Engineering a Human Factors Analysis Of A Novel One Atmosphere Diving Suit (ADS) Elbow Joint

by

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Abstract

An Atmospheric Diving Suit (ADS) is a one person anthropomorphic submersible which is used to facilitate undersea work while keeping the diver/operator at atmospheric pressure thus removing them from the harmful physiological effects associated with diving at depths. Most ADS in use today have limited range of motion/mobility due to the combination of rotary joints utilized. The joint discussed in this thesis differs from rotary joints, widely in use today, in that it is a bellows type joint which allows sixty degrees of motion in plane. The engineering required to allow this joint to operate under pressure is to maintain a constant volume as it travels throughout its range of motion. If volume changes while subjected to pressure from the ocean the joint will seek the position with the smallest volume. Energy would be required to move the joint from the position associated with the smallest volume, making the joint a poor design which could fatigue the operator. This thesis will explain the engineering behind maintaining the volume through a range of motion.

Material selection of the joint membrane is a critical component. When designing the joint to maintain constant volume throughout its range of motion an assumption of a perfectly flexible and inelastic material is made. We discuss the ramifications associated with a membrane which is not perfectly inelastic.

This thesis continues the work that has been completed in conjunction with a Small Business Technology Transfer (STTR) contract funded by the Office of Naval Research (ONR) between the Massachusetts Institute of Technology and Midé. The elbow joint prototype, developed and manufactured by Midé, was tested in a rig, designed and built at MIT, consisting of a water tank with the joint completely submerged. Range of motion for 15 subjects was captured using image processing software and qualitative interviews were conducted to capture the experience for users with different anthropomorphic measurements. A human factors analysis was performed which proved that the joint operated as designed in a shallow water environment. A prototype ADS consisting of rotary and bellows joints is also proposed.

Thesis Supervisor: Alexandra H. Techet

Title: Associate Professor

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The completion of this research could not have been accomplished without the significant support of many contributors. The following organizations and individuals were instrumental in the success of this project:

- Midé Technology for their enormous generosity in providing a prototype joint and time with engineers to share their knowledge and experience. Specifically, thanks to Luke Saindon and Jared Keegan.
- Phoenix International and Tom Bissett.
- My wife and children who provide the best reasons to work hard along with the best ways to unwind when a break from research is required.

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List of Abbreviations

ADS	Atmospheric Dive Suit
ONR	Office of Naval Research
STTR	Small Business Technology Transfer
ROM	Range of Motion
URC	Undersea Rescue Command
MVL	Man Vehicle Laboratory

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Chapter 1 Introduction

1.1 Motivation

The ocean is an extremely challenging environment to work in and to date less than 5 percent of the ocean has been explored [1]. Humans are constantly pushing the technological envelope and this includes operating at extreme depths in the ocean. The Atmospheric Diving Suit (ADS) enables humans the mobility and (sometimes) functionality to explore and work at depths up to 600m [2]. Some examples of industries that operate in these environments are oil and gas, marine salvors, military, and scientists.

A common problem associated with ADS usage is restricted mobility. The structure that protects the diver from extreme pressures and the underwater environment also inhibits movement. Some of my colleagues who performed theses in this field, (Wilkins and Colgary) [3],[4], showed that a task that could be considered routine, bolting and unbolting a flange, is difficult in an ADS and the effort required varies with the operator. This thesis will examine a new joint design which could possibly improve ADS mobility.

ADS are a specialized, small, and expensive subset of the diving industry. The US Navy, until recently, used ADS at the Undersea Rescue Command (URC) whose primary responsibility is to rescue a submarine's crew in the instance a mishap occurs and the submarine cannot surface. The US Navy funded research into a "next-generation, lightweight ADS" sponsored by the Office of Naval Research (ONR) in partnership under a Small Business Technology Transfer (STTR) contract, N13A-T029. Midè Technology of Medford, MA and Massachusetts Institute of Technology (MIT) are working together on the design and evaluation of a new joint that could enable greater mobility and functionality in an ADS. Midè designed and constructed a joint prototype which was provided to MIT to facilitate conducting a human factors analysis.

1.2 Problem statement

Improving the functionality of ADS could enable improved efficiencies of underwater operations. In this thesis we investigated, designed, constructed, and performed a human factors analysis of the joint prototype constructed by Midè. We explained the science which enables this prototype to function. We analyzed the results of the human factors experiment and distributed data to all stakeholders involved in order to facilitate the advancement in the science of ADS. We analyzed the joint for operability within current ADS designs and determined which components in conjunction with the prototype joint provides the desired Range of Motion (ROM) and functionality. We analyzed material selection of various components of the prototype joint and discussed their impacts.

1.3 Thesis outline

This study is outlined as follows:

- Chapter 2 describes the history and state of practice of ADS along with an explanation of engineering required which enables this prototype joint to function.
- Chapter 3 describes the design and construction of the experiment.
- Chapter 4 analyzes and discusses the results of the experiment.
- Chapter 5 provides conclusions and follow on study recommendations.

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Chapter 2 Background

2.1 State of the practice of Atmospheric Dive Suits

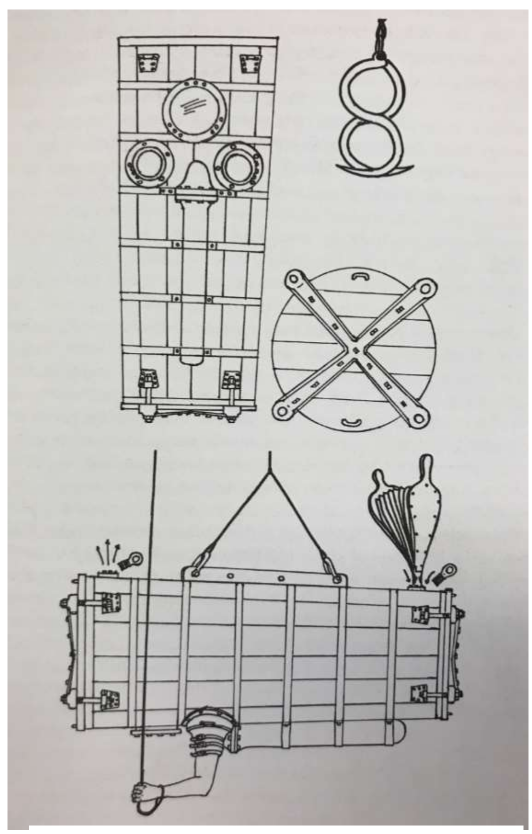

Figure 2-1 Mr. Lethbridge original Dive Engine

The first one atmospheric diving rig is usually given credit to John Lethbridge around 1715[5]. He called his invention a dive engine. It was constructed of tongue and groove boards in the shape of a barrel. It was strengthened with forged iron bars. Visibility was allowed by a glass porthole which aligned with the diver's head. The diver would enter the rig and stick his arms through oiled leather sleeves which would be sealed using buckle straps. The rig would then be sealed and the rig positioned and maneuvered by a crane. The diver would communicate with the crane by a rope, all of which can be seen in Figure 2-1. This rig allowed limited work to be done up to seventy feet. One wreck in particular that he is known for was the Slaterhoog, a

Dutch ship that went down in 60 feet of water with close to 3 tons of silver. Mr. Lethbridge recovered 90% of the silver over a nine year period.

Since Mr. Lethbridge's original diving rig many people have tried to improve on his invention, some of the more unsuccessful attempts are undoubtedly lying at the bottom of the ocean. Lethbridge's dive engine did not protect the operator's arms from temperature or pressure. Modern suits like the Exosuit® and Hardsuit®, are anthropomorphic one person submersibles which are designed to maintain the operator, arms included, at one atmosphere while allowing work to be accomplished. The most successful designs, to date, have used combinations of rotary joints to

Figure 2-2 Exosuit and Oceanworks 1200 demonstrate the use of rotary joints

facilitate motion. Rotary joints connect the segments of an ADS together and are usually constructed of aluminum alloy. Figure 2-2 shows the Exosuit and Oceanworks 1200, two examples of the leading suits in the industry, and their use of rotary joints.

ADS are employed predominantly by the oil and gas industry but have been employed in various sectors of underwater work. ADS is one tool that can be utilized to work in this environment.

Divers have the advantage of greater mobility and functionality at the work site but have the disadvantages of long decompression times and exposure to temperature. Remote Operated Vehicles (ROVs) have the advantage of removing the risk of placing a human in dangerous situations but might not offer the dexterity and situational awareness that a human on scene can offer. ROVs, divers, and ADS all have their uses and a detailed analysis usually occurs prior to deciding which method is suited to the task at hand.

The US Navy and commercial industries have been interested in a lighter weight ADS that is capable of "swimming". The Navy's design requirement is the suit must be less than 400 lbs, since at this weight a diver will be able to self-propel using his legs and fins. This Low-Weight ADS (LW-ADS) will allow a larger variety of launch craft (small boats) and enable the system's use in a broader mission capability. Midé in partnership with MIT's Man-Vehicle Lab endeavored to create a next generation ADS to solve these challenges.

