

# Morphing Upper Torso: A Resizable and Adjustable EVA Torso Assembly

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Traditional Extravehicular Activity (EVA) spacesuits incorporate either hard or soft upper torso subassemblies as part of their architecture. In either case, these components are of a specific, fixed size and lack provisions to make significant sizing adjustments across the envelope of the torso. To address this limitation, this project furthered the Morphing Upper Torso (MUT) concept, an innovative pressure garment that allows for resizing of the torso and precise repositioning of the neck, scye and waist planes. This concept was initially developed several years prior, and analytical and experimental models of the full MUT design (in which the back hatch of a rear-entry torso is interconnected with the waist ring, helmet ring and two scye bearings) have been used to demonstrate the feasibility of this novel space suit concept. These previous efforts showed that the torso could be expanded to facilitate donning and doffing, and then contracted to match different wearer's body dimensions. Using the system of interconnected parallel manipulators, suit components can be accurately repositioned to different desired configurations. The project described herein furthered this novel concept, focusing on development of higher fidelity mockups and updated analytical tools and models. New higher fidelity mockups were designed and fabricated, incorporating Link-net as the restraint layer. Link-net is a unique "netting" material created and manufactured exclusively by David Clark. In this application, Link-net may provide advantages in the MUT architecture, due to its ability to self stow. When the MUT is reconfigured and resized to smaller dimensions than the restraint is designed, ideally the restraint material will stow underneath the resizable linkages, and will not buckle, dive in, or create hot spots, as is potentially the case with traditional woven fabrics utilized as a pressure garment restraint. Additionally, various sizing mechanisms were considered and design trades performed to choose a design that allows quick, reliable, mechanical adjustments of the linkages. Ideally the crewmember must be able to quickly make adjustments to the torso size after donning the suit. If it is a suitport-compatible suit, these adjustments must be made with the suit pressurized. Concepts that are optimal for both unpressurized resizing and pressurized resizing were designed. Finally, the analytical models have been updated in this project to reflect the current baseline exploration suit geometry. Using these updated analytical models and the higher fidelity mockups, analysis was performed to quantify a reasonable range of sizing adjustments for a wearable prototype, as well as outlining the sizing architecture to outfit the entire future crewmember population.

## Nomenclature

CSSS	=	Constellation Space Suit System
DCCI	=	David Clark Company Incorporated
DOF	=	Degree of Freedom
EMU	=	Extravehicular Mobility Unit
EVA	=	Extravehicular Activity
HSIR	=	Human Systems Integration Requirements
HUT	=	Hard Upper Torso
ISS	=	International Space Station

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JSC	= Johnson Space Center
MUT	= Morphing Upper Torso
NASA	= National Aeronautics and Space Administration
NEO	= Near Earth Object
PSID	= Pounds per Square Inch Differential
SUT	= Soft Upper Torso
TMG	= Thermal Micrometeoroid Garment

## I. Introduction

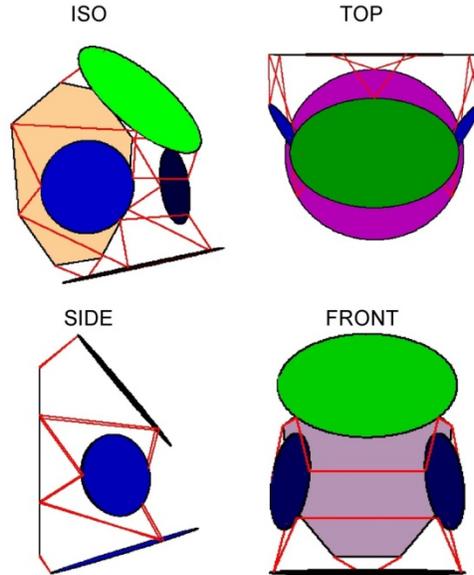
**T**O date there is no single, comprehensive solution to the challenge of making a suit resizable, highly mobile, lightweight, and easy to ingress/egress[1-8]. In light of these challenges, new and different suit architectures must be developed to enable astronauts to effectively perform future exploration. The concept developed here is the Morphing Upper Torso (MUT); an innovative pressure garment that does not compromise mobility nor don/doffability. It has the potential to be lightweight, resizable, easy to ingress/egress, and precisely fit a wide range of astronauts. By allowing for the correct alignment of the scye bearings (and other major hardware elements) and creating the most optimal fit, it also has the potential to mitigate crewmember injury [9]. Reduction in the number of sizes required to outfit the astronaut population could also simplify logistics without compromising fit quality.

## II. Background

The MUT architecture [1] is based on a soft upper torso pressure garment with dimensions that can be reconfigured to match the wearer's anthropometry. This requires manipulating the position and orientation (hereafter referred to as the "pose") of the waist ring, helmet, and scye bearings. The scye bearings are the bearings that provide shoulder rotation, and their pose is especially critical, as if their center of rotation is not exactly collocated with the center of rotation of the shoulder, the astronaut's upper arm mobility will be severely limited. The helmet-waist distance is another critical sizing parameter; too short and it is extremely uncomfortable, too long and the subject loses waist mobility and/or field of view. The capability to finely tune the pose of these four rings enables a closely fitting suit without customizing each suit and without sacrificing don/doffability.

This unique concept forms a system of interconnected parallel manipulators. Parallel manipulators are used in situations that require fine positioning, high stiffness and operation under high load, but are confined to small workspaces. Incorporating parallel robotics into suit design seems to be a logical design choice, as the strengths and capabilities of parallel manipulators map well to the requirements of a reconfigurable torso. The high pressure forces on the helmet, waist and scye rings create high loads. Additionally, while the physical dimensions of humans vary greatly, they all lie within a workspace that is compatible with a parallel manipulator. Finally, high accuracy and stiffness are clearly demanded, as the rings must exactly match the astronaut's dimensions to make for a highly mobile suit.

By connecting each hardware ring of the suit as a parallel manipulator with a set of adjustable linkages, as shown in Figure 1, the pose of each ring can be manipulated to match the wearer's dimensions. The rings are connected to the back hatch, which serves as an inertial ground, and interconnected to each other.



**Figure 1. Four views of the original Morphing Upper Torso analytical model. The red lines represent actuated tensile linkages, which can reposition the helmet, waist, and scye bearings**

Five progressive implementations of the MUT concept have previously been outlined [1]. The effort herein focuses on the first two, which pertain strictly to manually adjustable linkages and resizable suits. Implementations that involve active dimension changes or robotic exoskeleton assistance are beyond the scope of this effort. The focus is on a mechanical system of linkages that can be adjusted quickly and easily by hand, rather than actuators that require power and introduce unnecessary complexity. The first focus is on a system that can be quickly and easily adjusted with the suit unpressurized. The second focus is to extend the system such that it enables dimension changes while pressurized.

**Unpressurized Resizing:** Links would be lengthened during donning and doffing, then manually adjusted to desired individual dimensions prior to pressurization. This would enable one suit to precisely fit multiple users. High strength actuators are not required; instead, a simple, low-mass, hand-adjustable mechanism will be used to change the link lengths. This implementation would be a low-mass, low-complexity solution to many of the aforementioned problems facing suit designers. In fact, this system could actually fit each wearer better than custom made suits, as suit dimensions could be fine-tuned to accommodate body shape changes (due to different g-levels) that occur between the time the subject is fitted and the time of the EVA. Given a long-duration trip, each crew member's body shape will almost certainly change with time. Elongation of the spine can be expected during exposure to microgravity, amongst other possible changes. This system would ensure that the dimensions critical to suit mobility could adapt to match these changes.

