVA Suit Design Parameters

On this theme, Scheuring, Mathers, Jones, and Wear (2009, p. 121) state:

> Foot injuries also caused problems for EVA astronauts. One astronaut described an episode of 'excruciating, searing, knife-like pain' during an EVA. The astronaut attributed the pain to excess suit pressure bladder material inside the boot, but despite attempts at correcting the problem, the pain persisted with the development of a blister…Though the EVA was completed successfully, the astronaut described the pain from this injury as 'on the forefront of my mind'. Another astronaut had similar symptoms after his second EVA with resultant numbness and pain on the dorsum of his feet.

Because of these kinds of experiences and outcomes, under Human Health Countermeasures, the NASA Human Research Program (HRP) indicates that the design of EVA systems for *both lunar and planetary* EVA "requires mitigation" of the consequences for both operations and long-term health effects (Norcross, 2019).

**D. Causes of Foot and Ankle Discomfort and Injuries**

Let us delve deeper into the causes and nature of these injuries inflicted to the lower extremities through a combination of the suit layers and the boot features. Allison Anderson gives a brief overview of the scope of EVA boot injuries in her MIT dissertation:

> Although the EMU is designed with limited lower body mobility, astronauts must produce a counter torque by flexing leg and ankle muscles to maintain proper orientation while they work. Poor fitting boots and boot inserts allow the astronaut to rotate backward, causing the foot and toes to impact the top surface and rub (Strauss 2004). Additional discomfort is caused by the pressure bladder wrinkles, which cause blisters, contusions, abrasions and loss of feeling. On one EVA, this almost led to early termination of the EVA (Scheuring, Mathers et al. 2009). In training and during experiments to evaluate planetary locomotion and exploration procedures, the shifting body also causes the tops of the foot and distal toes to impact the boot (Strauss 2004, Norcross, Lee et al. 2009) [Anderson, 2014, p. 31].

Anderson, Diaz, et al (2012, Nov, p. 3) provide a graphical model of where on the astronaut body EVA injuries appear most prominently in Fig. 13. These authors cite the above paragraph as to the particular causes of ankle, foot, and leg injuries during EVA operations with the boots restrained in a foothold. Their graphical model highlights the areas of the body that sustain the most common injuries, including the ankle. Chapell et al describe the causes of foot injuries in 1-g training and simulation exercises (2017, p. 19).

> Injury occurs mainly on the top of the feet and on distal toes, and is associated with issues of boot fit. The foot is not well protected in the EVA suit, and there is no arch support built into the boot sizing inserts. The boot does not protect the feet from hard contact from the 1g effect on the front of the toes that takes place in training. There is also hard contact on the top of the feet while in the portable foot restrains [sic].

Anderson, Diaz et al (Nov. 2012, p. 2) elaborate on the contemporaneous EMU half-measures to mitigate this situation on the ISS. The problem with the sizing inserts installed in the boots as the users change appears to be that they constitute a leading cause of foot discomfort and injury:

> The protective comfort pieces are worn to mitigate some of the negative effects of wearing the ~140 kg spacesuit, . . . The primary component is the liquid cooling ventilation garment (LCVG). It regulates body temperature by circulating water through Tygon tubing so it flows over the body and absorbs heat from the skin. Additionally, the LCVG circulates air in the suit by moving air from the extremities returning it to the portable life support system (PLSS). The LCVG covers the body from the wrists to the ankles and neck . . . The boots are modified to accommodate multiple users with sizing inserts. These inserts partially fill the boot volume, but are not optimized for protection. An optional internal toe cover may be used to protect against impact. Current injury countermeasures accommodate thin strips of padding that can be sewn to the LCVG in areas where astronauts may feel hot spots of discomfort; however, they are not intended for long-term use.

**Fig. 13. Injury areas from conflict with the space suit. Please note the ankle injury area that runs down to the dorsum and instep. Courtesy of Anderson, Diaz, et al.**

Referring to previous suit experiments and simulations, Anderson, Diaz et al (2012, Nov, p. 4) argue:

> These efforts, however, have not focused on how the suit impacts and constrains the wearer and where contact between the person and the suit occurs, which is critical information to reduce EVA injury.
>
> The causes of these injuries may include improper suit fit, shifting or improper use of protective garments, and repetitive motion working against the suit. Current injury prevention is achieved by workaround modifications to the suit environment and individual physical training, **rather than by implementing substantive design changes.** Although this may be acceptable for short-term prevention, the system must be modified to find long-term solutions. A greater understanding of human-suit interaction would help achieve future suit designs to minimize injury caused by the next generation of spacesuits.[emphasis added]

The piecemeal and unsystematic use of "inserts" and "toe covers" — and the fact that they might be needed at all — is a contributing cause of foot injuries.

**E. Space Suit Injury Prevention Parameters**

Anderson, Diaz, et al (Nov. 2012, p. 7) propose a set of broad design and suit fit solutions that may apply equally to the boots as to the suit. They speak broadly in terms of "protection devices," although it is not clear why they think that some of these improvements involve "devices" rather than a holistic approach to suit design. For example, is "comfort" the result of a device or does it flow from the overall suit design, fabrication, and fit. In the sketch on page 8, they show "protection devices" high on the ankles, (but nothing on the feet because they do not show the feet). TABLE 3 displays these parameters cum requirements.

| **TABLE 3. Preliminary Design Requirements for Protection Devices<br>Courtesy of Anderson, Diaz, et al** | |
|---|---|
| **Desired Trait** | **Requirement** |
| 1. Comfort | 1.1 Decreases friction between suit and skin<br>1.2 Minimized hard impact between suit and body<br>1.3 Controls Body Moisture<br>1.4 Less prone to wrinkling |
| 2. Suit Fit | 2.1 Body restricted from shifting inside suit<br>2.2 Suit moves more naturally with the body |
| 3. Customization | 3.1 Size of protection system is adjustable or personalized<br>3.2 Shape of protection system is adjustable or personalized<br>3.3 Location of protection system is adjustable or personalized |
| 4. Maintain Functionality | 4.1 Maximum range of motion is maintained<br>4.2 Joint torques are not increased<br>4.3 Finger tactility is maintained |

The designs of space suit boots to date seem to regard the foot and ankle as static — almost passive — parts of the musculoskeletal system. ON THE CONTRARY, the foot and ankle make up one of the most active and dynamic parts of the body when walking.

**F. NASA EVA Injury Prevention Planning**

NASA has begun to take notice of the problems of EVA injuries. The 2020 EVA Roadmap — the most recent EVA Roadmap — begins to address ankle injuries, seemingly for the first time. However, although there are dozens of mentions of injuries in general, and discussion of shoulder and back injuries, there is no mention of foot injuries. Here is the statement on hip and ankle injuries (but no statement on knees).

> 3.7.6.7 Hip/Ankle Injuries during Functional Tasks
> A targeted effort to quantify hip and ankle injury mechanisms will be conducted for exploration tasks. Hip and ankle mobility is needed to maintain balance and is critical for ambulation. Additionally, proper boot fit is important for injury mitigation. Thus, the boot and hip suit designs concepts will be evaluated through HITL testing for EVA-like activities across different body shapes and anthropometry.

Boppana and Anderson (2020, p. 9) propose a solution for the creasing, folding, wrinkling pressure bladder. They advocate a system of "rolling convolutes" above and below the bridge of the foot to keep the bladder in place. They seem to assume that the phalangeal-tarsal joints bend as much as 90° in flexion. They also propose shoe laces to tighten the boot to keep the bladder in place. It is an interesting concept, but elides the fundamental contradiction of having the pressure bladder in the first place. Overtightening the laces would also tend to restrict foot flexion and extension.

## VII. Biomechanics of the Foot and Ankle

Any good footwear must work in concert with the anatomy of the foot and ankle, not against it. The skeletal-muscular system is exposed to four fundamental forces that impose loads and stresses on them. These forces are: Compression, Tension, Torsion, and Shear. All four of these forces can affect the foot and ankle, although shear is a comparatively infrequent or minor stressor. The footwear must support the foot and ankle and help protect them against these forces during all phases of walking and working.

### A. Walking: Flexion and Extension

The *OrthoPaedia* defines two phases and five stages of walking as shown in FIGURE 3. Notice how the foot and ankle move through these phases and stages. Walking involves the full flexion and extension motion of the foot and ankle. The downward motion of the ankle to "Toe Off" propels the body forward. The Apollo suit legs and boots inhibited this full foot extension and flexion, leading at least partially to the hopping method of locomotion.

The two main motions of the foot and ankle ensemble are flexion and extension. Flexion or flexing means bending the foot upward. Extension means straightening the foot as in pointing the toe. A key factor in the footwear allowing extension and flexion derives from how soft or stiff are the sole and upper of the boot or shoe. The arch or instep of the foot and the tops of the foot bones, particularly the tarsals and metatarsals play a critical role in the ability to extend of flex the foot.