2.2 Work completed to date on STTR

A Small Business Technology Transfer (STTR) contract funded by the Office of Naval Research (ONR) between the Massachusetts Institute of Technology and Midé, Topic N13A-T029, Contract # N00014-14-C-0291, was awarded August 22, 2014. Since that time a large volume of research has been accomplished in regards to developing a LW-ADS.

While researching space suits at MIT's Man Vehicle Laboratory (MVL) a technique to analyze joint Lines of Non Extension (LoNE) was developed. The Digital Image Correlation (DIC) method was used to analyze both elbow and shoulder joints and studied the variability between people of different sizes. The fundamental reason behind this research was to facilitate designing joints in a space suit. While space suits need to apply pressure to the humans inside them to maintain earth's one atmosphere, ADS have the opposite requirement of keeping the crushing pressures of the ocean at bay. The ideas and concepts generated by MVL and the LoNE translate to ADS joint design. Determining where the LoNE for elbows, knees, and shoulders are will allow better designs in the future. Figure 2-3 illustrates the method used to map the body during movements and the associated lines of non-extension that accompanies them.

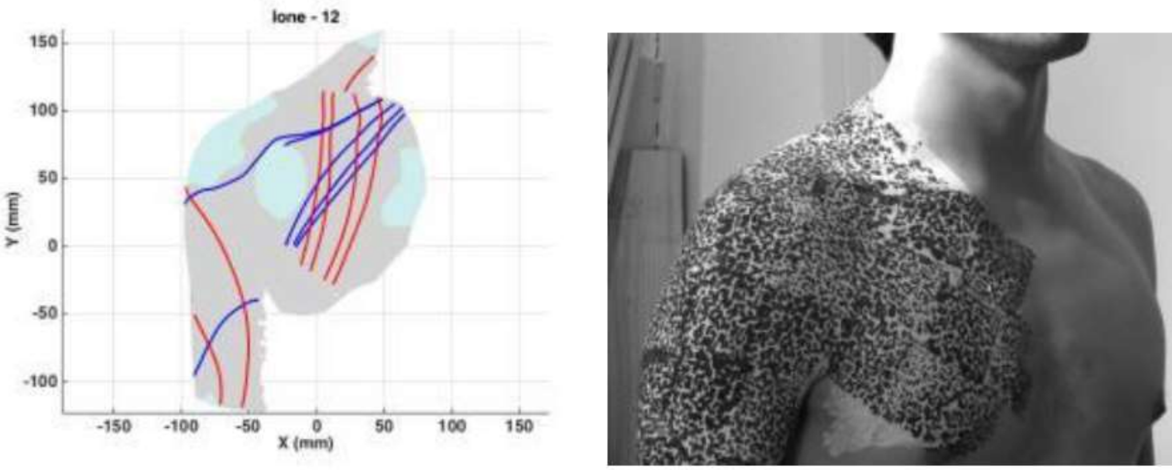

Figure 2-3 Lines of Non-Extension originally used for spacesuit design but carries over to ADS

Midé designed and constructed a prototype bellows joint that is designed to maintain constant volume throughout its range of motion. Midé performed tests of the joint underwater in simulated pressures up to 450 psi. They conducted material analysis along with finite element analysis. Midé's joint is proprietary and has patents pending so pictures nor detailed discussion of the inner workings of the joint will occur in this thesis.

2.3 Membrane Joint Modeling

Midé's design relies on the assumption that the volume in the joint will remain constant throughout it's ROM. It's important to understand the engineering and geometry required to make this happen along with what the potential forces an ADS operator might need to overcome at certain depths if the volume does not stay constant.

To analyze and solve these questions we need to assume some material properties and dimensions. The first assumption is that the membrane will be made of a perfectly flexible but inelastic material.

Figure 2-4 Prototype elbow joint provided by Midé including PVC hardware required for mounting and to sealing

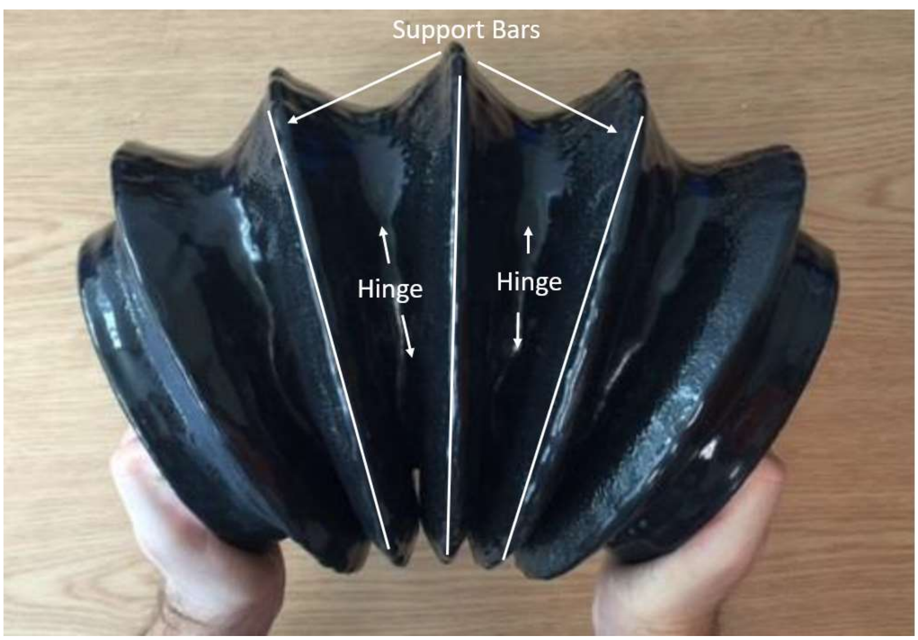

Figure 2-5 Functional depiction of joint shown in flexed position. Support bars are circular frames placed underneath membrane connected by internal hinges

To determine a method of maintaining constant volume in the joint we analyzed the problem in two dimensions. To better understand how the joint operates refer to Figures 2-4 and 2-5 which show the joint in a flexed and neutral position along with the supporting hardware required to for mounting to the tank. The internal workings of the joint have been intentionally not shown due to Midé's patents pending. Support bars provide the foundation for the membrane to rest on and the internal hinges, which can shift during joint movement, allow the support bars to move. We investigated the area formed by the polygon of two bars, the bottom one fixed and the top one which rotates through fifteen degrees. The graphics were generated from Matlab and the scripts are included as Appendix A. Figure 2-6 displays the dimensions of our two dimensional example as two bars which are 10 long separated by 2 when the bars are parallel. We will assume unitless properties for the description moving forward of maintaining constant volume throughout the joint's movement.

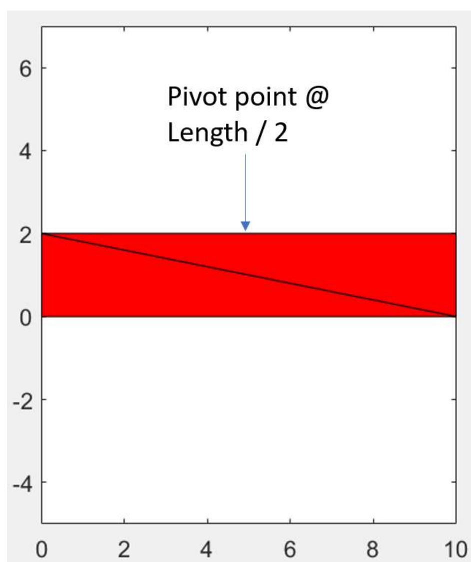

Figure 2-6 Demonstrates initial setup of determining the area between the two bars, the bottom one being fixed and top one allowed to rotate at its fixed pivot point

Figure 2-7 depicts the polygon and area enclosed as the top bar rotates through fifteen degrees. For this example the pivot point is maintained at the midpoint of the top bar. In this example the area of polygon decreases with the angle of deflection.

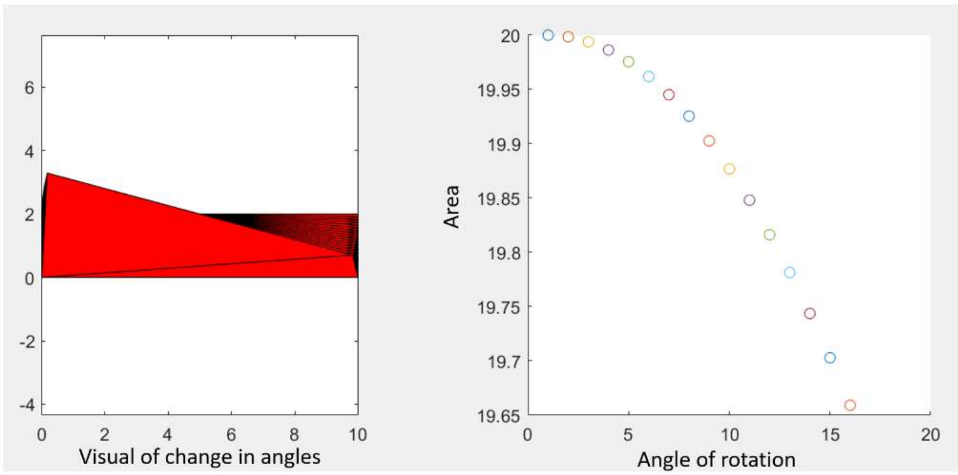

Figure 2-7 The left figure depicts the polygon as the top bar rotates through 15 degrees while the pivot point maintains a fixed position, the right figure depicts the area of the polygon as a function of the angle the top bar makes with the horizontal horizon

A script using Matlab's solver function was written to determine the direction and magnitude the pivot point would change to maintain the same area throughout fifteen degrees of rotation. Figure 2-8 shows the pivot point moves linearly to the left to maintain a constant area.