**Pressurized Resizing:** Links could be adjusted manually after pressurization, providing quick modifications for comfort, and enabling fine control of suit dimensions at any time, while the suit is pressurized. Similar systems have been envisioned and implemented in mockup EVA gloves and boots. The ability to resize the suit while pressurized is highly desirable, especially for a suitport-compatible EVA suit, in which all post-donning adjustments must be made with the suit pressurized.

The Morphing Upper Torso technology can be integrated into rear-entry or waist-entry torsos, as desired. For this project, the existing rear-entry David Clark Company Incorporated (DCCI) Soft Upper Torso SUT-1X prototype (Figure 2) served as the architectural platform for furthering the Morphing Upper Torso technology. The SUT-1X is a predominantly soft derivative of its predecessor the Mark III or MK III (H-Suit) rear-entry upper torso. The SUT-1X serves as an analog for researching, designing, developing, and proposing new technologies that are likely to align with NASA's ongoing efforts associated with their EVA technology demonstrator suits (Mark III, Z-1 and Z-2).



**Figure 2. DCCI SUT-1X (left) next to a Rigid Mockup of the Mark III Hard Upper Torso**



**Figure 3. DCCI SUT-1X at 8 PSID, with 200 lbs Simulated Man-Load at the Waist Plane**

### III. Anthropometric Analysis and Requirements Determination

To first determine the requirements/goals for a MUT architecture, a variety of anthropometric and sizing information was analyzed and synthesized, focusing both on determining the requirements for a prototype MUT that would be compatible with the Z-2, as well as determining the requirements for a multiple size MUT architecture that would outfit the entire future crewmember population. The goal was to determine the necessary number of torso sizes and the amount of resizing and adjustment needed in each plane. This involved study of the anthropometric range and determination of hardware sizes and overall torso sizing architecture.

Multiple previous EVA torso architectures and their sizing schemes were examined and studied, including the Extravehicular Mobility Unit (EMU) pivoted Hard Upper Torso (HUT), the EMU planar HUT [10], and the proposed HUT sizing system for an architecture based on the Mark III. The anticipated anthropometric range for the Z-2 [11] was also studied, as well as the entire anthropometric range from the 1st percentile female to the 99th percentile male [12]. The Human Systems Integration Requirements (HSIR) database was used extensively in this project. The critical dimensions for torso sizing for this anthropometric range have been extracted and are tabulated in Table 1 and 2, with Figure 4 included to pictorially describe each dimension.

**Table 1. Important Female Population Anthropometric Dimensions for Torso Sizing (Data extracted from the HSIR[12] database)**

HSIR No.	Dimension	Female						
		1st percentile	5th percentile	20th percentile	50th percentile	80th percentile	95th percentile	99th percentile
805	Stature	58.54	60.2	62.14	64.19	66.23	68.18	69.83
223	Chest Breadth	9.25	9.84	10.53	11.25	11.98	12.67	13.26
457	Hip Breadth	11.73	12.36	13.09	13.85	14.62	15.35	15.97
236	Chest Depth	7.51	8.16	8.91	9.7	10.49	11.25	11.89
506	Interscye	11.54	12.27	13.14	14.05	14.97	15.84	16.57
103	Biacromial Breadth	12.68	13.15	13.71	14.29	14.88	15.43	15.91
122	Bideltoid Breadth	14.94	15.61	16.4	17.22	18.05	18.84	19.51
735	Scye Circumference	12.56	13.23	14.02	14.85	15.68	16.47	17.14
946	Waist Front	13.41	14.05	14.81	15.6	16.4	17.16	17.8

**Table 2. Important Male Population Anthropometric Dimensions for Torso Sizing (Data extracted from the HSIR[12] database)**

HSIR No.	Dimension	Male						
		1st percentile	5th percentile	20th percentile	50th percentile	80th percentile	95th percentile	99th percentile
805	Stature	64.03	65.87	68.03	70.3	72.57	74.73	76.57
223	Chest Breadth	10.46	11.19	12.06	12.97	13.88	14.75	15.49
457	Hip Breadth	11.87	12.41	13.06	13.73	14.41	15.05	15.6
236	Chest Depth	7.8	8.4	9.12	9.87	10.62	11.33	11.94
506	Interscye	13	13.87	14.89	15.97	17.04	18.06	18.93
103	Biacromial Breadth	14	14.52	15.13	15.77	16.4	17.01	17.53
122	Bideltoid Breadth	16.98	17.73	18.61	19.53	20.45	21.33	22.08
735	Scye Circumference	15.12	15.91	16.84	17.82	18.8	19.73	20.52
946	Waist Front	14.41	15.11	15.94	16.81	17.68	18.51	19.22