Fig. 14 presents the five phases of walking. It illustrates how the foot and ankle move dynamically during walking. Enclosing the foot in a rigid boot assembly interferes with this natural cycle of movement, forcing the astronaut into unnatural and potentially inefficient patterns of locomotion.[8]

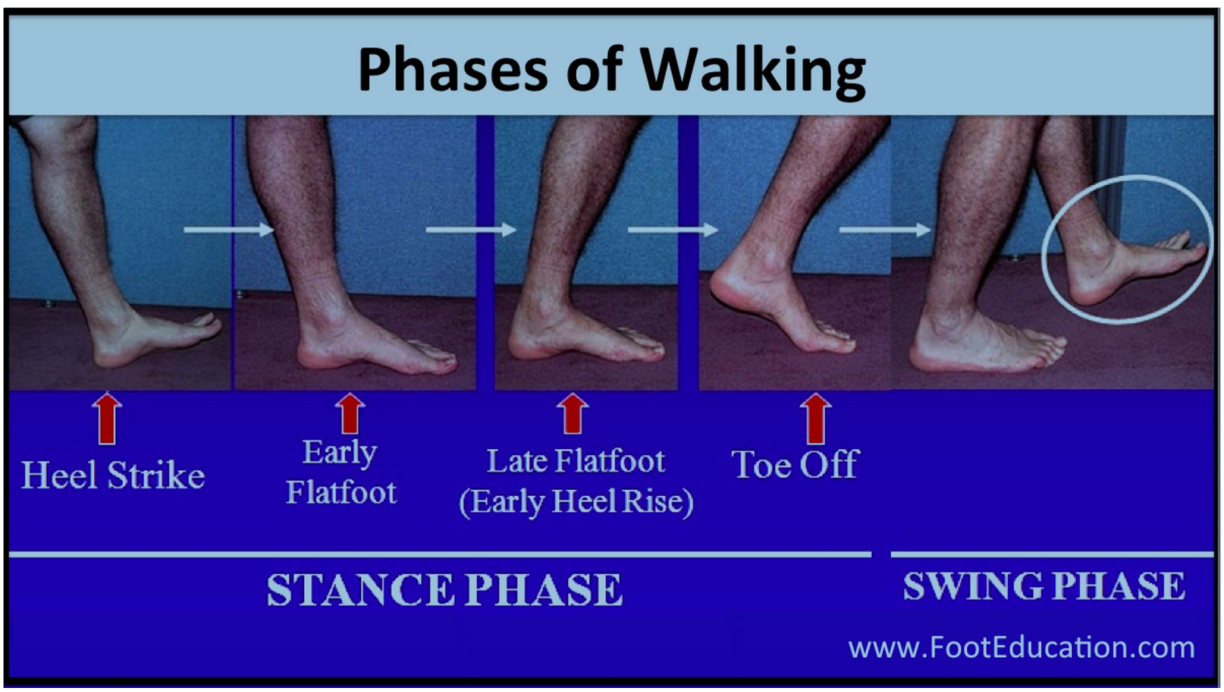


**FIG. 14. The two phases and five stages of walking. Courtesy of Foot Education.com**

It is useful to review the cycle of flexion and extension during normal walking movement:

- Flexion during "Heel Strike,"
- Extension during "Early Flatfoot,"
- Flexion during "Late Flatfoot,"

[8] It is essential to note the difference between 1-g on Earth and 1/6-g on the Moon. The loading, forces, and relative use of muscles may change but the biomechanics of the foot and ankle do not change.

- Extension during "Toe Off," and then
- Flexion during the "Swing Phase," leading to "Heel Strike" again.

**B. Structure of the Foot and Ankle**

In addition, one of the key skeletal configurations about which the foot and ankle both flex and extend is the axis that runs roughly on a lateral vector through the Lateral Malleolus of the Fibula and the Medial Malleolus of the Tibia. The Lateral and Medial Malleoli appear in Fig. 15a. The cartilage appears as blue. The long sheath of soft tissue cartilage below the Malleoli, the Talus, suggests why the ankle is so vulnerable to sprains and strains. Fig. 15b shows the Malleoli axis between the "ankle bones" that comprises the center pivot of ankle extension and flexion.

There is an important difference between the feet and other parts of the body with respect to space suits. In the upper body and the legs, it is advantageous for the suit bearings or convolutes to conform closely to the joints, notable the shoulder, elbow, hip, and knee. However, the foot and ankle may be too small to benefit much from such mobile joints. Instead, the foot especially may benefit from more room in the boot, such as a larger toe box. The foot and ankle may also benefit instead from the ability for the boot to flex in tune with foot extension and flexion.

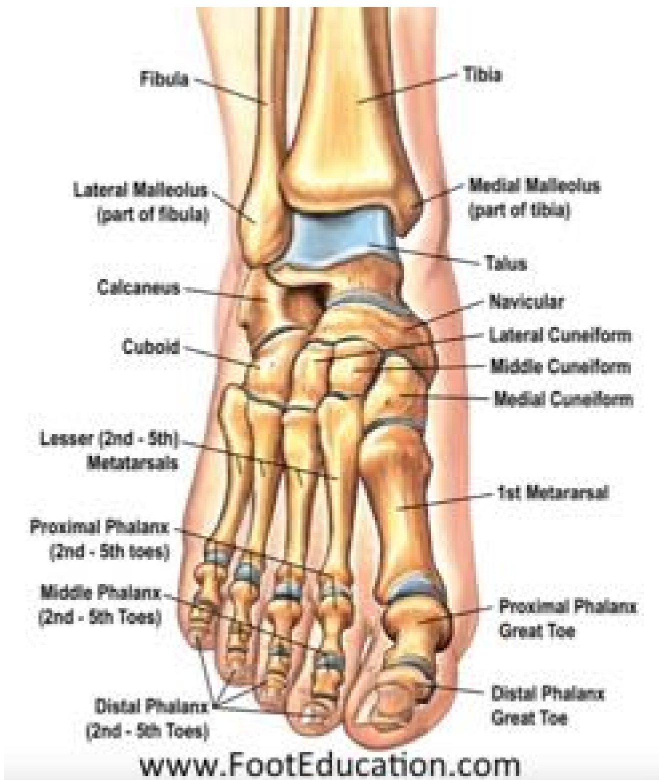


**Fig. 15a. Bones and Cartilage of the Foot and Ankle. Courtesy of Foot Education.com, via OrthoPaedia.**

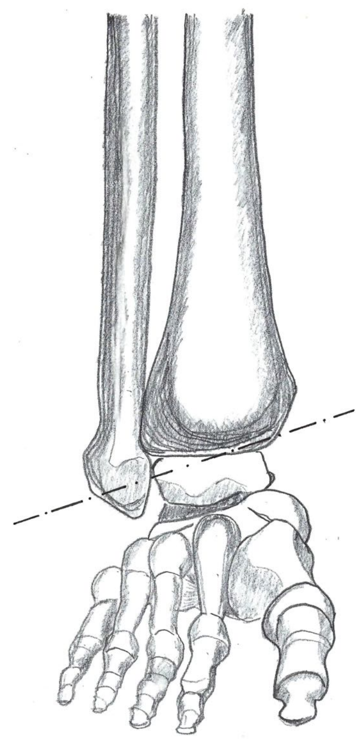

**Fig. 15b . Frontal sketch of the ankle showing the Malleoli ankle axis. By Marc Cohen, after Brockett and Chapman (2016).**

## VIII. Space Suit Boot Design Logic Trees

At the outset of this design research, it becomes essential to identify the key design assumptions and the consequences of high-level design decisions. The following three logic diagrams present a theoretical overview of this design problem space and potential outcomes for each decision path. In these schematics, the green shapes with blue text indicate the logic steps and decision points. The red outcome boxes with thin dashed lines indicate a potentially unsuccessful outcome. The green outcome boxes with green letters and heavy lines indicate a potentially successful outcome.

These three logic trees show responses to differing environmental conditions. The Pressure Regime refers to the ways in which the suit and boots protect the astronauts from the vacuum of space. The Hot Region refers to the conditions in the lunar equatorial region during the lunar day, particularly during lunar noon when the sun is at its most direct.[9] There, the major added threat to the foot is heating by conduction through the boot structure from the 140 C regolith. The Cold Region, specifically the permanently shadowed regions (PSR) near the South Pole have surface temperatures of about -200 C. Here again, the major added threat to the foot is heat transfer — heat loss — by conduction. In either of the conductive heat transfer extremes, the issue is to protect the foot by providing suitable materials and thermal conditioning to counteract the conductive effects.

### A. Space Suit Boot Pressure Regime Foot Protection

The central question concerning the pressure regime asks does the suit require a bladder as in the past Shuttle EMUs (also used on the ISS)? If it does require a bladder, should the inner boot go inside the bladder or should the bladder go inside the inner boot? The purpose of the inner boot is to protect the foot and ankle from the outer boot and the other things inside it that can cause rubbing, pinching, squeezing, crushing, abrading, and other symptoms that have been documented as harming astronauts' feet. Fig. 16 shows the Pressure Regime Design Logic Tree.

In conventional space suits, the bladder holds the pressure while the outer structure — of fabric, bands, convolutes and other devices — acts as the restraint layer to prevent the bladder from just inflating like a balloon. If the soft and flexible inner boot on the astronaut's foot goes inside the bladder, then perhaps it can do its job of fully protecting the foot. However, if the pressure bladder must go in the boot, it raises the specter of chronic foot and ankle injury from the same cause as astronauts have previously reported.

If no pressure bladder is required, then the suit outer primary structure must act as more than a restraint layer; it must hold the atmospheric pressure like the AX series of space suits from Ames Research Center. Not having a pressure bladder obviates the conflict with the feet and with the inner boot itself.