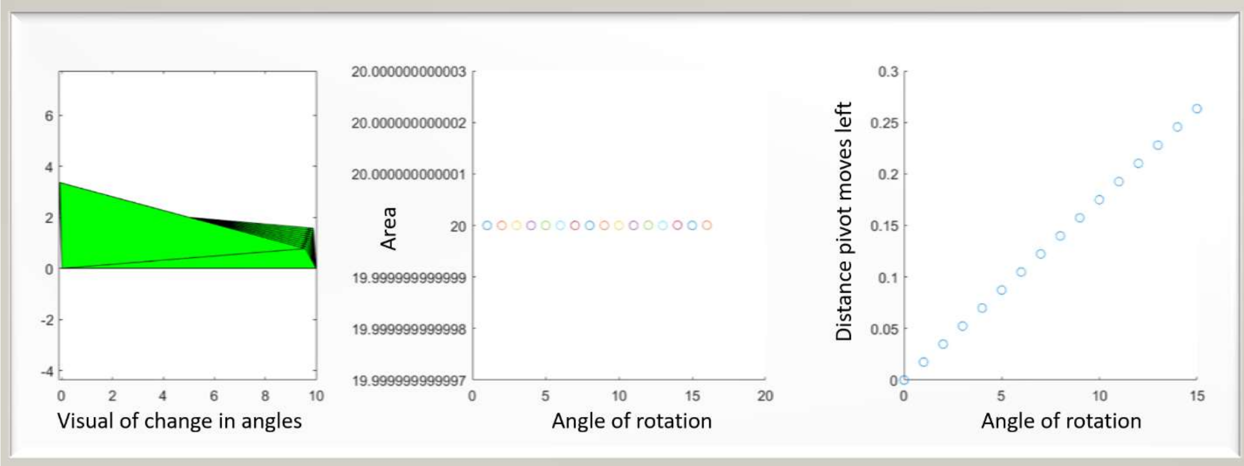

Figure 2-8 Left image shows the polygon as it rotates through 15 degrees, it's apparent that the pivot point shifts to the left as it rotates by viewing the top bar shift to the left. The center image shows the area being maintained at 20 while the top bar rotates and the right image shows the distance the pivot point moves left as a function of the top bar rotating. Notice the linearity.

My intuition, which turned out to be incorrect, was to initially model the membrane as a catenary. The problem with the catenary assumption is that gravity is the dominant force acting on the membrane and it's uniform in its direction. Figure 2-9 depicts this initial assumption. Gravity will not be the dominant force the membrane experiences, the dominant force will be the pressure exerted from the ocean. The membrane will be subjected to pressure which will be normal to the surface, thus making the catenary assumption invalid. Instead the membrane will be modeled, Figure 2-10, as a circular arc between the support ribs with sections of the membrane that are "laying down" on the ribs. This "lay down" portion needs to be considered when modeling the membrane.

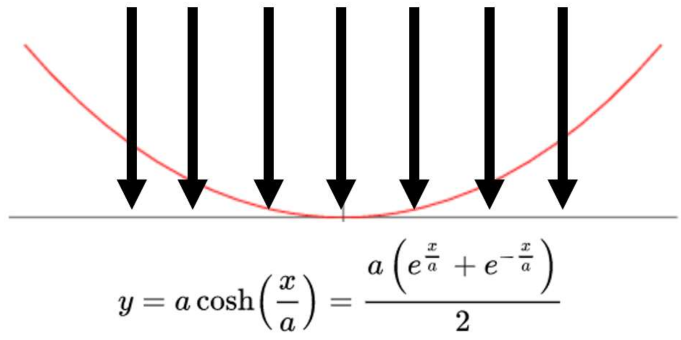

Figure 2-9 Initial assumption that the membrane should be modeled as a catenary, the uniform lines of gravity do not apply to the membrane underwater

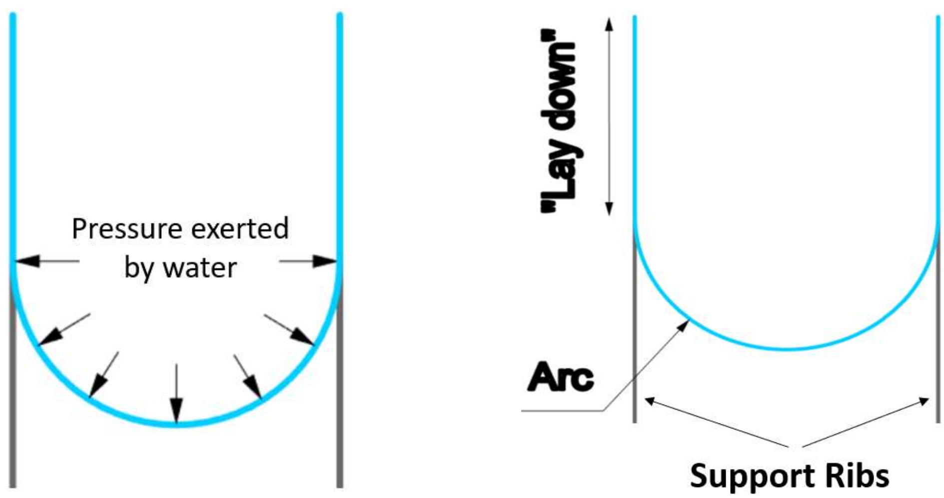

Figure 2-10 The left image shows the dominant force exerted on the membrane will be pressure from the water which will be exerted normal to the surface. The image on the right displays the assumption to model the membrane as a circular arc between the support ribs and the "lay down" which needs to be considered when modeling the membrane

To correctly model the membrane joint took me through a review in geometry. Using Pythagorean theorem, Figure 2-11, we were able to determine the arc size and position where "lay down" would occur.

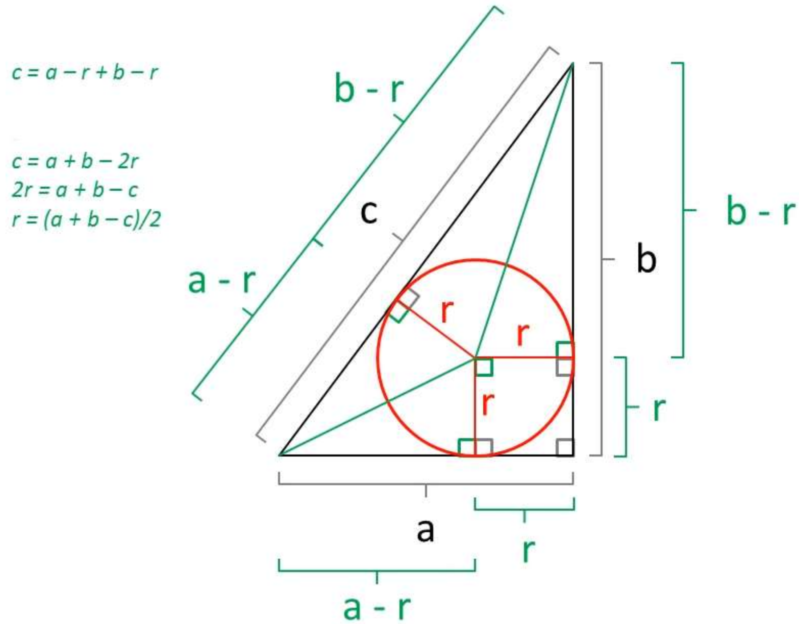

Figure 2-11 Pythagorean Theorem was used to determine the arc size, which correlates to the largest circle inscribed in a triangle, along with position and magnitude of "lay down"

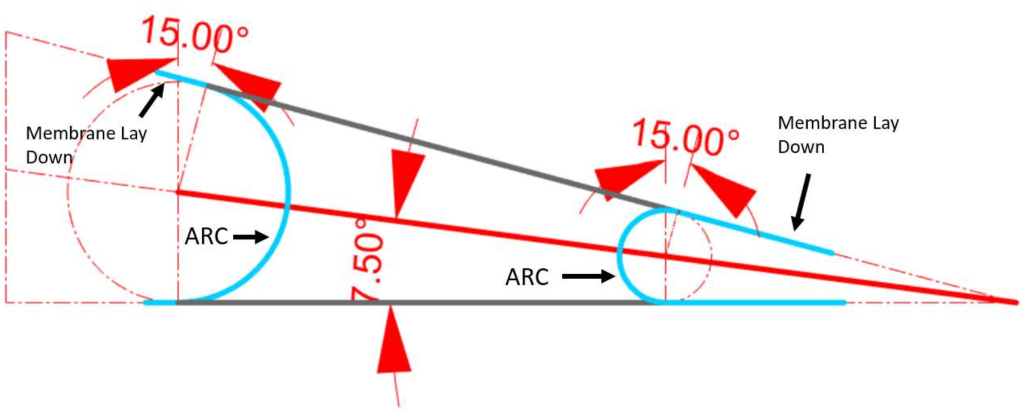

Figure 2-12 Set up illustrating geometric relations used to determine where the arcs start and end points will be located

To determine an initial value for the membrane length the joint was analyzed at a fifteen degree bend. A length is required that is long enough to allow the membrane to move throughout its full

ROM and not be "stretched" in tension. Stretching the membrane would lengthen it and invalidate our calculations and not be in line with our assumption that the material is perfectly inelastic. The large arc and applicable "lay down" was investigated for this initial value which are depicted in Figure 2-12. An initial membrane length of 5.3 was determined as a starting point by inspection.