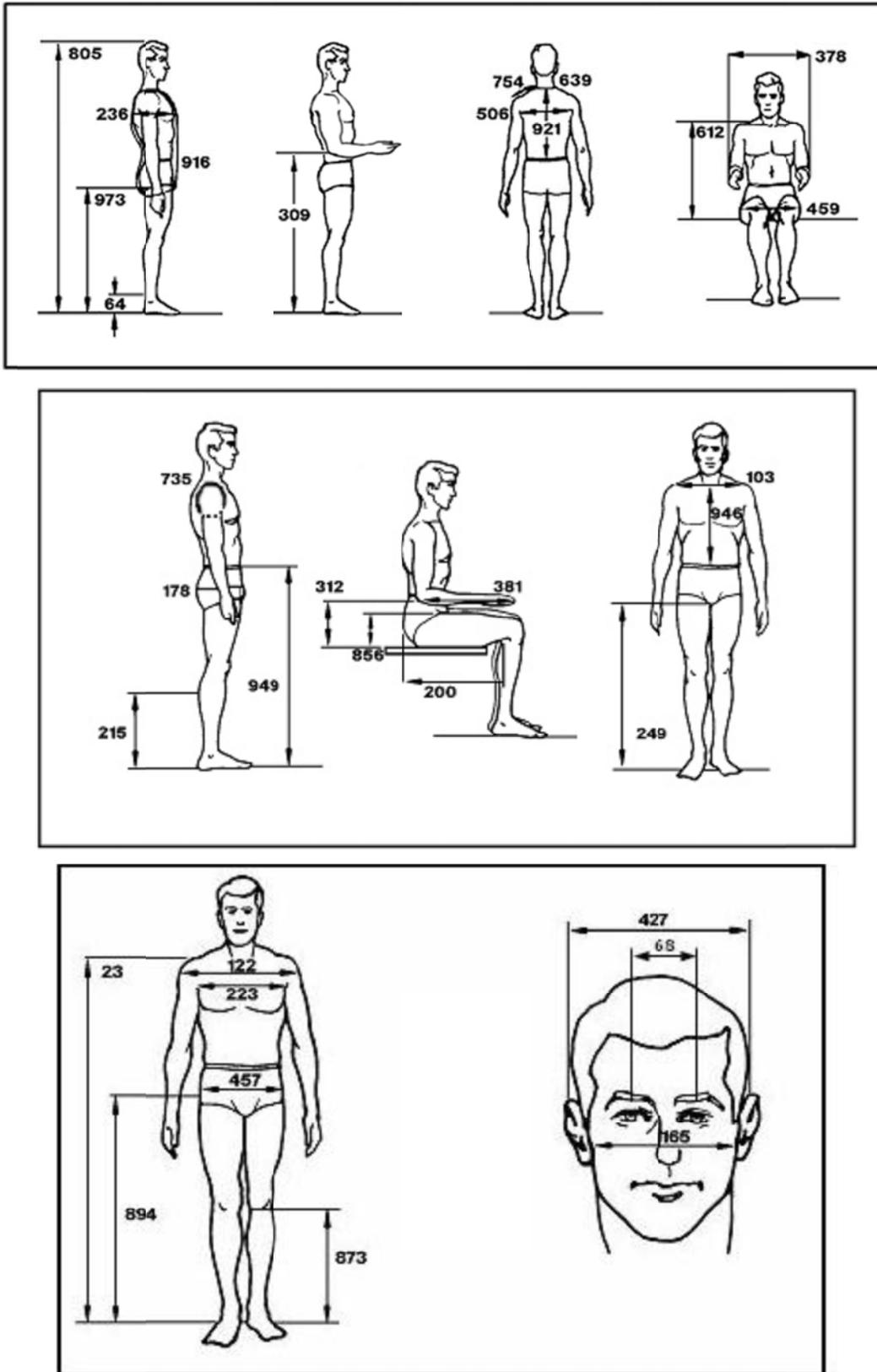


Figure 4. Numbering and pictorial descriptions of anthropometric measurements (Source: HSIR [12])

For each torso element (helmet, two scye planes, waist), all Degrees of Freedom (DOFs) were examined to determine which were critical, and the amount of resizability and reconfigurability for those that were deemed necessary. Clearly, rotation about the normal of each plane is not necessary for any of them, which leaves 5 possible DOFs. Given the strict focus on resizing, a symmetry assumption was made that one would always want to resize the torso such that it is symmetric about the sagittal plane. This eliminates two DOFs for both the waist and helmet (left/right translation, and left/right angle), and also assumes that the scye DOFs are coupled with each other – i.e. if one were to resize the left scye by 1”, one would also resize the right scye by 1”, for a reduction of interscye breadth of 2”. Similarly, the scye angles for the two bearings would be adjusted symmetrically.

Further examining the remaining DOFs for each plane, and comparing across entire sizing schemes for various historical suits as well as anthropometric requirements, the initial goals for the MUT prototype were determined to be as shown in Figure 5. The pertinent fixed dimensions for each DOF of the Mark III torso are included for reference. Note that given the large size of the Mark III HUT, these dimensions were assumed at the maximum end, such that the MUT could better accommodate smaller subjects, targeting the Z-2 RFP anthropometric range. The ranges of angles however are centered on the Mark III values, as these are generally accepted to work well for most applications and are likely optimal or near-optimal, but it is unknown if these truly are optimal nor what the optimum might be for various anthropometries. Providing the adjustment of these angles allows for experimentation to determine the optimums.

Plane	# of Adjustable DOFs	Adjustable DOFs	Amount of Desired Adjustment	Desired Minimum	Desired Maximum	Mark III
Helmet	1	Neck Ring Angle relative to back hatch	10 degrees	40 degrees	50 degrees	43.5 degrees
Scyes	5	Interscye distance	2 inches	12 inches	14 inches	14 inches
		Vertical Distance from Helmet Center to Scye Center	0.5 inches	8.1 inches	8.6 inches	8.6 inches
		Depth of Scye Center, relative to back hatch	0.6 inches	6.9 inches	7.5 inches	7.5 inches
		Scye angle relative to sagittal plane	20 degrees	20 degrees	40 degrees	35 degrees
		Scye angle relative to back hatch	10 degrees	15 degrees	25 degrees	20 degrees
Waist	2	Waist angle relative to back hatch	10 degrees	60 degrees	70 degrees	65.5 degees
		Vertical Distance from Waist Center to Helmet Center	1 inch	16.2 inches	17.2 inches	17.2 inches

**Figure 5. Summary of Desired Adjustability for MUT Prototype**

It is important to note that these are the initial goals for a wearable prototype – which has the unique objective of being compatible with existing hardware dimensions.

In addition to outlining goals/requirements for a prototype, a torso sizing architecture was developed to outfit the entire population, from the 1<sup>st</sup> percentile female to the 99<sup>th</sup> percentile male. It is unlikely that a future crewmember population will span this large anthropometric range, nor is it likely that a future spacesuit will be able to effectively accommodate this entire range, however it serves as a useful goal to endeavor towards, and can be scaled back as necessary in the future. The key goal as it pertains to the MUT is to show that a smaller number of torso sizes are needed to outfit a given population, than would be needed if fixed size torsos are used.

Using the anthropometric information, the analytical models (discussed in section V) were used to determine a multiple MUT sizing architecture, including the different hardware sizes, as well as the number of linkages required, and the amount of adjustment needed in each linkage.

#### IV. Linkage and Interface Design

A wearable, pressurizable MUT design requires quick, simple, mechanical adjustments in the linkages. If it is a suitport-compatible suit, these adjustments must be made with the suit pressurized. Various sizing mechanisms were designed and considered that are optimal for both unpressurized resizing and pressurized resizing. Discrete and continuous sizing options were investigated and traded, and optimum configurations identified. Additionally, the team examined the interfaces between the adjustable linkages and the MUT, considering factors such as wear, cycle life, pressure load, etc.

As it pertains to mechanisms, several potential issues and roadblocks were identified and discussed. Some factors that were identified include:

- Important to minimize crew time to perform the adjustments, as crew time is a scarce resource.
- Crewmembers will need access to the mechanisms through the Thermal Micrometeoroid Garment (TMG)
- Important to minimize dust in the mechanisms

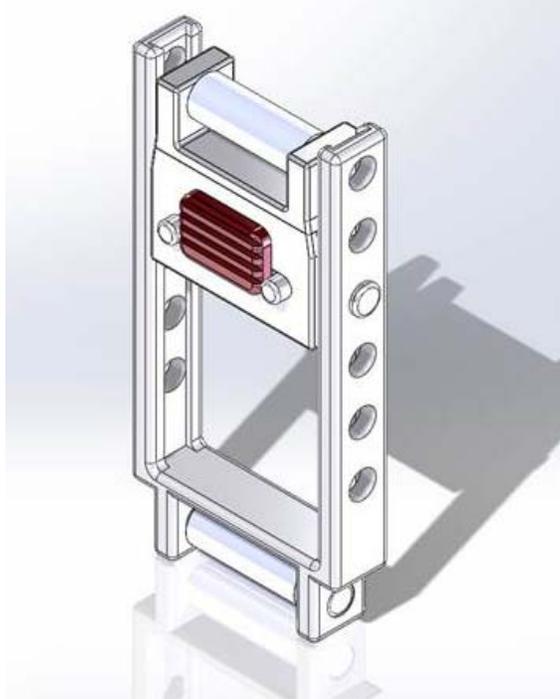
Leading concepts were identified to enable both unpressurized and pressurized adjustments. The leading concept for the unpressurized adjustments is a design based on the “ladders” (Figure 6), which are the hardware mechanisms used for resizing in the Constellation Space Suit System (CSSS) Demonstrator Suit [13]. The “ladder” connects two lengths of high-strength, low-elongation webbing. The webbing is looped over dowels, and is not removed once installed. The overall length of the linkage is adjusted by unlocking the mechanism (sliding the large red button down), squeezing the two round metal standoffs together, and selecting the desired length from the several pairs of holes on the bracket. The webbings would be integrated to the hardware with simple brackets, similar to those used in current suits such as the EMU and Z-1.