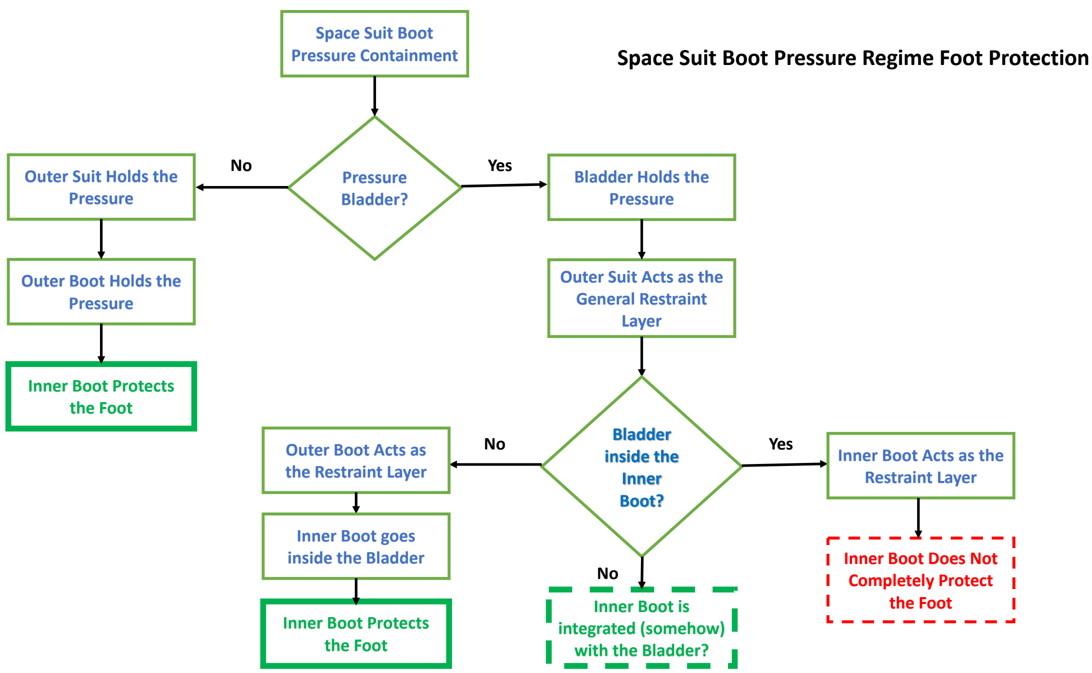


**Fig. 16. Boot Design Logic Tree 1: Pressure Regime.**

### B. Space Suit Boot HOT Region Thermal Protection

This design logic tree addresses the alternative approaches to cool the foot and ankle in a space suit boot. The first question is should boot cooling be passive or active? Passive "cooling" would rely on insulation and a liquid cooling garment (LCG) or liquid cooling and ventilation garment (LCVG) that reaches the ankle. Active foot cooling means running the LCG or LCVG into the boot. The second question asks where in the boot assembly should the LCG or LCVG run? Fig. 17 shows the Hot Region Design Logic Tree.

The Apollo missions landed in the equatorial and temperate regions of the moon at lunar dawn when it was coolest. The longest mission, Apollo 17 lasted 75 hours on the lunar surface. If any of the landings in the equatorial

---

[9] The Artemis Program currently has no plans for exploration in the equatorial or temperate regions.

zone had stayed on the Moon two weeks, they would have been subjected to the maximum surface temperatures of 140 C. (284° F). Neither the Apollo suits nor the Shuttle EMUs could endure that heat well above the boiling point of water. At present, the Artemis Program has no plans to send a mission to the equatorial region at Lunar noon. However, for the sake of thoroughness, we include it to provide a complete set of design logic trees.

Since the Apollo era, the NASA space suits have relied on the liquid cooling garment (LCG) to carry away the excess metabolic heat that astronauts generate from their bodies. In the lower extremities, the EMU LCG extends down the leg to just above the medial and lateral malleoli axis, the "ankle bones." There is no direct cooling of the foot. In the logic tree, a passive boot does not provide the option of "going anywhere any time," thermally speaking.

If the space suit boot incorporates cooling of the foot and ankle, the question becomes in which boot? The options are to:

1) Run the LCG/LCVG next to the skin inside the bladder and inside the inner boot,
2) Run the LCG/LCVG into the structure of the inner boot assembly, or
3) Run the LCG/LCVG between the inner boot and the outer boot.

Inside the boot assembly, the further from the skin of the foot and ankle, the less effective the cooling system is likely to be for metabolic heat. However, placing the LCG/LCVG closer to the pressure-holding outer boot, the more successful it may be at mitigating environmental heat gain.

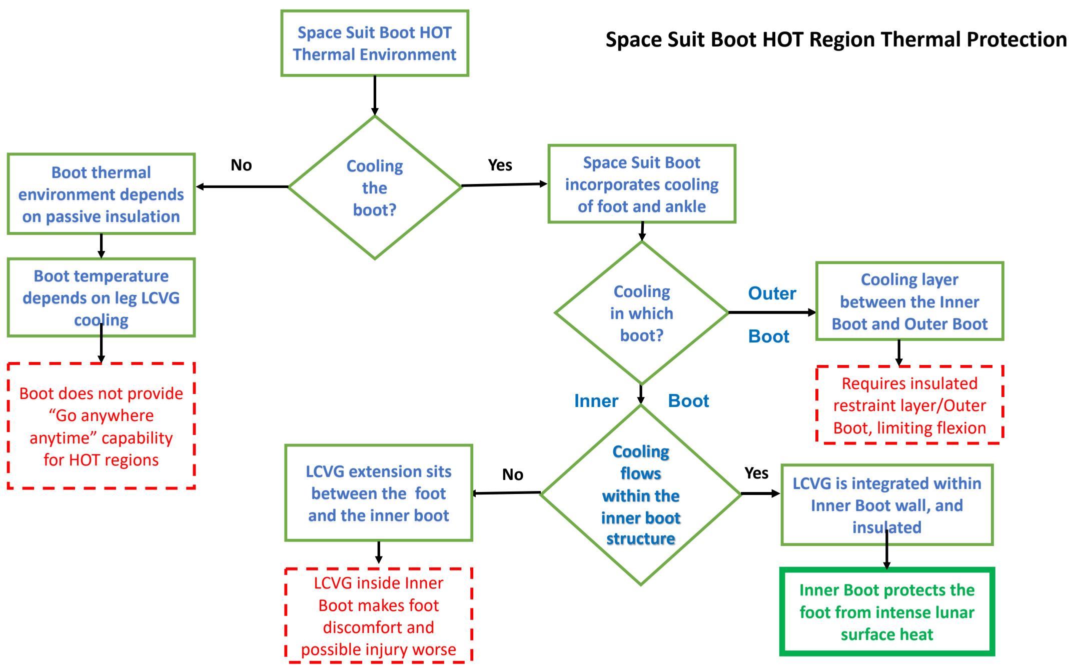


**Fig. 17. Boot Design Logic Tree 2: HOT surface environment.**

### C. Space Suit Boot COLD Region Thermal Protection

Space suits to date have not incorporated a dedicated heating system because the dominant problem has always been to reject excess metabolic heat via the LCG/LCVG. To incorporate a heating system for the lunar permanently shadowed regions where the temperature drops below -200 C, is a challenge on a greater order of magnitude than disposing of metabolic heat gain. It is unlikely that a liquid *heating* garment (LHG?) or derivative system could do the job of keeping the astronaut from freezing or suffering cold injuries such as frostbite and gangrene. This challenge would be especially severe in the feet where there would be conductive heat loss in addition radiative heat loss. The most likely solution would involve electric resistance heating. Fig. 18 shows the Cold Region Design Logic Tree.

So, the next question asks where to install this heating layer or system to keep the foot and ankle warm? Again, the choice falls among the options surrounding the inner boot:

1) Run the heating layer inside the inner boot — either inside the bladder or outside the bladder, if any —(where it could create a burn hazard),

2) Run the heating layer within the structure of the inner boot, or

3) Run the heating layer between the inner boot and the outer boot, which might require the outer layer to be extra insulated.

Each of these options presents profound implications for design of the boot assembly.

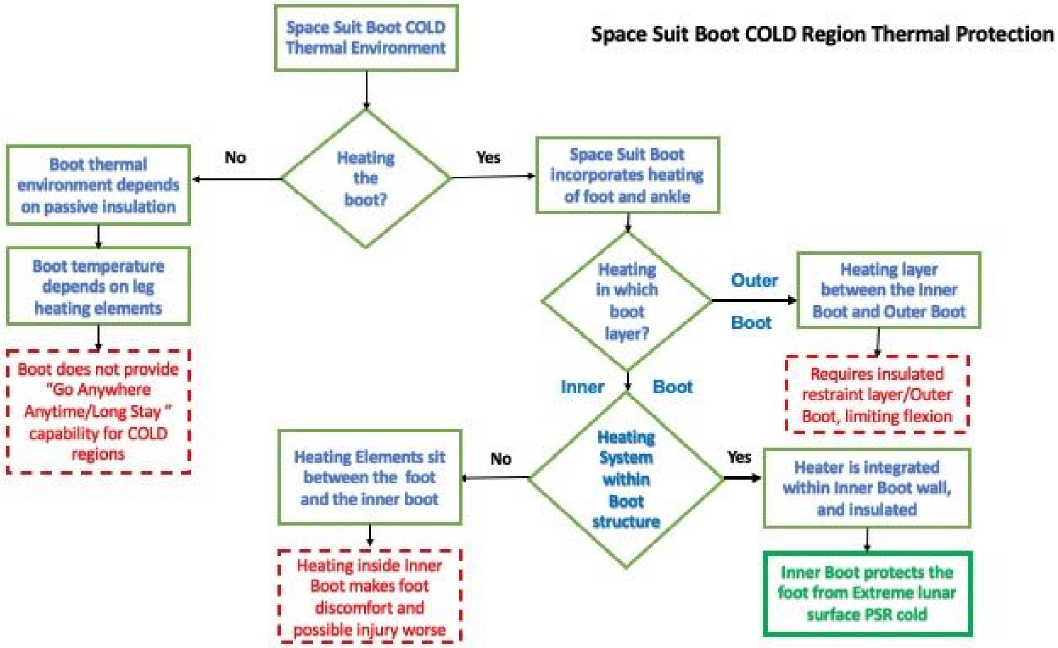


**Fig. 18. Boot Design Logic Tree 3: COLD surface environment.**

## IX. Footwear Surveys for Space Suit Boot Ensemble

This survey looked at a wide range of available shoes and boots that might have suitable design characteristics, features, qualities, or technologies that could be applied to a space suit boot. The approach was to look at the product line of major manufacturers of athletic shoes, hiking shoes and boots, sport shoes, and work shoes and boots. The distinction between shoes and boots is quite fuzzy. Some manufacturers call a four or six-inch-high shoe a boot, whereas the makers of boxing and wrestling shoes make them as high as 18 inches but still call them shoes. So, these terms become somewhat interchangeable.