The next step was to determine the area enclosed by the membrane and support ribs and keep it constant throughout the ROM. The final step was to validate that the initial membrane length was feasible. A Matlab script, using the solver function, was used to determine the appropriate shift of the pivot point to accomplish this. We utilized two different methods to check the area of the enclosed section.

1. **Polygon Method**

The polygon method utilized the polygon function which is built into Matlab. It calculates the area of a polygon.

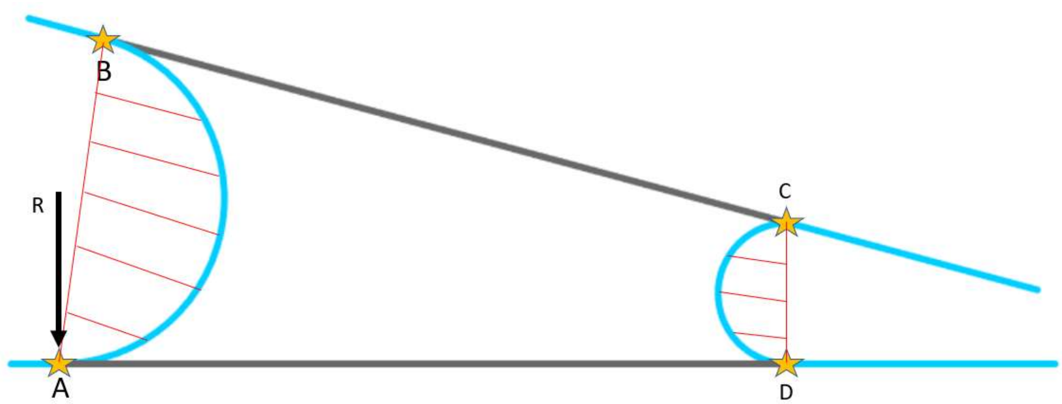

Figure 2-13 Polygon method used "Polygon" function in Matlab which calculates area bounded by polygon ABCD. The area of arcs AB and CD are then subtracted

Figure 2-13 depicts how the polygon would be defined in Matlab with points ABCD. After the area for the polygon is determined the areas for the circular arcs AB and CD are removed to provide the area encompassed by the membrane. The area of the arcs are calculated by:

$$Area = R^2 * \pi * \frac{180 - n}{360}$$

2. **Integration Method**

The integration method was used to verify the polygon method. It consisted of a two step process.

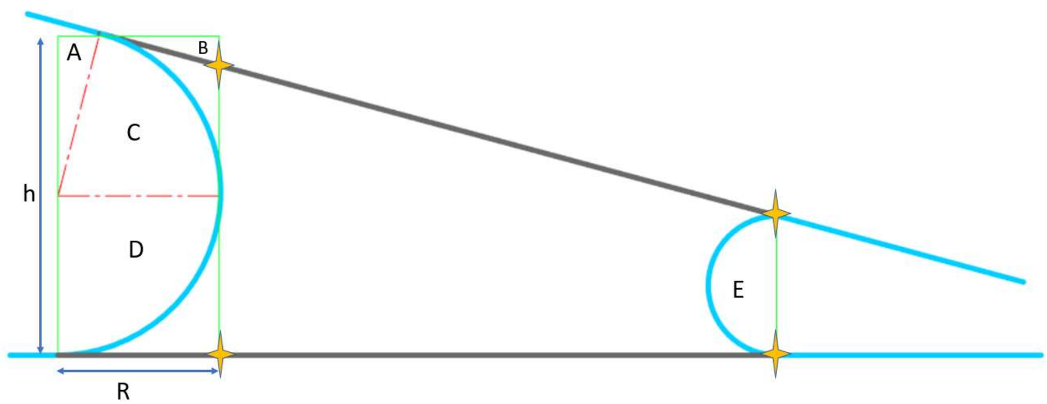

*Figure 2-14 Integration method uses a two step process. First step generates area on left side by R*h then subtracts areas A,B,C, and D. Second step generates area bounded by four gold stars then subtracts area of arc E*

The first step of the integration method dealt with the left hand side of Figure 2-14. The area of h*R was generated and then the areas A,B,C,D were removed. The second step of the method was to generate the area of the polygon shown by the gold stars in Figure 2-14 and then remove the arc area E.

The area of the unbent joint when the two bars are parallel and the assumed membrane length is 12.5416 as depicted in Figure 2-15.

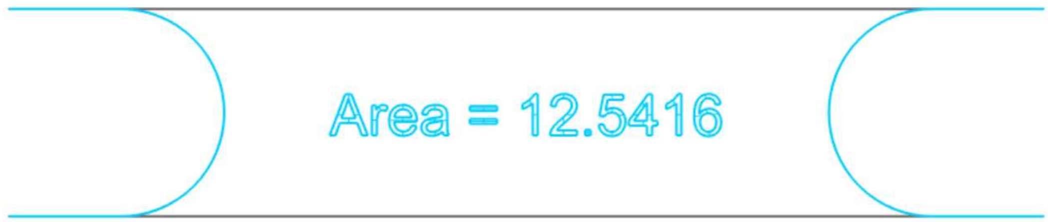

Figure 2-15 Area of unbent joint with assumed membrane length of 5.3

To maintain 12.5416 area through the joint's fifteen degree ROM requires a shift in the pivot point of 0.036 per degree to the right. Figure 2-16 shows the joint at 5, 10, and 15 degrees along with the graph showing the area being maintained constant. It can be observed that the pivot point shifts to the right by observing the top bar moving to the right. This is opposite to the direction the top bar moved when maintaining the area of a polygon without the membrane demonstrated earlier and shown in Figure 2-8.