**Figure 6. “Ladder” Design. These mechanisms were used effectively in the CSSS Demonstrator Suit [13]**

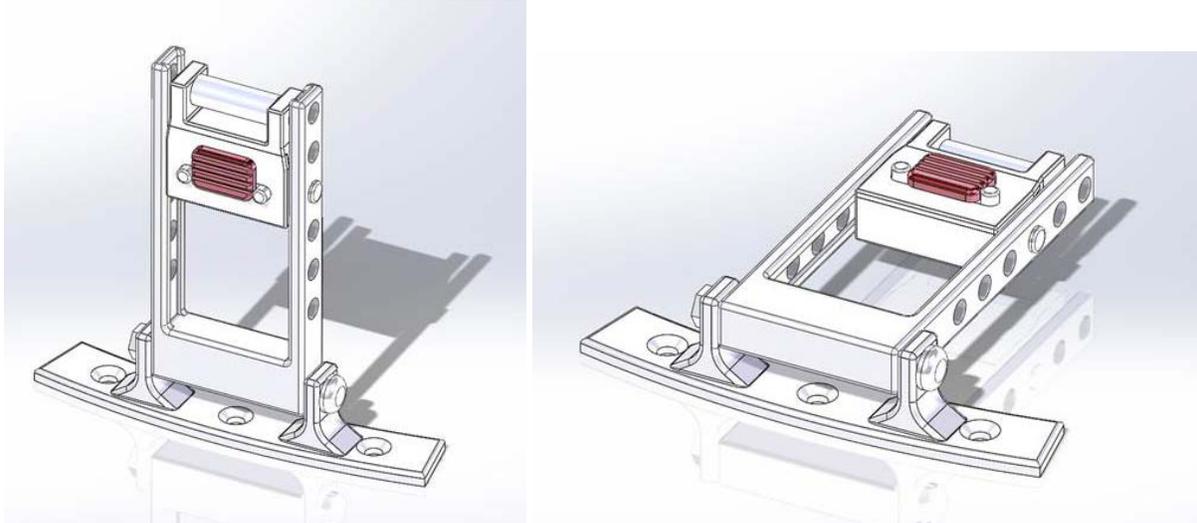
The concept is reliable, repeatable, quick and simple, in-line and low profile, doesn’t require tools, lockable, safe, and keeps the webbing firmly attached to the hardware at all times.

Several improvements over the first iteration hardware were designed, including slimming them down to reduce mass, and keeping the round slider standoffs centered so they can’t both slide to one side. A groove on the inside of the ladder was added, along the length, that serves to keep the mechanism in plane while making adjustments – this should significantly reduce the time necessary to adjust the length. The updated design is shown below.



**Figure 7. Updated "Ladder" design provides quick and easy adjustment of link lengths**

Additionally, a new design was developed that would integrate the ladder directly to the hardware. This would eliminate the need for additional bracket hardware at the interfaces. The ladder is pinned at the bracket, which allows it to swivel in and out of the plane of the ring as needed. The smaller component that adjusts within the ladder can also pivot about its pin. This combination allows for some curvature of the softgoods underneath the bracket. The ladder bracket is mounted in at least three of the ring's screws, and options of mounting it in five screws to reduce point loading at the interface are under consideration.



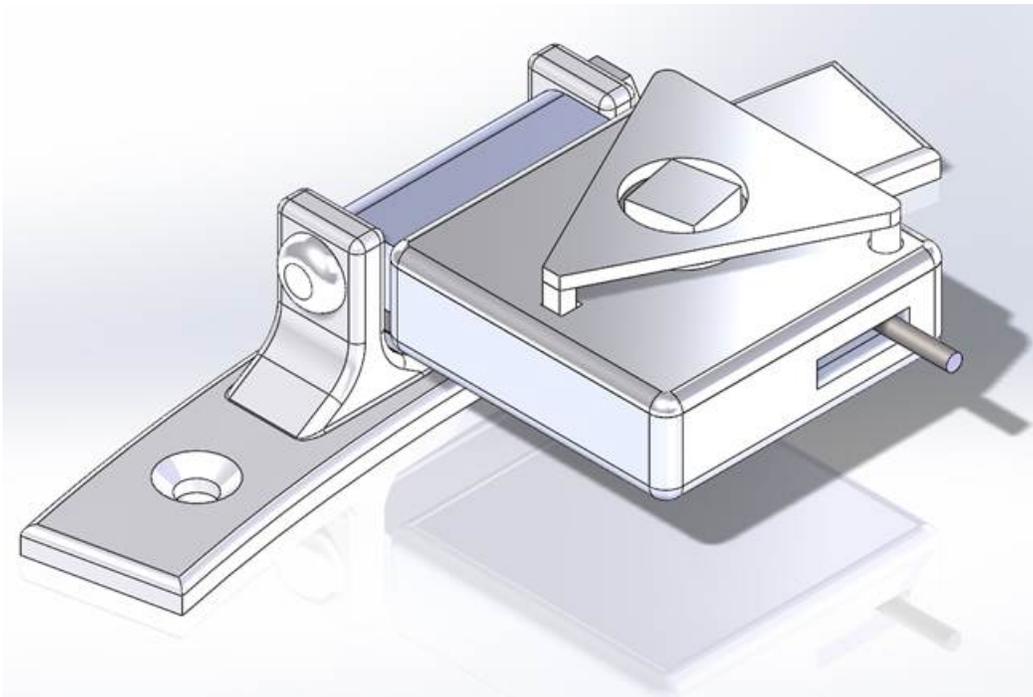
**Figure 8. Ladder design that interfaces directly to hardware. Note it can pivot as necessary to align with the torso component to which it is integrated**

With the baseline design in place, different size ladders can easily be designed to provide the required adjustability for each linkage. For example, some linkages require up to 2.6 inches of resizing, while others only require 0.5 inches - Figure 12 outlines the calculated amount of adjustability for each. Therefore, some ladders could have several pairs of holes (as shown), while smaller ladders would just have two to three pairs.