During the course of this research a question emerged about whether we can find a single 3D printable material that is flexible enough to respond to foot and ankle biomechanics and meet the full temperature range 140 C down to about -200 C. That question is still under investigation, but it raises the possibility that we cannot build a flexible spacesuit boot given current additive manufacturing capabilities and materials. If this limitation turns out to be the case, then we need to consider designing and building a rigid boot that meets all of the other requirements and success criteria. This realization led us to creating two categories under which to study the outer boot: flexible and rigid

That finding led us to four boot categories: the inner boot, the outer boot-flexible, the outer boot-rigid, or the overboot. In principle, the product as it exists "off the shelf" might qualify in total as fulfilling one of these categories. However, the only instance in which that occurred was for the inner boot. Stapleton, Eddy, and Hamill (2021, p. 7) are quite enamored of the use of a boxing shoe made by Title as a nearly perfect answer for the inner boot. So, in this survey, we included a review of several manufacturers of boxing shoes. We concur that a boxing shoe archetype may constitute the best "commercial off the shelf" solution for the inner boot. However, we imagine that there are many other boxing shoes "on the shelf" and selecting the best one or this application will require further analysis.

The sifting begins by process of elimination. Shoes (or boots) with features dangerous or inimical to one of the boot categories were discarded immediately (e.g., baseball or football shoes with cleats, golf shoes with spikes or hiking shoes with big lugs, for the inner boot etc.). Many companies fail to make wide shoes so any model without a wide option was out, and so on. What emerged was that with the possible exception of the boxing shoes for the inner boot, no shoe model could suit another boot category directly off the shelf.

Therefore, the second level of sorting involved examining all the innovative or advanced features of shoes and boots. In examining a product line, it was typical to find only a handful or perhaps even one model that offered a provocative or useful feature. Thus, the shoes and boots that appear as the results of this survey are there only for one or two aspects of their design, engineering, manufacture, or materials.

### A. Footwear Survey for Inner Boots

It is neither the intent nor the purpose of this task to design or develop a *de novo* or *sui generis* concept for a spacesuit boot. Rather, this approach focuses on surveying and identifying which precedents from the vast range of manufacturers and types of boots may appear most suitable for the interior and exterior spacesuit boots. Ideally, we would find a commercial off-the-shelf boot that can serve unmodified as an inner boot. Also, we would find advances, features, geometries, innovations, and new technologies that can inform and enhance the spacesuit boot.

Boxing shoes are a candidate for the internal boot. They are built for support and flexibility. They do not have lug soles.

*1. Adidas:*

https://www.adidas.com/us

Historically a purveyor of classic running and sports shoes, Adidas has branched out to make bespoke mountain biking shoes. The Adidas Five Ten Trailcross Gore-Tex® Mountain Bike Shoes offer several innovations:

- Modified Dotted Outsole—Fig. 19 shows this sole with Flat pedal performance of the Five Ten dotted outsole, modified at the toe and heel for traction off the bike. [This sole resembles Pirelli-dot flooring to the extent that the dots are not lugs, but provide a smooth yet non-slip surface to the pedals.]
- Neoprene Hook And Loop Ankle Cuff—A hook and loop neoprene ankle cuff provides a secure fit and stops debris from entering the shoe.
- Thinner Mid-Sole EVA—Slimmed down midsole EVA technology for all day comfort without losing the all-important Five Ten grip.

https://www.adidas.com/us/five-ten-impact-pro-mid-mountain-bike-shoes/FU7540.html?pr=product_rr&slot=3&rec=mt

Adidas also makes boxing shoes. The Adidas Box Hog in Fig. 20 appears to be taller than the Title boxing shoe. That added height may serve as an advantage to protect from rubbing against the outer boot top seal. The mesh upper could be breathable or be made breathable.

https://www.adidas.com/us/box-hog-4-shoes/GZ6118.html

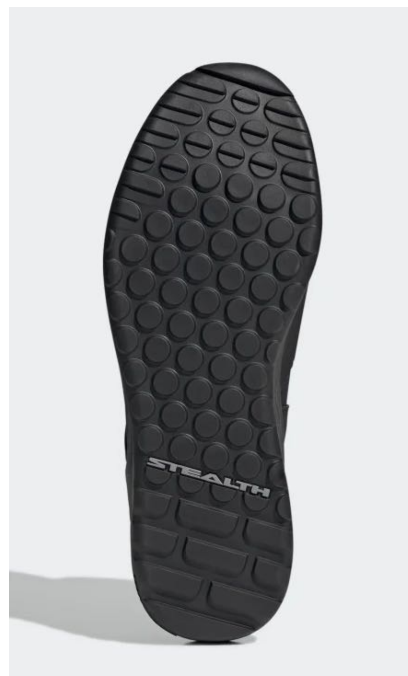


**Fig. 19. Adidas Mountain Bike *Stealth* "dotted sole."**

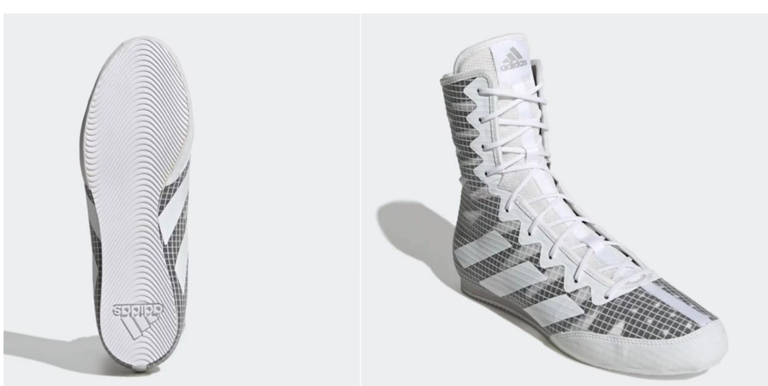

**Fig 20. Adidas Box Hog 4 boxing shoe. Please note the finely ribbed tread on the sole, and the mesh upper.**

| TABLE 2. Overview of Boot Survey for the INNER Boot | | |
|---|---|---|
| **Manufacturer** | **Model** | **Features** |
| Adidas | Five Ten Trailcross Mountain Bike Shoe | • Modified Dotted Outsole,<br>• Thinner Mid-Sole EVA |
| Adidas | Box Hog Boxing Shoe | • Thin ribbed sole,<br>• Breathable mesh upper |
| G.H. Bass/Bass Outdoor | Remi Bootie | • Front and back zippers |
| Irish Setter | Vaprtrek | • UltraDry™ construction<br>• CuShin™ comfort tongue<br>• ENERG high-rebound material<br>• RPM™ lightweight composite |
| Lowa | Explorer II GTX Mid | • Softer, Lighter, more Flexible design |
| Merrell | Fullbench Tactical | • Bellows Tongue |
| New Balance | 589 ESD | • Wide flanged composite toe cap (large toe box),<br>• REVlite midsole lightweight cushioning |
| Nike | Air Jordan, Air Force | • Air Sole,<br>• Complete shoe construction |
| Nike | Hyper KO boxing shoe | • Fine-ribbed tread |
| Redwing | King Toe ADC | • King Toe® toe box,<br>• SWEN-FLEX® non-metallic, Puncture-resistant insoles |
| Title Boxing | S2 GEL Superior Boxing Shoe, Speedflex Encore Tall Boxing Shoe | • GEL impact absorbing padding<br>• Very finely ribbed sole |

2. *G.H. Bass/Bass Outdoor:*
https://www.ghbass.com/bassoutdoor/

The women's Remi Bootie offers a practical idea that might be an asset to the internal boot. The Remi Bootie sports both a lace-up front and a zipper in the back from the top to the heel. That could be useful for quick don/doff of the inner boot, provided it does not degrade flexibility, foot protection, or support.
https://www.ghbass.com/bassoutdoor/bass-remi

3. *Irish Setter:*
https://www.irishsetterboots.com/

The Irish Setter Vaprtrek is a traditional-looking 8" high hunting boot with a camouflage finish, but it promotes some innovative features that could enhance the inner boot:

UltraDry™ construction combines a moisture management lining with waterproof components for dry, long-lasting comfort and performance.

CuShin™ comfort tongue technology was designed to minimize pressure some feel on their shin from the top of the boot tongue. A four-way stretch nylon offers relief and flexibility while walking, and an internal padded waffle mesh maintains premium comfort.

ENERG Strategically placed this high-rebound material brings high-end athletic shoe technology to more practical applications, delivering a recharging burst of energy with every step.

RPM™ is a breakthrough composite material that significantly reduces the weight of the boot, providing extreme comfort and added endurance. Engineered to provide the durability and strength of traditional materials without the extra weight.

ScentBan™ is an Irish Setter exclusive scent control process, ScentBan™ is added to various materials from leathers to linings to footbeds, killing bacteria that cause odors. It raises the question of chemical toxicity in a closed atmosphere as well as prolonged proximity to the human skin.

https://www.irishsetterboots.com/hunting-boots/Vaprtrek-02815.html?cgid=hunt

*4. Lowa*

https://www.lowaboots.com/

The Lowa Explorer II GTX Mid is one of the few boots from any of the manufacturers to promote softer, lighter, and more flexible shoe design. A potential candidate for the inner boot except for its "grippy" outsole.

https://www.lowaboots.com/mens/backpacking/lowa%C2%AE-explorer-ii-gtx-mid-anthracite-lime.

*5. Merrell:*

https://www.merrell.com/US/en/home

The Merrell Men's "Fullbench Tactical" boot sports a "bellows tongue" to keep out debris, which is an interesting concept. However, it comes only in medium width. The exhaustive use of Vibram soles means that nearly all the Merrell boots have 5mm lugs on them, which is disqualifying.

https://www.merrell.com/US/en/fullbench-tactical/48769M.html?dwvar_48769M_color=J099437#cgid=boots&prefn1=genericSizeType&prefv1=M&prefn2=size&prefv2=11&start=1

*6. New Balance (NB):*

https://www.newbalance.com/

New Balance is one of the few athletic shoe companies that retained substantial manufacturing in the USA. That means they had to justify their higher productions costs with better shoes.[10] That said, the interesting item from NB is one of their work shoes the 589 ESD. Presented in Figs. 21a and 21b, this work shoe is one of the lightest weight available. It promotes these features and properties:

**Fig. 21a. New Balance 589 ESD Work Shoe. Note the generous height of the toe box.**

- Wide flanged composite toe cap provides added
- protection for people who work in hazardous work environments. Meets ASTM F2412-18 & ASTM F2413-18 I/75 and C/75 impact and compression safety standards.
- Slip-resistant outsole tested according to ASTM F2913-18 to provide superior traction under various surface conditions.
- REVlite midsole delivers incredibly lightweight cushioning
- Large Toe Box

**FIG 21b. New Balance 589 ESD Work Shoe. Note the non-protrusive tread pattern.**

*7. Nike:*

https://www.nike.com/

Nike makes truly iconic high-top basketball sneakers. The Nike Air Force and Air Jordans meet some of the basic criteria of good support and no lugs. The Air Sole offers a high degree of impact absorption to the bottom of the foot and some thermal insulation. The Air Jordan 1 Stealth shown in Figs. 22a and 22b comprise the epitome of a high-top with a lot of padding. A simple thought is that the Air Jordan with a custom 23 cm high upper might make a complete solution for the inner boot.