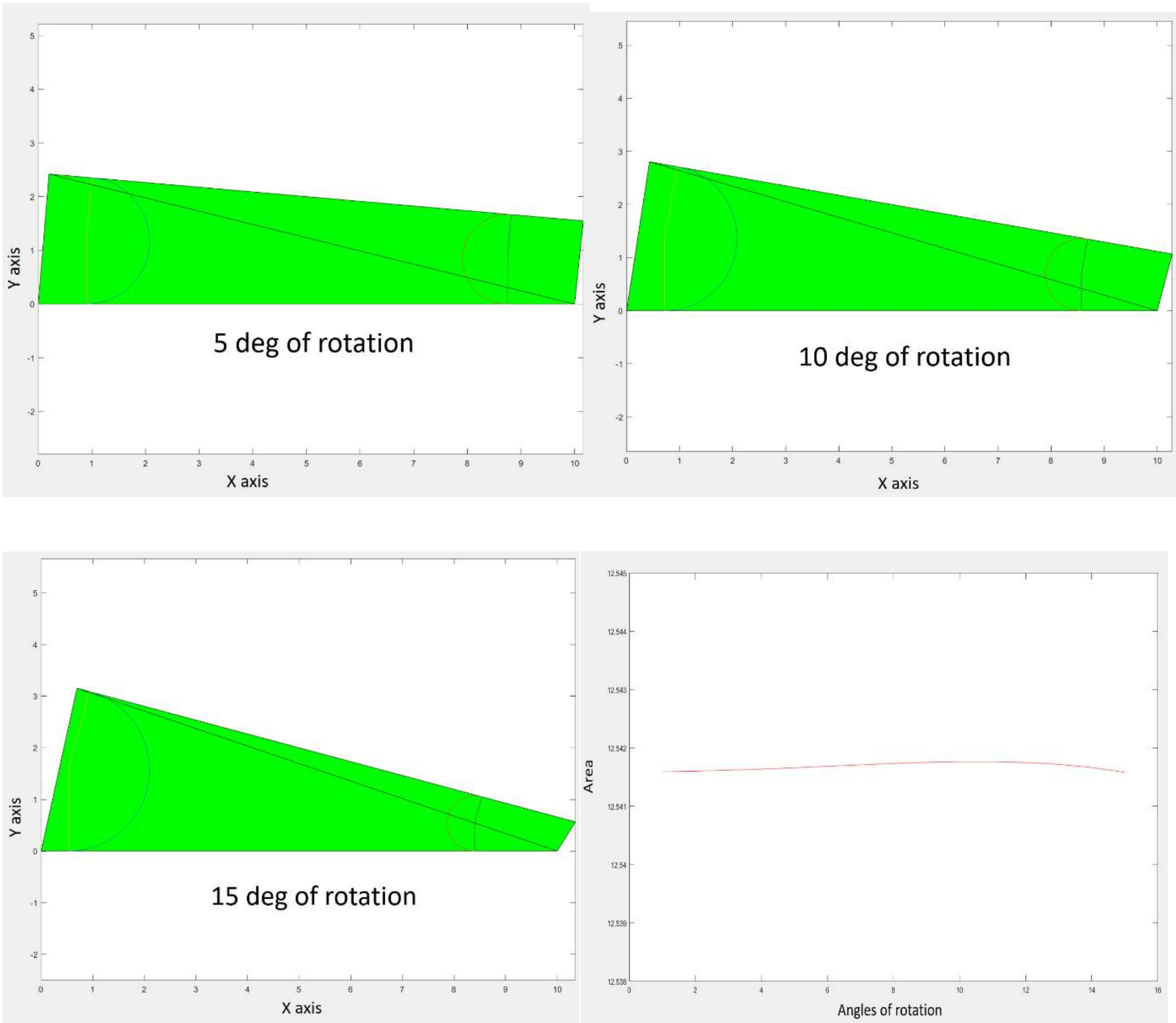

Figure 2-16 Joint at 5, 10, and 15 degrees. The pivot point shifts to the right to maintain the area throughout its ROM

We have demonstrated that it's theoretically possibly to maintain a constant area through the joints ROM of fifteen degrees. This principle could be applied to four joints that would be combined in series for a total of sixty degrees ROM.

Chapter 3 Experimental Design and Methodology Used for Human Factors Analysis

3.1 Overview

This chapter discusses the design and experiment associated with conducting a human factors analysis on Midé's prototype joint. Midé carried out extensive testing on their prototype. All of their testing either involved the prototype being acted upon from the outside by an external force or a mechanical device placed inside the joint which was designed to mimic a human arm. Capturing results from human subjects is important to ensure that all human factor issues are documented.

Testing consisted of taking anthropomorphic measurements of subjects followed by the subjects proceeding through an experiment in which they inserted their arm into the test rig and moved their arm through their ROM. Their ROM was captured with a camera and image processing software was utilized to determine what the ROM experienced by the subject was. Once all data was collected it was analyzed to see if any trends existed.

3.2 Set up and design

The prototype joint requires a pressure differential to engage the bearings. To apply external pressure to the joint two options were available. The first being to construct a pressure vessel capable of applying an appropriate external pressure to engage the bearings and the second was placing the joint in a water tank which will apply pressure related to the height of water. The water tank, being the most cost effective, was chosen as the appropriate vessel. A large 757 liter plastic tank was chosen.

Figure 3-1 757 liter water tank

The tank is constructed of polyethylene and weighs 34.5 kg. Density of fresh water is 1.025 kg/Liter. Seven hundred fifty-seven liters of water in addition to the tank brings the weight of the full tank to 810 kg.

$$1.025\frac{kg}{liter} * 757\ liter + 34.5\ kg \approx 810\ kg$$

Equation 1

The tank was placed in the former propeller testing tank at MIT which has appropriate drains and water sources. The tank was placed upon a stand to allow the subjects to insert their arm while standing in a natural/comfortable position. Unistrut, P1000, 1 5/8" steel framing was chosen to support the tank. The tank is constructed in such a way that the load is distributed through built in footpads positioned approximately at each corner which is shown in Figure 3-2. The stand was designed so the columns were positioned underneath the footpads, this allowed us to ensure appropriate column loading safety factors are met and the beam loading will be insignificant. A safety factor of six was achieved for the stand holding the water tank. The material properties of the Unistrut materials are included in Appendix B.

Length of legs = 1016 mm	Force of water and tank = 7.95 kN
Max allowable load for column = 13.6 kN	Each leg supports = 2 kN

Figure 3-2 Stand constructed so that columns are placed below footpads which reduces beam loading and allows a safety factor of 6 to be achieved for column buckling

The prototype joint that was supplied by Midé was outfitted with a PVC flange to allow attachment to the water tank. Initial inspection of this set up led us to believe that the circumference of the PVC pipe would be too small for a large portion of test subjects, including myself, because my arm wouldn't fit inside of it. The flange would also not allow the elbow to be positioned in the center of the joint and we were concerned that this could affect the experiment. The images below show the original flange and how the flange wouldn't allow the elbow to be positioned in the middle of the joint.

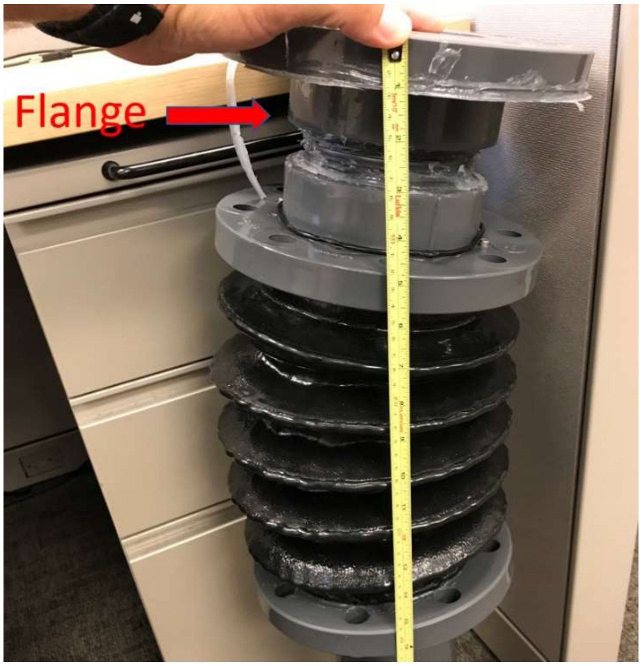

Figure 3-3 Prototype joint provided included a flange which would facilitate mounting of joint to the test tank. Image on the right shows that the subject's elbow would not be positioned in middle of joint during experiment and modification of the flange is necessary

The circumference of the smallest section of the flange was 29.9 cm which would statistically pose a challenge since the mean bicep flexed circumference is 33.1 cm[6] and it would be reasonable to assume that some sort of flexion would be required to move the elbow joint.

	Mean	5 %	95 %
Bicep circumference relaxed (cm)	30.8	27.2	35
Bicep circumference flexed (cm)	33.1	29.4	36.9
Elbow circumference (cm)	27.8	25.6	30.2

Table 1 Anthropomorphic Data

To allow a statistically significant pool of subjects to participate in the study and to ensure that the elbow would be positioned in the middle of the joint, alterations to the PVC flange were investigated and ultimately it was decided to modify the flange by cutting away the inner portion of the PVC ring which is positioned on the outside of the tank. A final entry size circumference of 34.6 cm was achieved with this modification allowing 95% of the population to be eligible to participate in this experiment. A watertight seal was accomplished with the use of gaskets and sealant. This modification caused the joint to be mounted at approximately twenty degrees from horizontal which had to be accounted for later during image processing.

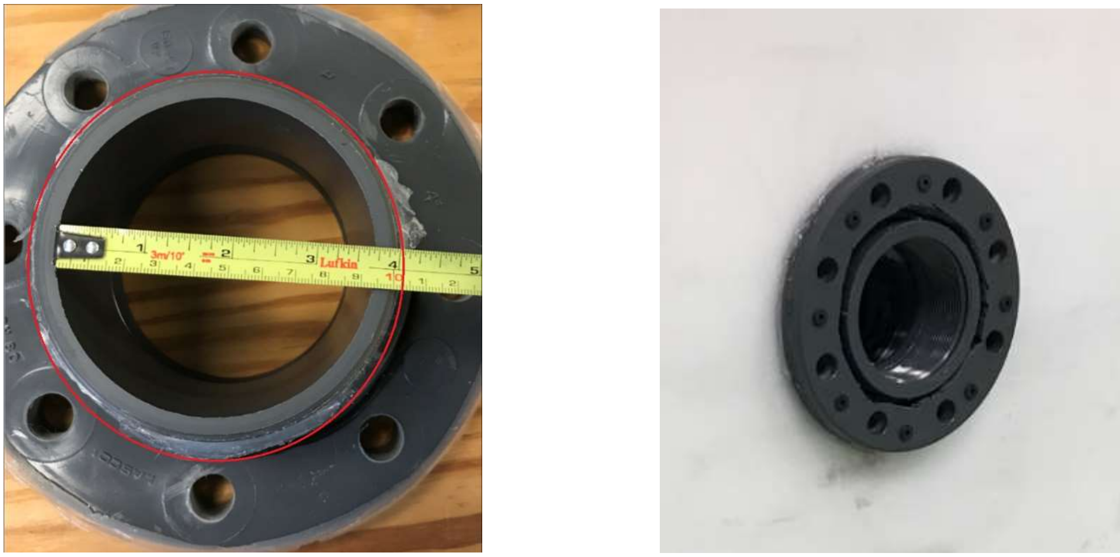

Figure 3-4 The red circle on the left image displays the material that was removed to allow subjects with average measurements to participate in the experiment. Image on the right portrays the flange mounted onto the test tank.