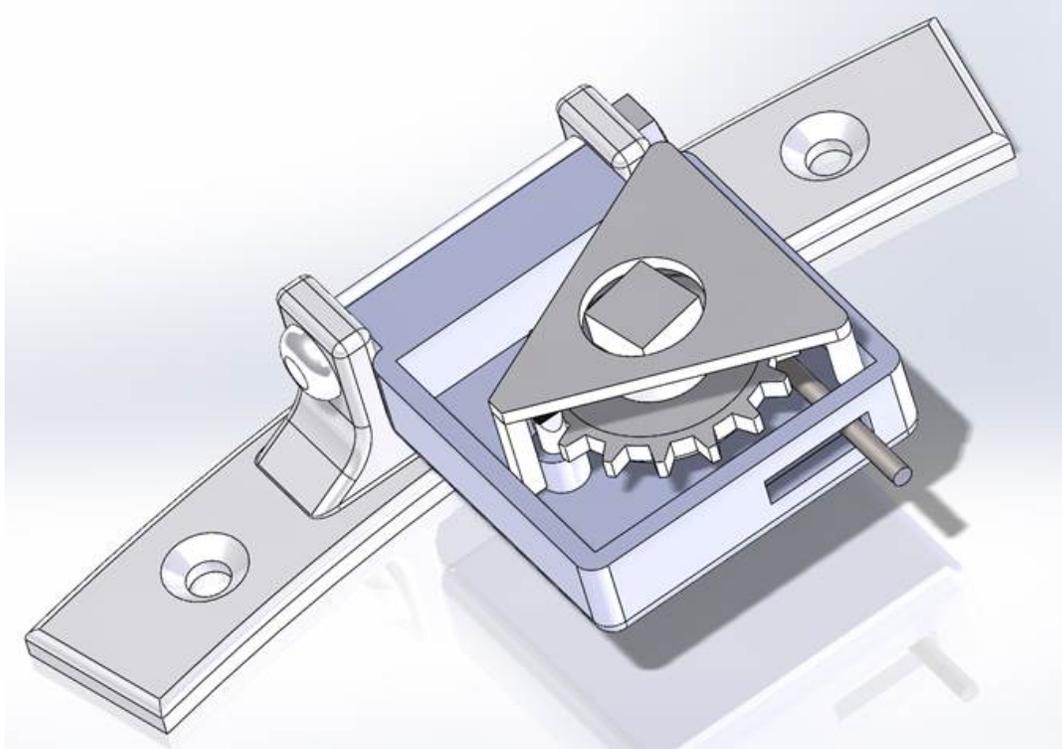
Determining a leading candidate for the pressurized adjustability was extremely difficult. Given that the subject would be making the adjustments while already in the suit pressurized, it is important to locate the mechanisms such that the subject can reach them. The subject needs the mobility – when the torso is not in the optimal position – to reach the mechanisms. This could be difficult, and ultimately some linkages may need to be adjusted unpressurized, and then a few adjusted while pressurized. Alternatively, crewmembers may have to help each other, resizing each other's suits once on EVA. This is not ideal though as one would like the capability to resize one's own suit.

Additionally, the crewmember will need to be able to access the mechanisms through the TMG – this complicates integration and dust issues. The crewmember needs access to the mechanisms through the TMG for unpressurized resizing as well, but in that case, the crewmember is not yet on the EVA and therefore (presumably) not exposed to the dusty environment.

After several design iterations, the pressurized resizing concept is shown in Figure 9 and Figure 10. A high strength flexible coated cable is wound on a spool. As the cable is wound on the spool, the length of the linkage connecting the two hardware interfaces decreases. The box with lid is approximately 1.7" x 2" x 0.55". The spool is ~0.8" in diameter, providing ~2.5" of adjustability of the cable length (one revolution). Referencing Figure 12 below, which details the amount of adjustability required in each linkage, this is sufficient for all linkages.



**Figure 9. Final Concept for Pressurized Resizing Mechanism**



**Figure 10. Final Concept for Pressurized Resizing Mechanism (Lid Removed)**

The square head on the mechanism, and the triangular locking pin-depression plate, will be accessible through the TMG, while the rest of the mechanism is in a protective box, reducing the potential for dust to affect the mechanism. A dust seal could also be integrated on the slot for the cable, which would allow the cable to slide in and out of the box while the seal “brushes” the dust off and keeps dust out of the box.

The square head could be turned manually with a standard wrench or ratchet wrench, or could be turned with a Pistol Grip Tool. The gear teeth are designed to work in concert with the locking pin to lock the length of the cable. Pushing the tool onto the triangular locking-pin depression plate depresses the locking pin, allowing the wrench to turn the spool. Removal of the tool causes the pin and the triangular piece to return to their initial positions (they are mounted on springs), locking the mechanism.

This mechanism is the leading concept to enable pressurized resizing of the linkages. It should enable quick, simple, automatic locking, reliable resizing, while the system is under load. It will be accessible through the TMG, while still protected from lunar or Martian dust. The mechanism does not require any specialized tools for use, crewmembers could use existing tools to perform the resizing.

## V. Analytical Modeling

Development of analytical models is at the core of Morphing Upper Torso development. The system of interconnected planes and linkages creates a complex mathematical problem. Numerous prior modeling efforts have analytically captured the relationship between the linkage lengths and the pose of the torso elements, as well as calculating workspaces. Herein the analytical models were updated to replicate the DCCI SUT-1X hardware geometry, as this is congruent with NASA’s advanced EVA prototype suits (Mark III and Z-1). These models were used to feed into requirements development and to evaluate other sizes of hardware, to determine a torso sizing architecture that could outfit the entire anthropometric range.

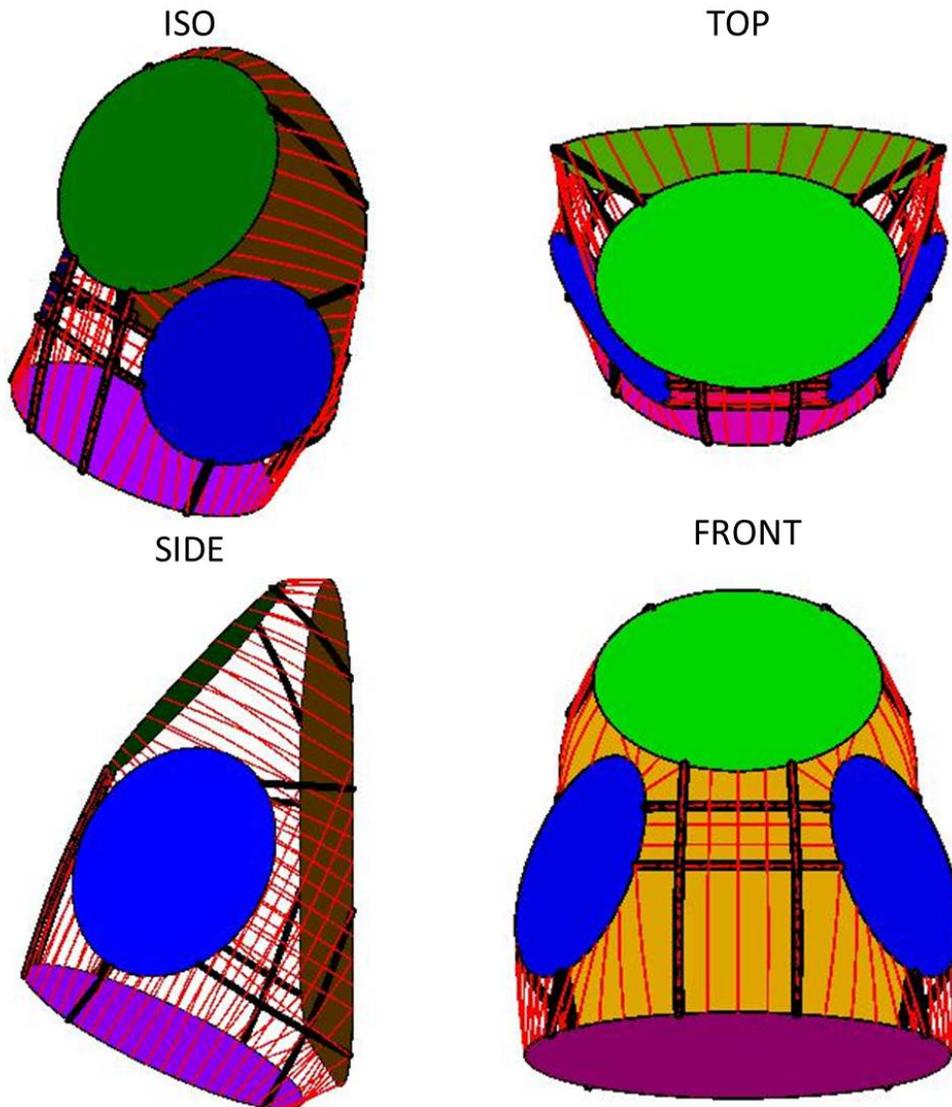
The proper geometries of all the hard elements, as well as the relative position and orientation of all the elements (congruent with the Mark III – as identified in Figure 5) were input into the model. In these updated models, the blue circles represent the scye planes, the green circle the helmet plane, the waist is represented in purple, the back hatch in yellow, and the red lines represent the softgoods. The red lines have been curved proportionally to the internal pressure, to simulate the behavior of softgoods under pressure load.