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[10] First Author's physical therapist recommended the NB 990 series athletic shoe as the best all-around cross trainer on the market.

https://www.nike.com/launch/t/air-jordan-1-stealth.

**Fig. 22a. Nike Air Jordan 1 Stealth basketball high top left elevation.**

**Fig. 22b. Nike Air Jordan Stealth Sole with low relief traction designed to pivot on the ball of the foot.**

Nike also offers a boxing shoe. The HyperKO Limited Edition shown in Fig. 23 seems to be their top of the line. In incorporates a kind of reinforcing strap across the front and a fine-grained ribbed tread. It does not appear to be as high as either the Adidas or Title boxing boot.

https://www.athleteps.com/nike-hyperko-limited-edition-multiple-colors/?sku=634923-410-125&msclkid=1b28169e112211628a65759cfd263390


**Fig. 23. Nike HyperKO boxing shoe. Please note the fine ribbed tread on the wrap-around corner of the outsole. Please note also the tight toe box, which may pose problems if the pressure bladder must also go inside.**

*8. Redwing Shoes:*
https://www.redwingshoes.com/

The Redwing King Toe ADC 8” work boot looks like a traditional boot but it incorporates many innovative safety and comfort features that may not be found together elsewhere. These promoted advanced features that may be relevant to a spacesuit inner boot include:

- Has the King Toe® toe box that is 44% larger than other work boots, so more comfort and “wiggle room,”
- SWEN-FLEX® non-metallic, puncture-resistant insoles are manufactured from high-strength, woven fibers [may be relevant to the Overboot].

https://www.redwingshoes.com/work/mens/waterproof/King-Toe-ADC-03552.html

*9. Title Boxing:*
https://www.titleboxing.com/

The Title "Fighting S2 GEL Superior Boxing Shoes" offer some promise with respect to technology, shown in FIGURES 19a and19b. They are designed to transfer the loads of punching through the body down through the legs to the floor. The GEL refers to padding in strategic places in the boot. This GEL features in a "shock suppression" feature. These shoes come in 21.6 cm (8.5 inch) height, close to the 23 cm height of the external boot. The boot shown in the image in Figs 24a and 24b show the Speedflex Encore Tall Boxing Shoe. It does not appear externally as functionally different than the Fighting S2 GEL Superior which can cost twice as much. The Speedflex Encore offers the possible advantage of undoubtedly being higher than the 23 cm outer boot height of the outer boot. A taller inner boot could offer an advantage for protecting against chafing from the seal between the outer boot and the lower leg section.

**Fig 24a. Title Speedflex Encore Tall Boxing Shoe, side view.**

**Fig. 24b. Title Speedflex Encore Tall Boxing Shoe, view of sole. Please note the nubbly texture.**
https://www.titleboxing.com/boxing-shoes/fighting-s2-gel-superior-boxing-shoes

## B. Overview of Boot Survey for the Rigid Outer Boot

This selection of boots is shown here essentially for their conventional and traditional characteristics of protecting the foot in outdoor and work environments. Adapting these boots as templates for a rigid spacesuit boot would exploit the character of their envelope but disregard their capabilities for direct foot and ankle support.

**TABLE 3. Overview of Boot Survey for the RIGID OUTER Boot**

| Manufacturer | Model | Features |
|---|---|---|
| Irish Setter | Pinnacle | Primaloft® Fiber fill Insulation. TEMPSENS, temperature- and sweat-sensing technology. |
| Keen | Philadelphia Insulated Waterproof Work Boot. | Single piece molded upper, Large toe box |
| Red Wing | King Toe ADC Work Boot (Large toe box) | 400g 3M™ Thinsulate™ Ultra, thermal insulation |

*1. Irish Setter:*
https://www.irishsetterboots.com/

The Irish Setter Pinnacle is an outdoors and hunting boot that shares many of the Vaprtrek features discussed for the inner boot. With the Pinnacle, we can consider three features that may prove relevant for a rigid outer boot, shown in Fig. 25. These features include:

**Fig. 25. Irish Setter Pinnacle hunting**

- **ArmatecXT™** Many times more abrasion-resistant than the predecessor ArmaTec™, this specially formulated new compound delivers an extremely durable layer of extra protection. Placement of ArmaTecXT™ in high wear areas helps preserve and lengthen the life of the boots.
- **Primaloft®** is a fiber-fill insulation designed for repeated compression and durability over time. Featuring 90% post-consumer recycled fibers made from plastic bottles, this unique low-bulk construction maintains loft and traps body heat even when compressed. Coupled with a permanent water-repellent treatment with high-density construction, this insulation keeps feet warm in dry or wet conditions.
- **TEMPSENS** This technology reacts to your body temperature and sweat level to keep you dry and comfortable. When you're hot, this innovative Swiss technology cools you down by vaporizing moisture and removing body heat. And if you're chilly it retains your body heat to keep you from getting too cold. It's like your personal thermometer.

https://www.irishsetterboots.com/hunting-boots/Pinnacle-02704.html?cgid=hunt

**Fig. 26. Keen Philadelphia insulated work boot.**

*2. Keen:*
https://www.keenfootwear.com/

Keen Philadelphia Insulated Waterproof Work Boot shown in Fig. 26. This boot shows a pragmatic approach to design. The upper is molded from a single piece of leather, which meets the sole at a thick welt. The welt would not have a place in a spacesuit outer boot, but it gives an indication of where the outer boot structural shell would curve under in its transition from upper to instep. It sports a big toe box that seems almost to turn upward at the front, which would probably allow ample room for the inner boot to be inserted if the Outer Boot was larger.

At the eight-inch nominal height, the Philadelphia is just ~2.5 cm lower than the required outer boot height of 23 cm. That spacing leaves ample distance for the leg to boot sealing ring along with a possible sizing ring. The top of the actual 3D-printed outer boot would be cut straight across and level, parallel to the sole of the shoe.

*3. Red Wing Shoes*
https://www.redwingshoes.com/

The Red Wing King Toe 8” ADC Work Boot may provide a template for a complete outer boot — a semi-rigid boot — at least in the toe box, the mid-shoe, the instep, and the heel as shown in Fig. 27. Such a semi-rigid boot might become “climactically necessary” where the local environment is either too cold or too hot for the flexible materials that are necessary for a bio-mechanically responsive boot.

**Fig. 27. Red Wing King Toe 8” ADC Work Boot**

For the rigid boot, the upper would obviously need a change from lace-up to a solid pressure vessel. This EVA boot would be less responsive to foot and ankle biomechanics, but it might create an accommodating enough outer boot that it would be possible to provide custom cushioning that prevents the inner boot from slipping.

*6. Red Wing:*

- 400g 3M™ Thinsulate™ Ultra, thermal insulation
- Meets ASTM Safety Standards for protection against puncture,
- Meets ASTM Safety Standards for protection against electrical hazards,
- Meets Canadian CSA safety standards,

https://www.redwingshoes.com/work/mens/waterproof/King-Toe-ADC-03552.html

**C. Footwear Survey for Outer Boots – Flexible**

The survey turned up a few very creative ideas for a flexible outer boot. The viabilities of these technologies and design features for the outer boot depends largely on the suitability of the additive manufacturing material to meet the extremes of the temperature range.

| TABLE 4. Overview of Boot Survey for the FLEXIBLE OUTER Boot | | |
|---|---|---|
| **Manufacturer** | **Model** | **Features** |
| Keen | Portland Flex | • Flex Bellows over the upper and sides |
| Salomon | Combi Prolink unisex cross-country skiing Nordic boot. | • Rotational joint that aligns with the medial and lateral malleoli axis across the ankle |

*1. Keen:*
https://www.keenfootwear.com/

Keen makes a very big deal about "flex" boots and shoes, including a rubber bellows on the uppers of some models. Keen presents 63 models with the flex bellows on the uppers and a few where the rubber bellows wraps around the sidewalls of the boots. 63 may seem like a lot, but they appear to consider the medium and wide lasts as separate models.

In the field of shoe and boot technology, Keen Footwear has developed, engineered and produced several hiking and work boots with a rubber bellows or "flex" piece integrated into the upper. On some of the shoes and boots, the bellows stretches across the top of the arch, allowing flexion and extension along the (aeronautical) X axis. On at least two of the boot models, the bellows extends down and across the sides of the boot, affording greater mobility than in the top or the arch-only bellows. Since the structure of the rest of the boot upper will be rigid, it might be necessary to employ a wrap-around flex bellows on the top and the sides of the 3D printed space suit boot. The Keen Portland Flex boot with wrap-around flex bellows appears in Figs. 28a and 28b.

https://www.keenfootwear.com/search/?q=flex&start=0&sz=36 - tile-18 retrieved 2019.

A patent search for all patents and patent applications assigned to Keen, Inc did not turn up any patents or patent applications that disclose the flex bellows. It is possible that Keen is licensing the flex bellows from a third party, but it has been difficult to find given the abundance of industrial shoes, boots, and mechanical bellows patents (1400+).[11]

The Keen flex bellows boots comprise a remarkable breakthrough for the design of any boot and also possibly for the space suit outer boot. The next step is to make inquiries with the design and engineering departments at Keen to learn more about this innovation.