Video recordings of the experiment were taken with a GoPro HERO 2 positioned in the tank above the elbow joint. Figure 3-5 shows how the GoPro is mounted 33 cm above the elbow joint and positioned in the middle.

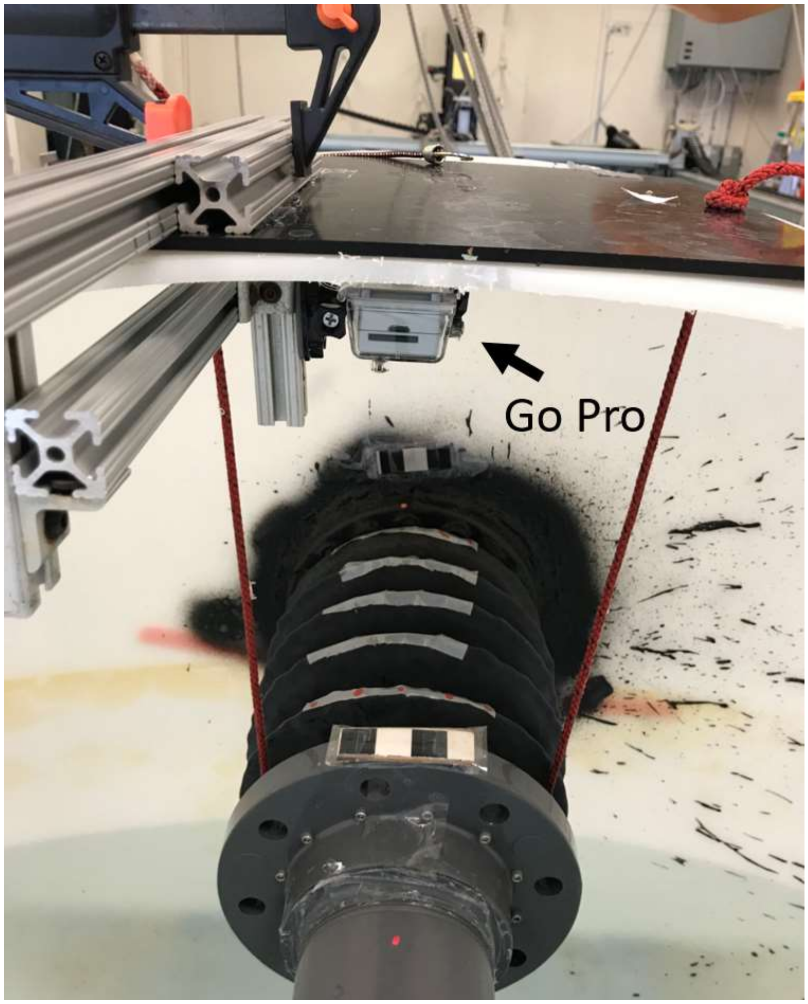

Figure 3-5 GoPro mounted 33 cm above and positioned in the middle of joint

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Chapter 4 Results and Discussion

4.1 Human factors analysis

Experiments that are conducted where humans are involved are required to gain approval from the Committee of the Use of Humans as Experimental Subjects (COUHES). Federal mandate ("The Common Rule," 45 CFR pt. 46) and longstanding MIT policy require that the COUHES review and approve ALL research involving human subjects that is performed under the auspices of MIT. The COUHES requires the personnel who will be administering the experiments to undergo specific training and the experiment procedures to be provided to them for review. The approved COUHES forms are included in Appendix C.

Test subjects were provided documentation outlining the experiment and what they should expect. It described the measurements that would be taken first. The measurements were: relaxed bicep circumference, elbow circumference, elbow to fingertip, and armpit to fingertip. The next part of the instructions explained the procedure. It consisted of inserting one arm and then bending it through the maximum ROM fifteen times, then switching arms and repeating fifteen times. After the first round movements are completed the subjects are interviewed and qualitative feedback is recorded. The procedure is then completed for a second time.

4.2 Pressure required to engage bearings

The prototype joint Midé provided requires pressure to be applied to engage its internal bearings. Without these bearings engaged the joint tends to bind and does not move smoothly. The required pressure to engage the bearings was unknown at the beginning of the experiment. It was determined by submerging the joint to the top and then in increments of 5 cm, stopping at each increment and attempting to maneuver. Movement was not smooth until 30 cm of water above the joint was inserted which applied 2.98 kPa (0.433 PSI).

4.3 Video Analysis

The experiments were recorded with a GoPro and the video data was uploaded to Tracker® video analysis software. Tracker® software tracks the reference dots painted on the joint. There are multiple settings and functions that can be chosen in Tracker® but we chose to record the maximum angle the dot moves in relation to a reference plane which we aligned longitudinally with the center of the joint. The images below depict this.

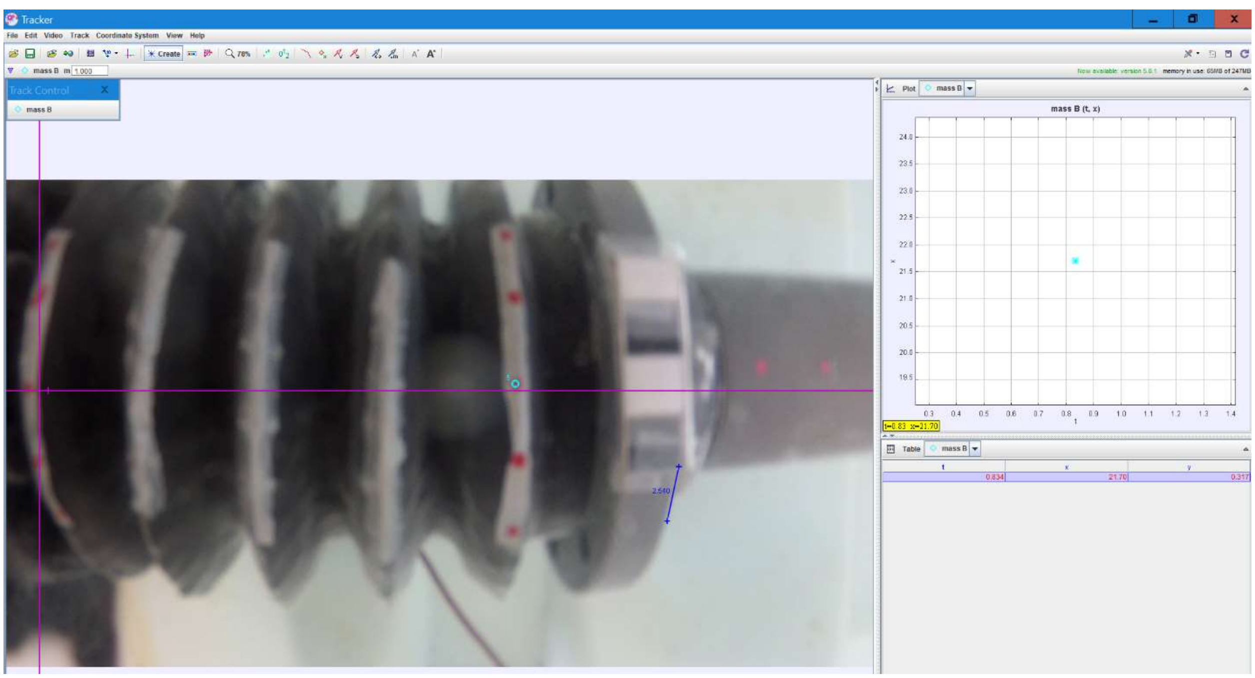


Figure 4-1 Tracker screenshot displaying initial condition and x-y axis. The blue dot will be tracked as it moves throughout its ROM