The analytical model can now be used to evaluate different positions and orientations of the helmet, scyes, and waist. For example, all the limits identified in Figure 5 can be input into the model, to determine if there are any limitations associate to the hardware dimensions.

Several different configurations of linkages were investigated. Some of the considerations for determining the placement of the linkages include:

- The linkages must provide control of the DOFs outlined in Figure 5
- The fewest number of linkages are desired to minimize hardware and complexity
- However, in some cases, contrary to the above bullet, two linkages in parallel provides a better solution than a single linkage, to manage significant pressure and man loads
- Longer linkages are desired to enable more reconfiguration and to provide real estate for the mechanisms in line with the linkages

The configuration shown below appears to be the most promising to enable the desired reconfigurations.

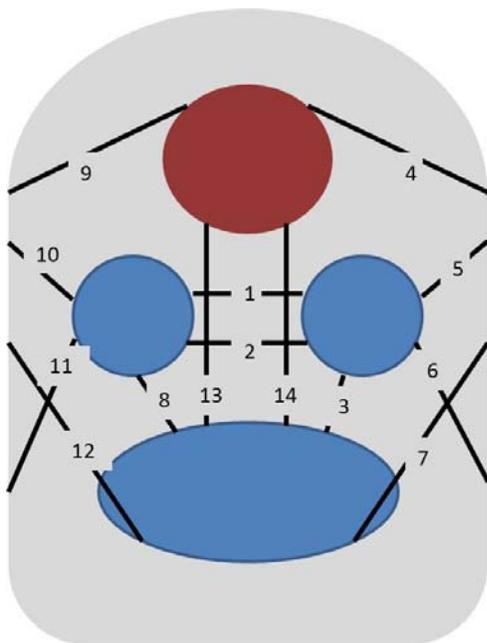


**Figure 11. Four views of the updated analytical model, with the baseline linkage configuration**

The two linkages that connect the top of the helmet plane to the back hatch, provide control of the helmet plane angle. Two linkages were used rather than just one at the top of the helmet, as there is limited real estate between the top of the helmet and the back hatch, and this would have created too large of a point load. Similarly, two

linkages connect the front of the waist to the helmet, and two connect the back of the waist to the back hatch, these four linkages control the waist angle and the waist height. Four linkages were used to distribute the loads – especially considering the very large man loads that can be applied to the waist plane, both during donning and during walking tasks. Each scye plane has five connection points, enabling control of five DOFs, recognizing that the DOFs are coupled by the two linkages across the front of the chest. It is assumed that the linkages connecting the right scye to the waist and back hatch would be adjusted symmetrically with the linkages connecting the left scye to the waist and back hatch.

The analytical model was employed to determine the amount of adjustability needed in each linkage. Determining the maximum and minimum length for each linkage is not as simple as just modeling the maximum and minimum poses for the torso, as some linkages will be at their maximum in different configurations. Thus an analysis was performed, wherein all of the various maximum and minimum dimensions and angles were modeled and the link lengths tabulated, and then the maximum and minimum length for each linkage was recorded. The linkage numbering scheme is pictorially depicted below, and the lengths and total amount of adjustability needed in each length is tabulated.

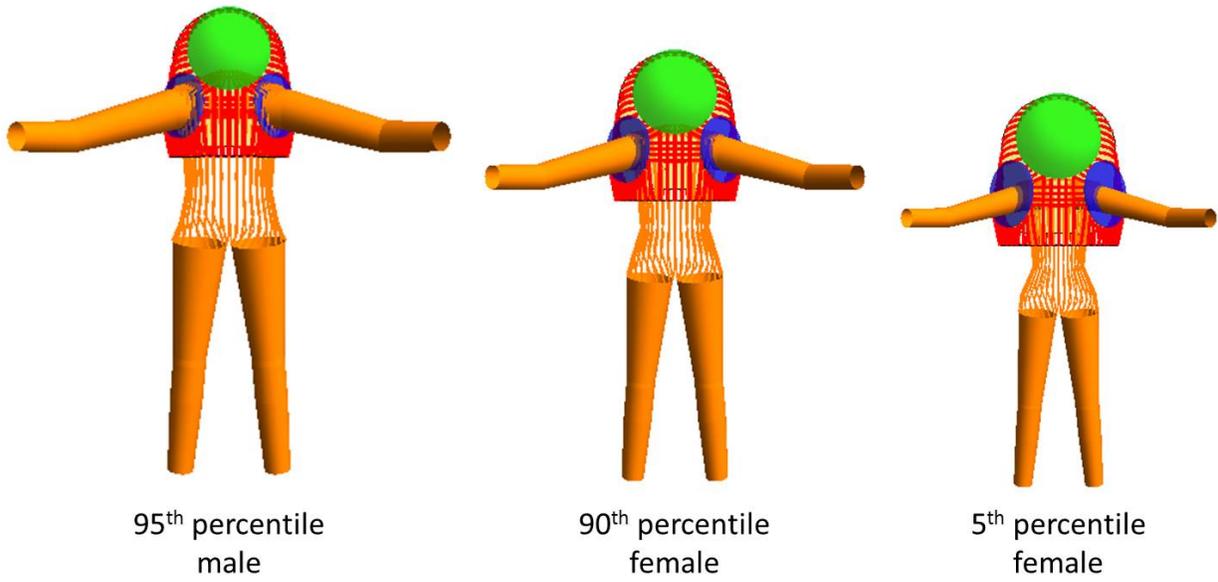


Linkage	Minimum Length	Maximum Length	Amount of Adjustability in Linkage
1	5.6	7.7	2.1
2	6.3	8.3	2.0
3	2.8	3.8	1.0
4	6.6	7.2	0.6
5	3.3	3.8	0.5
6	7.3	7.9	0.6
7	8.1	9.8	1.7
8	2.8	3.8	1.0
9	6.6	7.2	0.6
10	3.3	3.8	0.5
11	7.3	7.9	0.6
12	8.1	9.8	1.7
13	8.8	11.4	2.6
14	8.8	11.4	2.6

**Figure 12. Linkage numbering scheme and required adjustability in each linkage**

To address the issue of a multiple size, MUT sizing architecture to meet the entire anthropometric range, analytical models were created that allow any size person to be drawn graphically. The models use the HSIR anthropometric database, and source over 40 dimensions, to produce any size model “mannequin”. These mannequins can then be “placed inside” the torso, in virtual space, and the dimensions of the torso adjusted to provide the optimum fit. In the figures shown below, the “mannequins” are drawn in orange. All figures below are to scale.