[11] The one patent assigned to Keen that comes somewhat close to the bellows upper is "Toe portion of a shoe upper," US Design Patent D533,712S, insofar as it shows a section of different material incorporated into the upper. But this application appears to be purely ornamental reasons.

**Fig. 28a. Side view of the Keen Portland Flex men's waterproof boot. The yellow section is the flex bellows.**

**Fig. 28b. Oblique view of Keen Portland Flex men's waterproof boot, showing flexion.**

*2. Salomon:*
https://www.salomon.com/en-us

**Fig. 29. Salomon Combi Prolink unisex cross-country skiing/skating Nordic boot.**

Salomon may produce the widest range of outdoor footwear for running, hiking, and skiing of any company. Of particular interest is Salomon's "Combi Prolink unisex skating Nordic boot." for cross-country skiing in Fig. 29. This model features a rotational joint that aligns with the medial and lateral malleoli axis across the ankle. Cross-country skiing demands pronounced extension and flexion of the foot, and this axial "pin-joint" serves to enhance those movements, and protect the ankle joint from injury.

Ankle injuries are a common problem in cross-country skiing. Renstrom and Johnson (1989) surveyed cross-country skiing injuries in Sweden:

> *The most common overuse injuries included medial-tibial stress syndrome, Achilles tendon problems, and lower back pain. Most common among traumatic injuries were* ***ankle ligament sprains and fractures,*** *muscle ruptures, and knee ligament sprains* [Emphasis added].

What is so fascinating about this Salomon shoe is the way it is designed protect against these specific ankle injuries. We would not expect much overuse of the tibial-medial joint or the traumatic injuries to the ankle area from over-flexion or over-extension. However, this external mechanism—or something like it— may provide a way to allow greater flexibility in a flexing outer boot while strengthening the overall configuration.

https://www.salomon.com/en-us/shop/product/pro-combi-prolink.html#color=39130

### G. Footwear Survey for the Overboot

Like the survey for the outer boot, the survey did not reveal many products and features that apply in any obvious way to the overboots. However, the few that did turn up may offer profound implications for how to build a better space suit boot. These innovations include a heat protective sole and an integrated gaiter.

| TABLE 5. Overview of Boot Survey for the OVERBOOT | | |
|---|---|---|
| **Manufacturer** | **Model** | **Features** |
| Asolo | Eiger XT GV EVO | • Full height gaiter cover with zipper front may offer dust protection. |
| Brooks Running Shoes | Caldera 6 | • "Sticky Sole" with widely spaced lugs that do not pick up mud or dirt, so they can "stick to the trail." |
| Irish Setter | Pinnacle | • ArmatecXT™ compound is many times more abrasion-resistant than typical shoe leather. |
| L. L. Bean | Mountain Classic | • Sole Plate for protection against "rocks and roots" |
| Red Wing | King Toe ADC Work Boot | • HRO sole has been tested against contact melting to 246 C (475° F). |
| Salomon | Escape Outpath | • Integrated gaiter cover with drawstring top may offer dust protection |


**Fig. 30. Asolo Eiger boot with integrated gaiter with a front zipper and extra thick rubber toe.**

1. *Asolo:*
https://www.asolo.com/en/

The Asolo Eiger XT GV EVO boot incorporates a full height gaiter to keep out show and ice, as shown in Fig. 30. This gaiter includes a front zipper to make it easier to don and doff the boots and to lace and unlace them. The simplicity of the zipper may be a nice idea, but the acid test would be how it would perform after being covered in lunar dust. Never the less, the simplicity and clean lines of the Eiger gaiter show the thought and care that went into it.

2. *Brooks Running Shoes:*
https://www.brooksrunning.com/en_us/

Like its corporate name suggests, Brooks makes excellent running shoes and also walking shoes. However, they do not make boots.

One interesting Brooks shoe is the Caldera 6, a trail running shoe, that they promote as excellent for both dry and wet conditions by virtue of its "sticky sole" in Fig. 31 This sole has wide spaces between its lugs, which would tend to reduce the amount of mud it picks up. What is ironic about the nickname for the sole is that it is designed to not be literally sticky, but to be less sticky where picking up mud is concerned. What the nickname is meant to suggest is that it helps the runner stick to the trail. Dust adheres to space suit boots but it does not clump on thickly like mud. Never-the -

**Fig. 31. Brooks Caldera 6 trail shoe's "sticky sole" with widely spaced lugs.**

less, the widely spaced lugs may pose an option to consider for better traction on boulders, regolith, and rocks.

3. *Irish Setter*

https://www.irishsetterboots.com/sale/Pinnacle/02700.html

The Irish Setter Pinnacle features an exterior compound, Armatec or ArmatedXT that is especially resistant to abrasion. It might be a great material to test for the sides of the Overboot.

4 *L. L. Bean:*

https://www.llbean.com/llb/shop/474?page=footwear&csp=f&nav=gnro-hp

The Mountain Classic includes a "sole plate" for protection against "rocks and roots." Alas, it comes only in regular width, but the raw material could be custom cut to fit the Overboot.

https://www.llbean.com/llb/shop/125326?page=mens-mountain-classic-waterproof-hiker-mens&bc=&feat=Mens%20boots-SR0&csp=a&searchTerm=Mens%20boots&pos=88

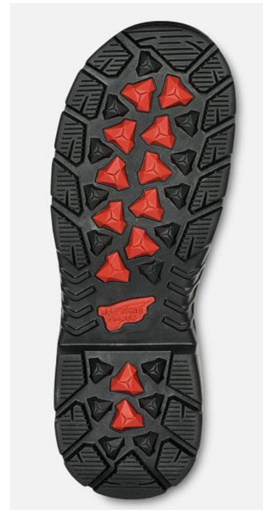

**Fig. 32. Red Wing King Toe ADC sole with HRO heat resistance rating of 246 C (475° F).**

7. *Redwing Shoes:*

https://www.redwingshoes.com/

The Redwing King Toe ADC 8" work boot features what appears to be a unique thermal protection feature, the HRO sole, which they claim has been tested against melting to 246 C (475° F). The HRO sole appears in Fig. 32. This material could prove helpful to the Overboot sole. The other side of the heat resistance question concerns how this sole or any sole will perform in -200 C cold in the permanently shadowed regions (PSR). Embrittlement or cracking of the sole material in cold could emerge as a major problem. Eventually, it may even be necessary to be able to switch readily from a PSR cold overboot to an equatorial noon overboot (140 C).

8. *Salomon:*

https://www.salomon.com/en-us

Like the Prolink Combi reviewed under Flexible Outer Boot, the Escape Outpath unisex Nordic boot incorporates a swivel mechanism across the medial-lateral malleoli axis, albeit off a somewhat different design. A further notable feature is that this boot sports an integrated gaiter as a protection against snow and ice intrusion. This gaiter with its apparent elastic drawstring top could serve as an example for a dust protection cover to the outer boot as shown in Fig. 33.

https://www.salomon.com/en-us/shop/product/escape-outpath-prolink-lg4977.html#color=43819

**Fig. 33. Salomon Escape Outpath boot. Please note the pivot aligning with the malleoli axis.**

## X CT-Scan of the Salomon Nordic Boot

Our team selected as our investigation candidate boot the Salomon *Prolink 'Escape Outpath'* (Salomon SAS, Épagny-Metz-Tessy, France) boots, USA size 11. This boot is designed for on- and off-trail cross country skiing.

### A. Objectives

The objectives of CT-scanning the sample boot are as follows:

1) Examine an advanced design and technology athletic boot to see how it is constructed as a potential model for a space suit outer boot.

2) Investigate a boot designed especially to help protect the foot and leg from injury, in this case to protect the ankle.

3) Evaluate the design, construction, and mechanics of a boot designed to be flexible as a way to protect the ankle and foot.

**Fig. 34. One of the Boots on the Imaging Table with the C-arm in position below it.**

The boot scanned is the Salomon Prolink Escape Outpath, an on- and off-trail cross-country ski boot.

## B. Equipment

Co-author Bennett acquired Cone-beam Computed Tomography (CT) scans of the boots using a Siemens Zeego* C-arm system (Siemens Healthineers, Erlangen, Germany). Fig. 34 shows one of the boots on the "table" of the Siemens Zeego scanner with the C-Arms visible above and below the imaging platform at the Stanford University School of Medicine Radiology laboratory.

These acquisitions were conducted at 64 kVp, 11 mA, 1.0 mm focal spot, 0 mm Cu added filtration, using a large-volume scan of 454 projections. Bennett selected a normal kernel for a standard filtered back-projection reconstruction, yielding an isotropic voxel size of 0.5 mm for the reconstructed volumes.

## C. Process

Bennett took separate scans of each boot, left and right. Cone-beam metal artifacts were observed in the CT reconstruction and minimized using window/level and image segmentation techniques. Half scans of each boot were stitched together using *Invivo 3D* software (Anatomage Inc. Santa Clara, USA.)