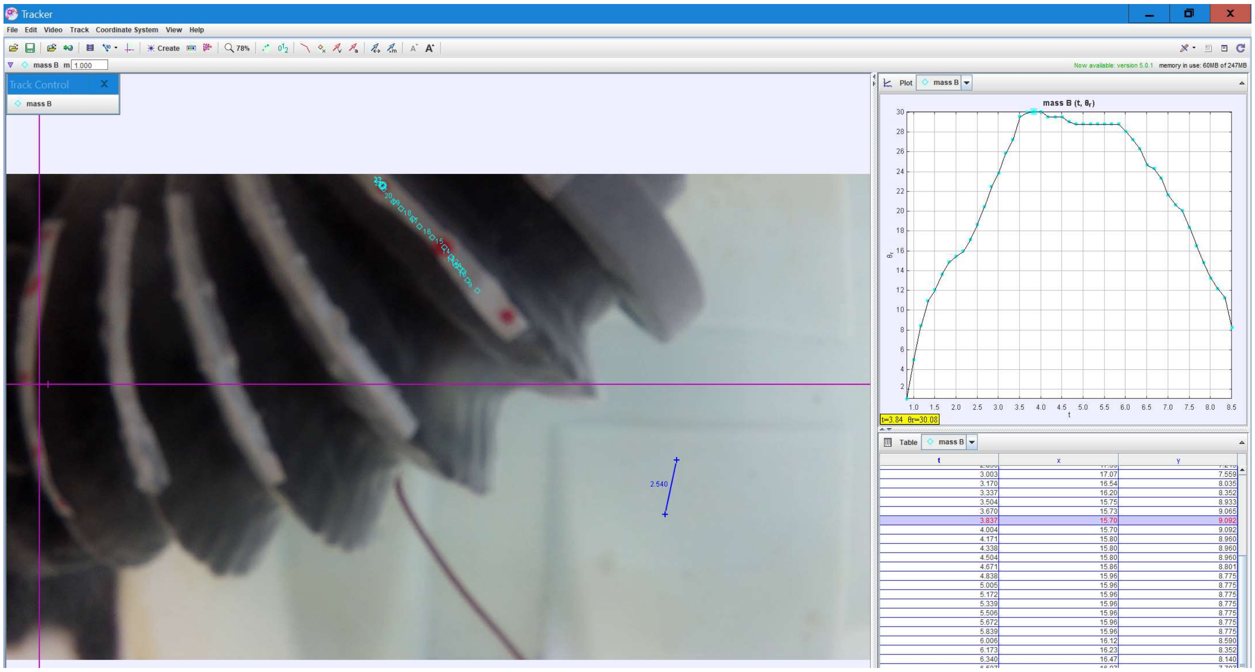


Figure 4-2 Tracker screenshot at max bend angle. The blue dots depict the tracking of the joint through its movements and the graph on the right shows angle measurements in relation to the origin

Once the maximum angle has been determined using Tracker®, a screenshot of the image is imported into RHINO where the angle between the reference plane, the portion of the joint mounted to the tank, and the end of the joint that moves freely is determined. They are displayed below as A (reference) and B (unconstrained).

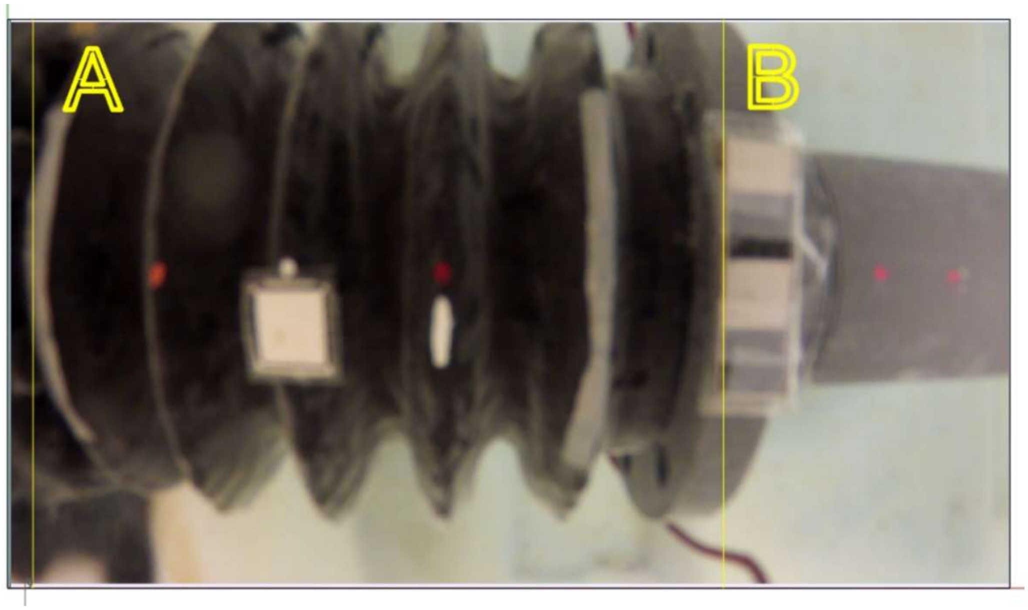


Figure 4-3 "A" is fixed reference plane while "B" is unconstrained and will be used to measure angle the joint traveled through

Using RHINO's angle measurement function to measure the angle between lines A and B gives the ultimate ROM of the joint. Figure 4-4 illustrates the measurement taken between the fixed and unconstrained planes.

Figure 4-4 RHINO screenshot displaying angle measured between reference and unconstrained plane

Calibration of the angle outputted by Rhino was necessary for two reasons. The first one being that the joint was mounted twenty degrees off horizontal. This is illustrated by the image below which shows an arm that is mounted twenty degrees off of the horizontal plane will appear to have moved fifty eight degrees in the horizontal plane after it is moved through its entire sixty degrees.

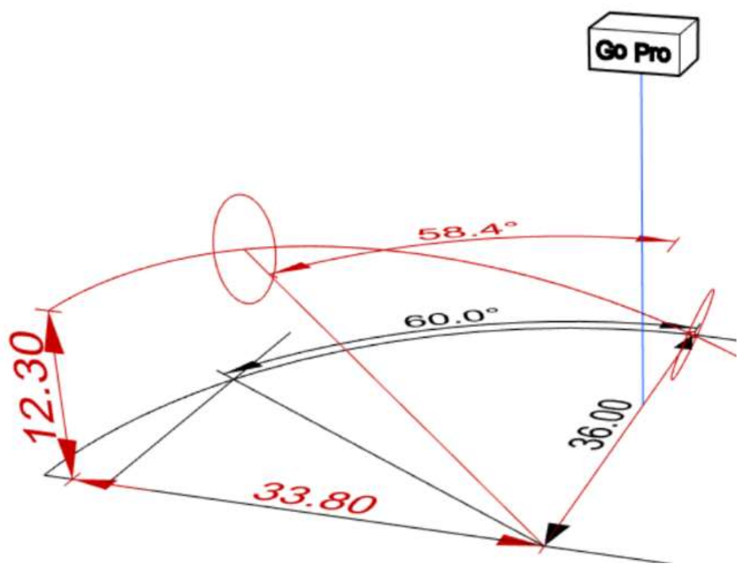


Figure 4-5 Due to the prototype joint being mounted 20 degrees off of the horizontal axis it is necessary to calibrate the measurement of the joint. When the joint moves 60 degrees it is viewed to have moved 58 degrees. The perception angle of the GoPro also contributes to a measurement of less than 58 degrees which requires calibration

The second being the perception angle the GoPro perceives since it's mounted 33 cm above the joint. The calibration was accomplished by constructing a two dimensional jig with the same dimensions as the prototype joint. This jig simulated all four convolutions of the joint at fifteen degree bends for a total sixty degree bend of the joint. The jig was installed in place of the joint and it was determined that a visual angular reading of fifty four degrees corresponded to the full flexion of sixty degrees. Using this calibration data a factor of (60/54) was applied to the Rhino results.

4.4 Analysis of Data

Fifteen subjects participated in the program. Fifteen subjects is not a large enough sample size to ensure statistically sound results and therefore a relatively high margin of error could occur. The anthropomorphic data for the fifteen subjects are listed in the table below.

Arm length, armpit to fingertip (cm)	armpit to elbow (cm)	bicep circumference (cm)	elbow circumference (cm)	armpit to entrance of rig (cm)
71.5	26	28	26	5
78	29	27	27	11
66	23	35	29.5	16
74	25.5	30	29.5	5.5
72	25	32	31	5
73.5	23	38	30.5	13.5
65	23.5	25.5	23	3
74	28	32	29.5	5
76	30	30	27	5
70	24	26	26	5
72	25	29	27	5
70	26	35	31	14
77	35	30	31	7
72	25	30	30	5
66	24	39	32	15

Table 2 Anthropomorphic data of subjects

The following table displays the ROM for each participant along with mean, standard deviation, and median data for each arm. Data is also presented with the removal of one outlier which fell outside of two standard deviations.

Right arm ROM (degrees)	Left arm ROM (degrees)
33	36
49	50
51	48
52	51
52	57
53	39
54	59
55	43
55	54
57	59
57	58
57	58
59	59
59	59

Outlier

Right average ROM	Right Std Dev	Right Median	Left ROM average	Left Std Dev	Left Median
53	6	55	52	8	55

Data with one outlier removed

Right ROM average	Right Std Dev	Right Median	Left ROM average	Left Std Dev	Left Median
55	3	55	53	6	57

Table 3 Average, median, and standard deviation of ROM for all test subjects. The data on the bottom displays the information with subject's whose data was more than 2 standard deviations outside of mean removed. One subject could not participate in experiment due to his arm not fitting in joint and his zero data was not used.