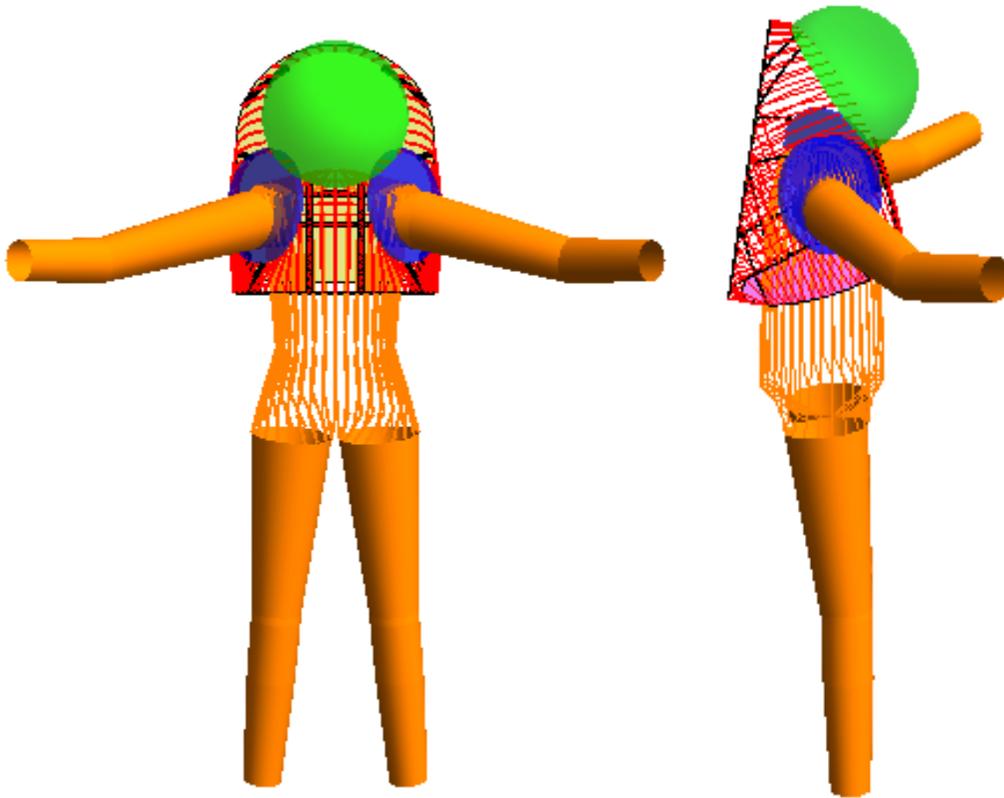
It is important to note that no real human is a specific percentile, ie. the 5th percentile female, or the 95th percentile male, do not exist in real life. Each person has unique dimensions, and may be 95th percentile in stature, and have other dimensions that are 30th percentile. These first figures show three different size mannequins drawn within the Mark III geometry and configuration.



**Figure 13. Example of capability of analytical model. Three different mannequins drawn within the Mark III configuration torso**

It is clear that the Mark III torso fits the 95th percentile male quite snug, with the head well positioned in the helmet, the scye bearings near-optimally placed on the shoulders, and overall a good fit. The 90th percentile female, and especially the 5th percentile female, clearly do not fit this torso very well, as the scye bearings are too wide, the waist is very loose, and their head is not well positioned in the helmet, which will limit their downward field of view.

The next figure shows the same 90th percentile female, inside the reconfigured MUT. This has the same hardware geometry as the Mark III, but has the resizing capability outlined above.



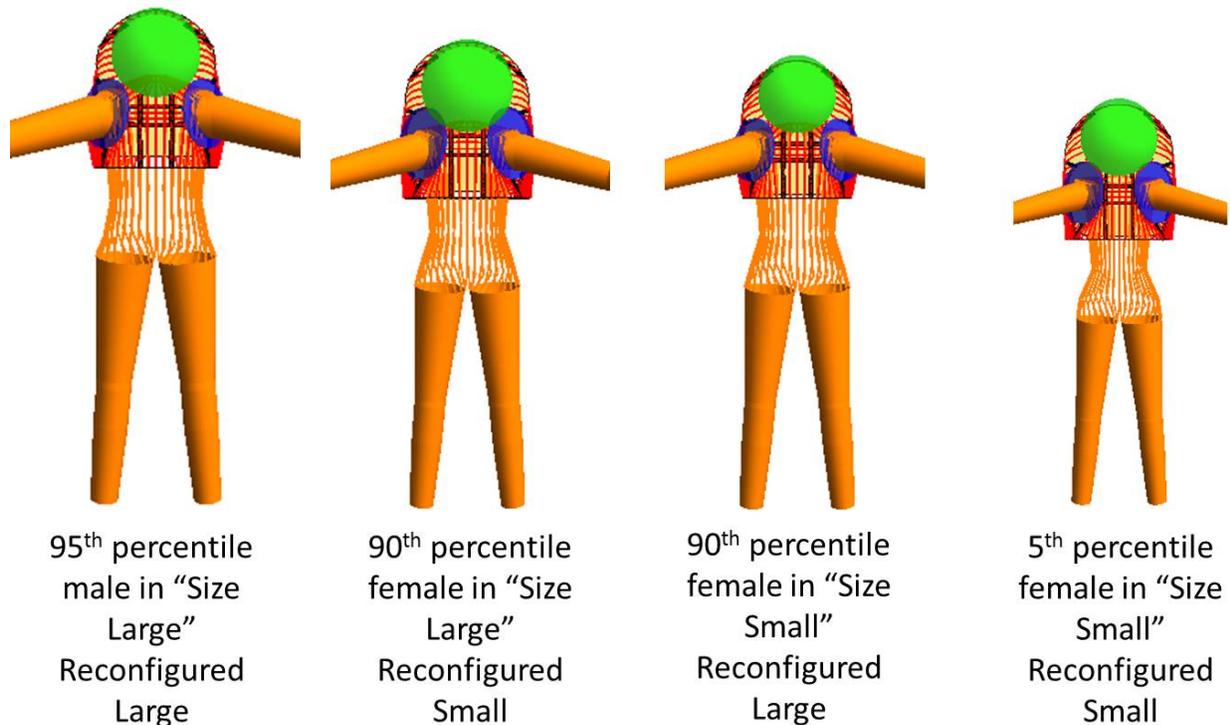
**Figure 14. 90th percentile female, inside reconfigured MUT, front and side views**

After much experimentation with the analytical tools, it is clear that the hardware limitations prevent a single MUT from accommodating the entire anthropometric range. However, iterating with the analytical tools, a preliminary analysis suggests that two sizes of reconfigurable MUT torsos could accommodate the entire range.

To address the smallest end of the anthropometric range, a second set of torso hardware geometries was designed. Several different geometries were tried, working within the constraints that the upper end of the range that this smaller torso will fit must be able to get their hips through the waist opening, and must be able to don the suit through the new (smaller) hatch. Ultimately the baseline smaller torso has a smaller helmet (11" diameter), smaller scye bearings (7.5" ID, scye carriers have OD of 9 inches), the major axis of the waist is ~15.5", and the hatch opening is 16" wide (compared to 18"), and a total of 21" tall (compared to 23.5").

This preliminary MUT sizing system for the entire anthropometric range therefore has two sizes, with some overlap in the sizes. The "small" fits females from the 1st to ~95th percentile, and males from the 1st to ~20th percentile. The "large" fits from ~80th to the 99th percentile female, and ~20th to the 99th percentile male. The "small" has an interscye range from 10-12", and the large from 12-14".