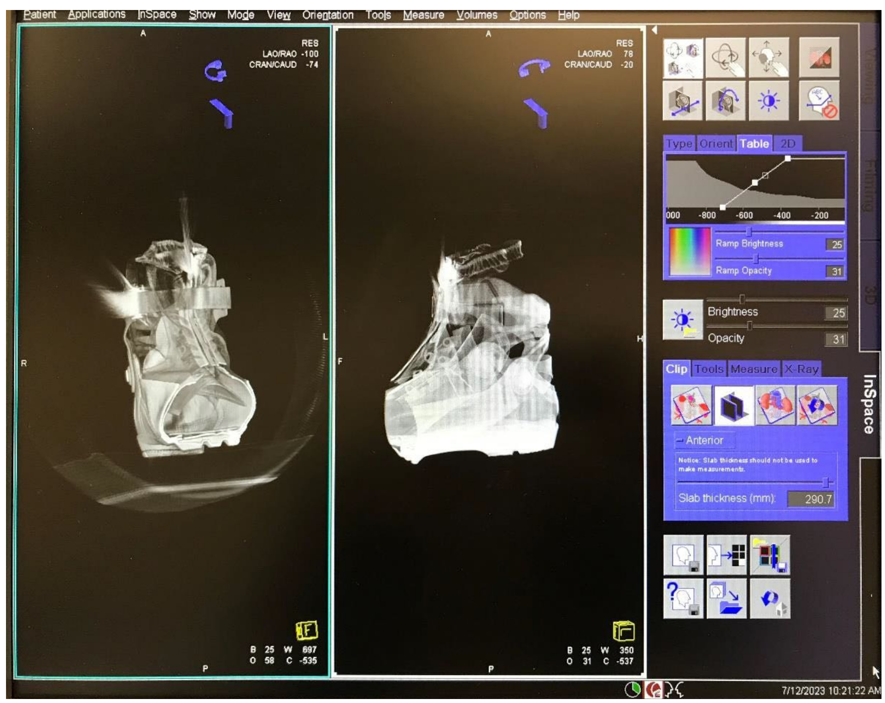


**Fig. 35. 3D X-ray Reconstruction Rendered Volume showing two views of a boot with a section cut through the frontal plane of the boot "mid-foot."**

The DICOM-formatted images were converted to an STL-formatted dataset using *Materialise Mimics Innovation Suite* (Materialise NV, Leuven, Belgium) and fully segmented. It differentiates metal from hard plastic and from soft woven material. The STL was imported as a triangular mesh and decimated by 50% producing a rendered solid model in Fig. 35 in SolidWorks (Dassault Systèmes SE, Vélizy-Villacoublay, France).

Figs. 36a and 36b scans show the boot rendered as a mesh. FIGURE 32a shows an initial image in the form of an x-ray reconstruction rendered volume. In this image, the reconstruction makes a transverse cut through the body of the shoe from the dorsal top to the sole at the bottom approximately "mid-foot." FIGURE 32b shows a complementary longitudinal cut along the sagittal plane.

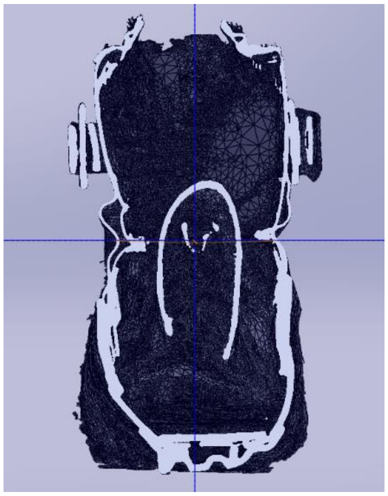

**Fig. 36a. Frontal View of the Boot with the Mesh Cut through the Frontal Plane**

**Fig. 36b. Side Section View of the Boot with the Mesh Cut through the Sagittal Plane.**

**D. Results**

The results of this investigation include several stages of representation constructed from the raw CT-Scan data. They lead to a 3D-printable digital model of the boot. The formats of these progressive images are single projection X-ray, solid mesh, and 3D printable model. Fig. 37 shows a "simpler" single projection x-ray of the Escape Outpath boot. At the right-center the x-ray shows the boot's pivots that align with the malleolus axis between the "ankle bones." One of these pivots appears in the same locations in Fig. 38, the solid mesh representation of the boot. Fig. 39 shows the final digital model of the boot, from which it is feasible to 3D print a replica of the form, mechanism, and structure.

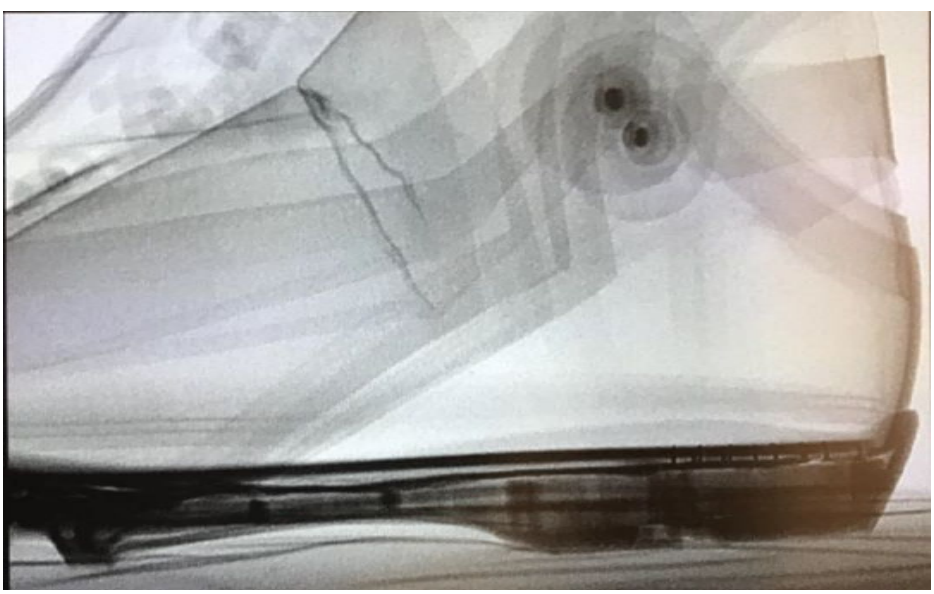

**Fig 37. Shows a Single Projection X-Ray that Reveals the two Pivot Points on either side of the Boot that Align with the Malleoli Axis for the Purpose of Promoting Ankle Performance and Protecting the Ankle at the Same Time.**

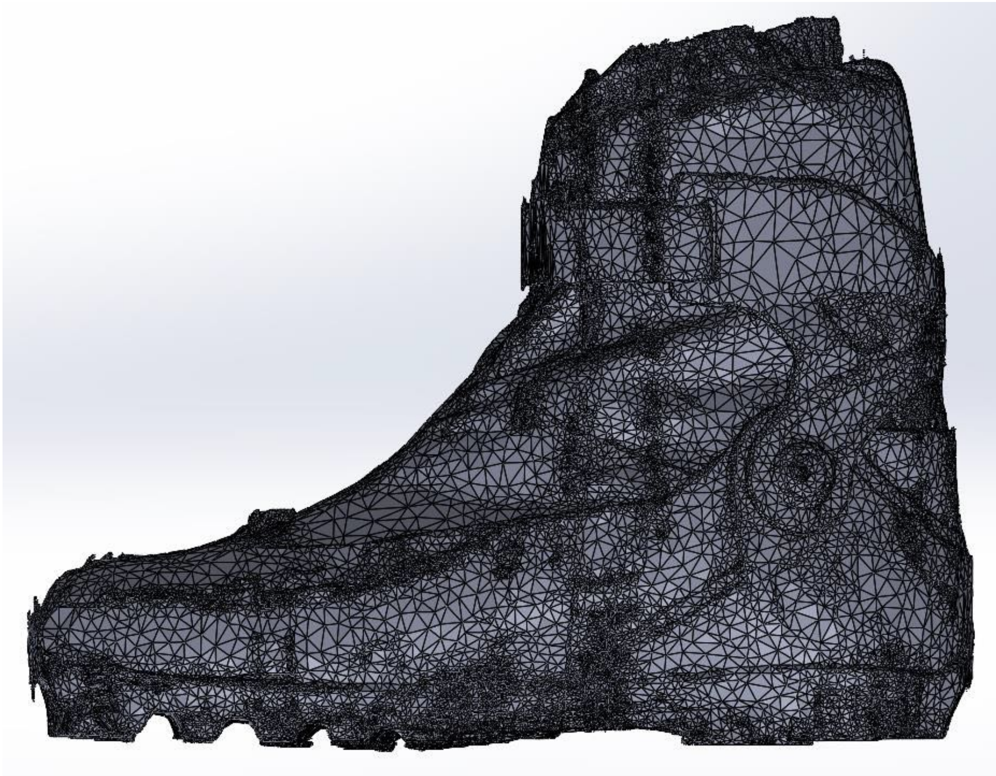

**Fig. 38. 3D Triangular Mesh Representation of the Boot, Revealing its Functional Highlights. The Pivot Appears Aligned with medial and lateral malleoli axis. The Sole Displays the Instep, Arch, and Traction Lugs.**

**Fig. 39. 3D digital model of the Escape Outpath that can be used for 3D-printing. Please note the malleoli axis pivot. The integrated gaiter with drawstring appears at the top of the boot.**

### E. Takeaways – What We Learned

This experiment showed that it is possible to CT-scan a boot and process that image data into a 3D structural triangulated solid mesh and from there into a 3D-printable model. This mesh model can then be used to design and mold a boot — either an Inner Boot or an Outer Boot — to fit precisely the foot of an individual astronaut. This technique would be especially important for designing an Outer Boot – Flexible or Rigid. If the Outer Boots cannot be made personal and individualized because of limitations on resources or stowage space, then it should be possible to design them to fit the outside of an Inner Boot.

Another valuable outcome is the ability to see the boot cut through any plane: front, sagittal, top-horizontal or even on a diagonal. The software model was set up to take "slices" at 1 cm increments along each of the x, y, and z axes so that it is possible to zoom in on the structure at virtually any point or cut-plane. This feature will serve handily to program the 3D printing of a boot.

## XI Findings

Very little in this study turned out as expected or as it appeared at first. There were surprises. The findings are presented in reverse order from the footwear survey to highlight some of these surprises. Generally, the strategy behind this study is to find the outstanding and innovative features across the whole relevant market of athletic, outdoor, and work boots, and to borrow them as shamelessly as possible. The main method of borrowing is to take a very high-resolution CAT-scan of the most suitable boots and their features. In addition, where a desired feature is a trademarked or patented material or technology, we can buy or license it.

Perhaps designing a rigid outer boot can be seen only as a kind of disappointment. In the earlier part of this study (before this interim report) we found NASA and university documentation of ankle and foot injuries incurred during EVAs. Even in the proposal to NASA, we identified recorded cases of injuries to the feet as a key concern for the design of the space suit boot system. The solution appeared to involve creating a flexible boot that can allow the foot, inner boot and outer boot to flex or extend in concert. If we are limited to a rigid boot, while it is still feasible to ensure that the inner boot and outer boot move together to some extent, it would undermine the foot and ankle biomechanics.

### A. Overboot Findings

The main surprise is that there will probably need to be different overboots for different temperature ranges because of limitations on the materials available for the soles. The Red Wing HRO sole material, rated to 246 C would seem to be ideal for lunar noon in the equatorial regions. Perhaps, there may exist converse materials at the other end of the temperature scale that might be good for extreme cold but not for heat.

In terms of treads for the outsoles, there are a multitude of designs from industry. The one that attracted our attention is the Brooks Caldera 6 "sticky sole," which refers to keeping the shoe stuck in place. But in fact, the wide spacing between the lugs would reduce the tendency to pick up regolith and other materials in the treads.

There are multiple designs for integrated gaiters that can serve as models for dust covers. The main issue that arises is the means of fastening these dust covers that include sting ties, elastic, and zippers. How well these various closure methods will exclude lunar dust without becoming clogged by it themselves remains an open question

### B. Outer Boot – Flexible Findings

The inspiration that led to this study was the strategy to make the inner and outer boots conform as closely as possible to the natural biomechanics of the foot and ankle. In this way, we found two outstanding technologies that help the foot to flex and extend naturally in the boot.

One key to achieving increased mobility in the 3D-printed outer boot may be to incorporate a bellows geometry over the arch and sides of the foot. This advanced structure will allow the foot and ankle to flex as the astronaut bends or leans forward on one foot.

The idea of a flex bellows to allow bending and flexing originated during the Apollo Program with the Ames AX-1 hard Space Suit, which used a waist bellows ring. The next version, the AX-2 integrated two waist bellows rings and the inventor proved under pressurization that he could bend over at a right angle to his legs. With this solid history in mind, we were delighted to find the Keen Portland boot that features a flex bellows in the upper, allowing the foot to flex far forward and to extend back the equivalent. This flex upper seemed like an excellent template and the next question was how flexible to make the sole of the outer boot.

Making the transition from two materials (a metal bellows attached to fiberglass) to a single material in additive manufacturing in continuous metal thin layers should be comparatively straight forward. The additive manufacturing/3D printing design and process confers the ability to control the thickness and local rigidity or flexibility of the single material.

With respect to preventing or minimizing ankle injuries, we were amazed to find that Salomon makes a series of cross-country skiing and skating Nordic boots that feature an axial pivot device that aligns with the ankle to help protect it from injury and overuse. We imagine that it would be possible to integrate such a device into a pressurized boot with a flex bellows upper.

### C. Outer Boot – Rigid Findings

For a model for the rigid outer boot shell there are several excellent work and outdoors boots that provide the geometry, systems of padding, and insulation that should be sufficient to provide a template for design. The three leading candidates: Keen, Irish Setter, and Red Wing. These brands all provide excellent design, fabrication, performance, and durability. It is difficult to choose a "winner" from among them, but probably any of the three might serve sufficiently well for a boot lacking all flexibility.

### D. Inner Boot Findings

The inner boot is the most like a conventional shoe on Earth. There are hundreds of candidates for a model or template among the vast variety and output of the shoe and boot industry.

The main surprise for the inner boot was that in 2021 at ICES, Stapleton, Eddy, and Hamill proposed using a *Title* boxing shoe 8.5 inches high as the inner boot. They assert that it meets nearly all their criteria for the inner boot, is readily available as a COTS item and is "wonderfully flexible." We concur that such a boxing shoe may be a "magic bullet" for the inner boot. However, we reserve judgement about which boxing shoe is truly best. Also, we are not prepared to rule out a high-top basketball shoe like the Air Jordan with the upper extended up to 23 cm. This caution derives from the use cases of the boxing shoes and other athletic shoes. The issue is how long does a boxer wear a boxing shoe compared to how long a basketball player wears a high-top or a runner wear a running shoe.

The question of inner boot height seems still quite open. A taller boot may help protect the shin and calf against chafing on the sealing ring between the outer boot and lower leg of the spacesuit. A taller boot might also make it easier to plug in the fittings of the LCG/LCVG into its top edge if the inner boot becomes part of the LCVG subsystem. The Apollo space suit stopped the LCG at the top of the boots. The Artemis LCVG does the same. That suggests that they are not considering incorporating the inner boot into the cooling system or using the boots or the xEMU during the lunar noon in the equatorial regions.

## XII. Open Questions:

### A. Allocation of functions

- What is the best allocation of functions between the internal and external boots for foot comfort, protection, and support?
- What is the best allocation of functions between the Outer Boot and the Overboot?
- What is the best approach to dust control, mitigation, and removal?
- How do survivability concerns affect the design of the boot assembly?
- How do operations considerations factor into the design of the boot assembly?

### B. Dimensions and Geometry

- How high does the internal boot need to rise within or above the Outer Boot (23 cm high Outer Boot = 9.055 in).
- Where is the best application and shapes for foot cushioning?

### C. Insulation

- Where is the best application and allocation of thermal insulation?
- What are the distinctions between conductive insulation and radiative insulation in terms of materials and application?

### D. Cooling and Heating

- Does the LCVG run down into the internal boot, around the foot?
- Does the LCVG integrate into the internal boot, connecting with tubes imbedded in its thickness?
- Would it be possible and desirable to integrate foot heating and cooling functions into the inner boot or around the inner boot?
- Should the inner boot be ventilated to "breathe" and release perspiration into the general suit atmosphere?
- How do we analyze the boot to separate heat gain and loss by radiation from heat gain and loss from conduction through the sole of the boot?

### E. Boot Generalizability versus Specialization

- Will we need two different overboots: one for the PSR and another for the equator at lunar noon?
- Will the overboot tread need to be customized for different terrains? The regolith in the PSRs has been grinding smooth for up to 2 billion years of space weathering. The regolith on crater rims is much newer and so is likely to be much rougher and sharper.
- Can there be one boot design for all regions and "climates" of the Moon or will we need different boots for very hot (140 C) and very cold (-200 C to -225 C)?

## XIII Conclusion

The design of a space suit boot is outwardly a simple problem. However, upon analysis in depth, it proves to be much more difficult than it first appears. This difficulty derives from the several subsystems including pressure envelope, restraint layer, cooling function, heating function all of which need to be integrated within anthropometric and ergonomic parameters for the best performance. Confounding these issues, the ambiguity about the precise performance objectives creates a situation in which physical integration of the subsystems gives rise to potential functional, operational, and spatial conflicts.

The pressure bladder is a leading cause — if not THE leading cause — of foot trauma and injury in the space suit boot. The bladder "creases", "folds", and "wrinkles", inflicting pain that can be severe. Eliminating the pressure bladder would be the best way to eliminate foot pain and injuries. Second to the bladder as a source of foot trauma is the use of "sizing inserts" and improvised padding and patches that seek to respond to the problems with boot sizing but actually can make them worse.

Eliminating the pressure bladder means that the outer structure of the suit must hold the pressure as a simple "hard suit." To the first author's knowledge, NASA has never reflown the "soft goods," the pressure bladder, so eliminating it also obviates a supply chain problem. Without the pressure bladder, the way is clear to implement a simple inner boot to protect the foot from trauma. This inner boot can provide a channel to bring cooling and

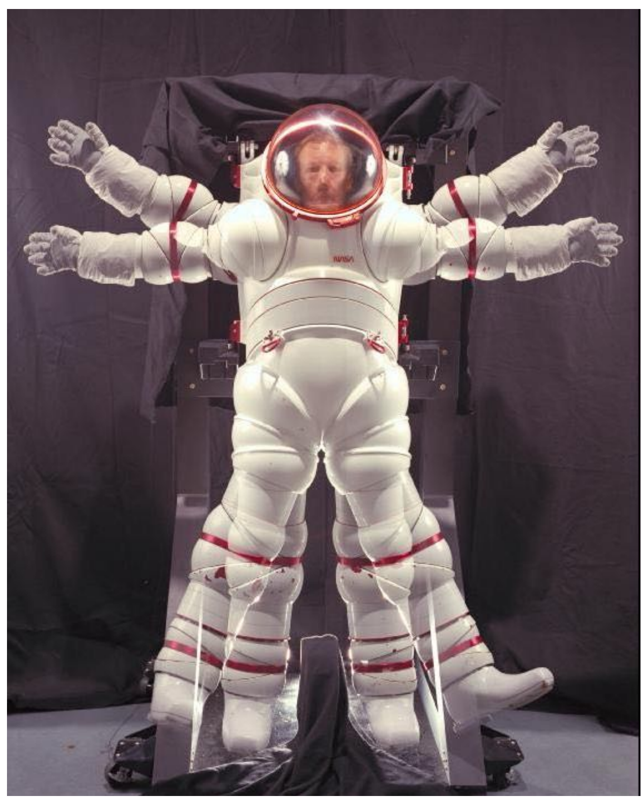

**Fig. 40. Dynamic view of the AX-5 Space Suit, circa 1988, with Phil Culbertson, Jr demonstrating its mobility.**

ventilation to the foot. It may also provide appropriate outer surfaces on which to mount electrical resistance heaters for the extreme cold of the PSRs.

Avoiding or resolving these conflicts comprise the heart of these design challenges. These conflicts become manifest early in this report, as shown in the three logic diagrams. It becomes apparent that it will be almost impossible to design one boot that meets all these environmental challenges successfully. One way to parse the problem is to decide that there must be different boot (and perhaps suit) designs for cold and hot environments, and perhaps also for the "normal" or more temperate lunar environments.

In conclusion, from the perspective of foot and ankle injuries, it would be better to implement a space suit with a structural pressure vessel such as the AX-5 hard suit. This type of suit has no intrinsic conflicts with the biomechanics of the foot and ankle. Instead, it could easily incorporate a flexible outer boot that responds to foot and ankle biomechanics into the overall pressure envelope. The AX-5 appears as Vitruvian Man in FIGURE 40.

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