To demonstrate the overlap, the figure below shows both sizes in both their smallest and largest reconfigurations. The 90th percentile female is in both the "Size Small" MUT (reconfigured to almost its largest size), and in the "Size Large" MUT (reconfigured to almost its smallest size). Each particular subject that falls within the overlap range will have preference based on their individual anthropometries – for example a small female with large shoulders may prefer the "Size Large" MUT in its smaller configuration, as the scye hardware is larger.



**Figure 15. Two sizes of MUT covering the entire anthropometric range**

As discussed in section VI, all mockup fabrication to date has been with the Mark III hardware. The spacesuit community at large has a great deal of experience with these dimensions. The smaller torso dimensions outlined here do not have the same experience base. It would be an exciting opportunity to develop a small torso to investigate any currently unknown issues associate to these smaller geometries.

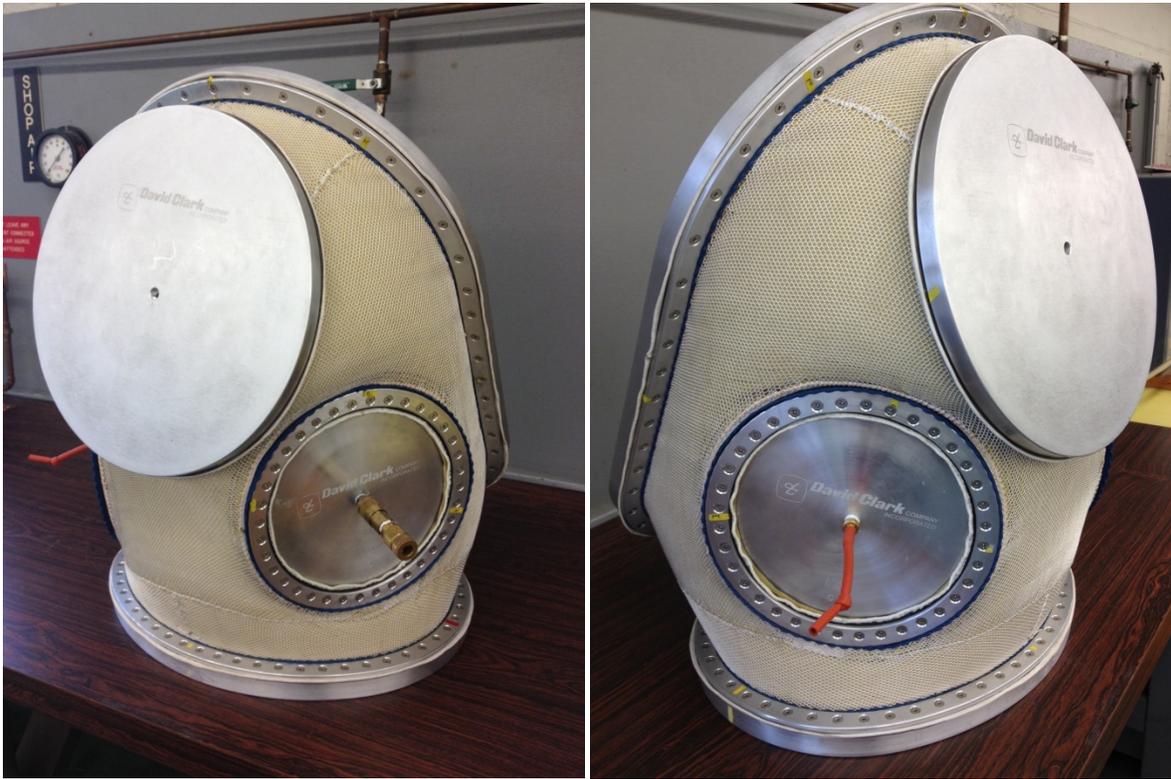
## VI. Mockups

For prototyping purposes, a link-net mockup of a Soft Upper Torso was fabricated. Link-net is a unique “netting” material created and manufactured exclusively by DCCI. Link-net has been used in numerous high-altitude pressure suits and space suits as a restraint layer, as it is designed to provide mobility when the coverall is pressurized, while at the same time maximizing comfort when the suit is unpressurized. This functionality is made possible through a unique construction and the use of advanced materials. This construction allows the Link-net panels to “self stow” when compressed, thus preventing the “diving in” typical of other traditional woven restraint fabrics.

In this application, there is no need for unpressurized comfort, as an EVA suit is not worn unpressurized (other than during donning/doffing). Link-net though may provide advantages in the MUT architecture, due to its aforementioned ability to self stow. When the MUT is reconfigured and resized to smaller dimensions than the restraint is designed, ideally the restraint material will stow underneath the resizable linkages, and will not buckle, dive in, or create hot spots. Using link-net as the restraint may prove to be extremely advantageous to the MUT concept.

The patterns for the DCCI SUT-1X were optimized for link-net construction. The patterns were divided into multiple link-net patterns, focusing on orienting the link-net such that it can compress and self stow in the proper orientations so as to allow resizing. The patterns were designed through a combination of traditional pattern design techniques, as well as analytical tools developed in Mathematica. Several link-net mockups were fabricated.

Additionally, loop-tape was integrated along all of the clamping rings. This enabled relatively low-cost and simple integration of resizing linkages, without having to manufacture expensive brackets that mount to the hardware itself. Photos of the mockup are shown below. Note the orientation of the link-net in the different areas of the torso, allowing the link-net to stow and the torso to resize.



**Figure 16. Link-net MUT Mockup**

Multiple linkages of various sizes were fabricated that can be laced into the loop-tape, to experiment with multiple reconfigurations of the torso in a simple, repeatable way. These linkages have to be unlaced and relaced for each reconfiguration, so they are clearly not representative of the linkage design that includes quick and simple adjustment, but they do provide a simple means to experiment with the link-net mockup, and evaluate in concert with the analytical model. Given the limited budget of this project, fabrication of hardware elements such as sizing brackets that mount directly into the hardware was not feasible.

Based on the results of the requirements definition and the analytical modeling, the linkages were integrated to the torso to demonstrate torso reconfiguration. Two example reconfigurations are shown below. In the first, it is demonstrated that the interscye distance can be reduced by  $\frac{1}{2}$ " , the scye angles have been adjusted by 5 degrees, and the waist height has been adjusted by  $\frac{1}{2}$ ". In the second, the interscye distance has been reduced by 1.5".



**Figure 17. MUT First Reconfiguration Demonstration**



**Figure 18. MUT Second Reconfiguration Demonstration**

It is clear from the mockup fabrication and experimentation that Link-net is ideal as the restraint layer for the MUT technology. Rather than bunching, folding, creating hot-spots and potentially creating accelerated wear locations, the Link-net nests underneath the linkages, restraining the gas container as needed. It enables large adjustments of the suit components and should enable much greater cycle life as compared to traditional woven fabric restraint materials. Link-net is suggested as the baseline restraint material for future efforts.

## **VII. Conclusions and Recommendations**

A Morphing Upper Torso would be beneficial for any future exploration mission and any future EVA suit. The ability to resize the torso will minimize the number of discrete sizes needed yet allow for some “customization” among individual wearers. The additional mobility provided by such a close fitting suit for all crewmembers will be extremely beneficial for exploration of the Moon, Mars, NEOs, or future ISS construction and maintenance tasks. Furthermore, the ability to resize the suit torso during long duration missions also provides a means to address body dimensional changes associate to long duration exposure to microgravity and thereby enhance the overall performance and efficiency of the suited crewmember. NASA will benefit by ultimately implementing this technology into future suit designs, and hence improving suit logistics, minimizing costs and maximizing crewmember productivity.

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