The data shows that the prototype arm comes very close to meeting its designed sixty degrees ROM. Some possible reasons for not reaching the sixty degree ROM goal is unfamiliarity with the equipment and the prototype joint dimensions being too small which will be discussed in the qualitative review section.

An initial hypothesis was that subjects who had their elbow positioned in the middle of the joint would be ideally positioned and have the greatest ROM. The data below suggests that there is not a link between elbow position and ROM.

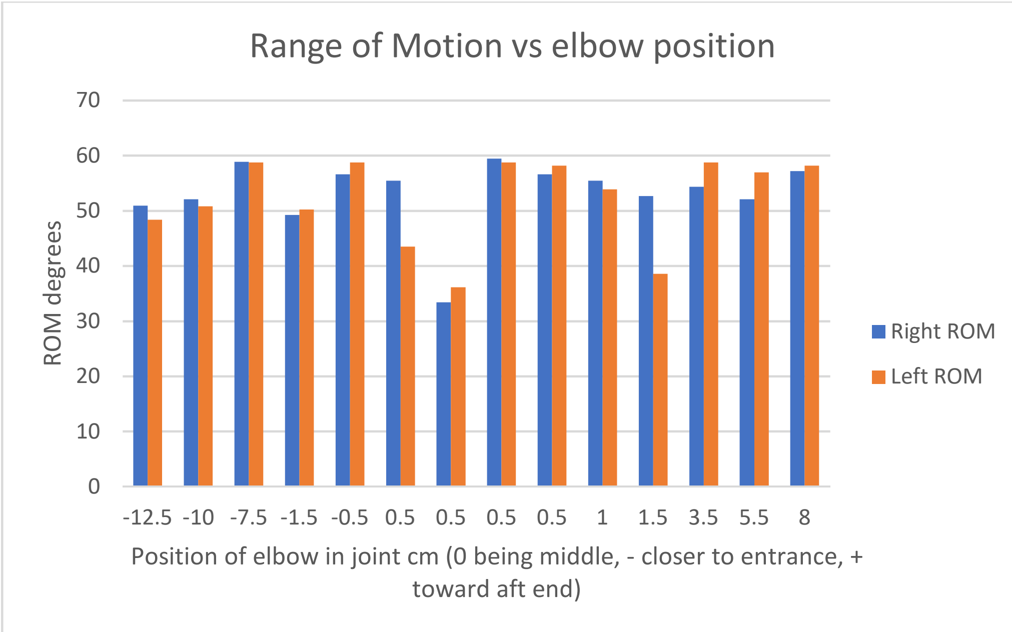


Figure 4-6 Range of motion vs elbow position. Initial hypothesis was that subjects whose elbow was positioned toward the middle of the joint would have greater ROM than those positioned toward the ends. Data invalidates this hypothesis.

Due to the dimensions of the prototype joint it was considered that subjects with larger biceps might be constrained as they maneuvered and flexed their bicep through the experiment. The data does not show any trends to suggest this however.

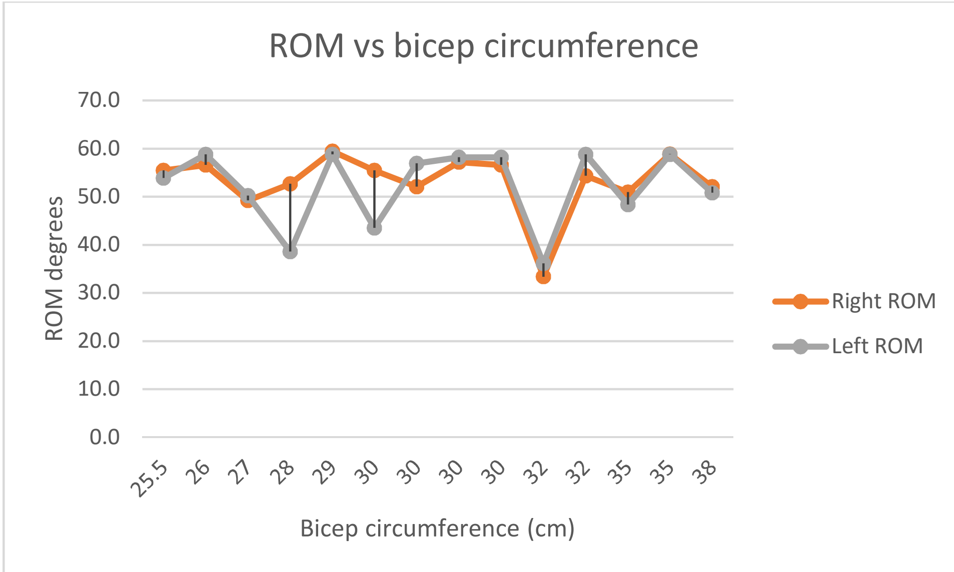


Figure 4-7 Due to the small size of flange entry it was hypothesized that personnel with larger biceps would realize a decreased ROM. The data suggests that there is no correlation however.

Data showing the relationship between arm length and ROM is displayed below. The data does not trend significantly in either direction.

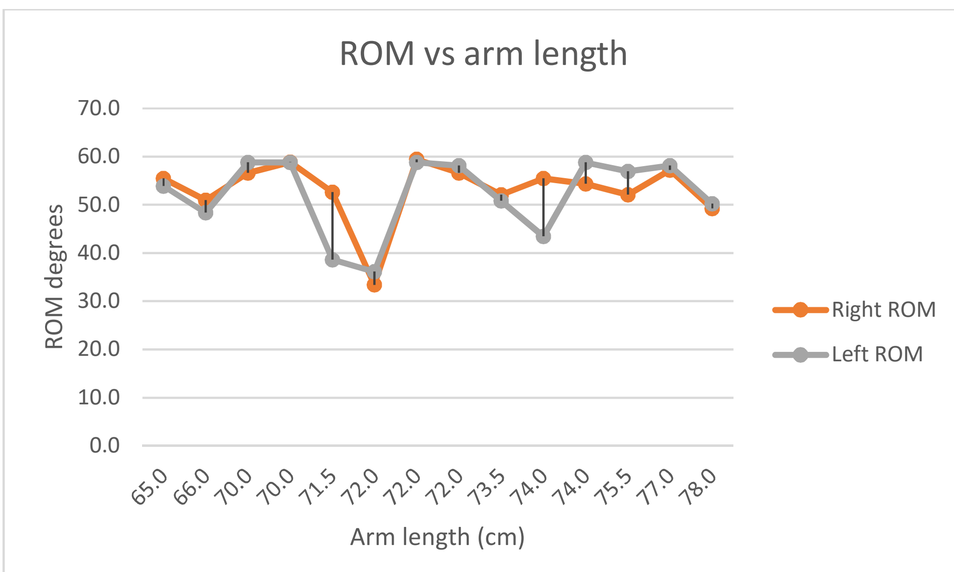


Figure 4-8 Range of motion vs arm length

During and after each round of experiments subjects were asked to describe the movement of the joint as either smooth or binding and comment on any incidents such as pinching, etc.. Six of the fifteen subjects reported their elbow or bicep being squeezed in the joint during flexion and that it was uncomfortable and probably not conducive for long periods of work. Two subjects reported hair being pinched in the joint. The outlier reported that his elbow was severely squeezed during the experiment and didn't allow full ROM. One subject with the largest bicep size, 39 cm, could not fit his arm inside of the joint. All of the participants dominant hand was their right. This correlates to the Right arm ROM being slightly higher than Left arm ROM.

4.5 Safety issues associated with elbow joint

The human elbow has a ROM of around 150 degrees[7]. Consider zero degrees to occur when the arm is fully extended and 150 degrees when flexed, bringing the wrist up near the bicep or shoulder illustrated in Figure 4-9.

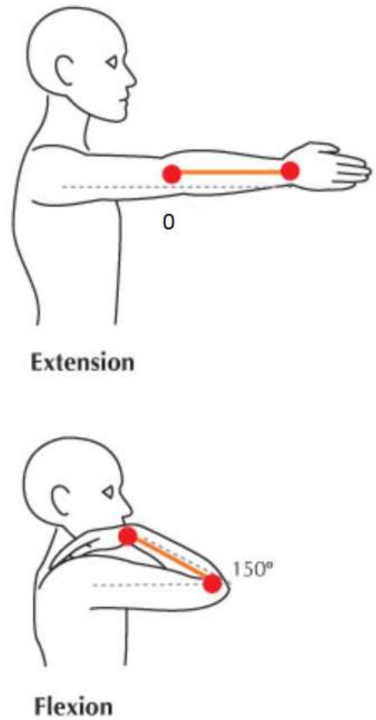


Figure 4-9 Typical range of motion of elbow is 150 degrees

What the elbow joint does not allow is reverse flexion. Because the prototype joint can move sixty degrees in either direction the user could be subjected to forces which could cause injury. An injury like this could occur in a variety of ways while working in hazardous underwater conditions. Another factor to consider is the water itself. A strong underwater current could possibly apply enough force to induce a moment which could cause injury as well. It is difficult to assign values to the "human machine" in regards to what its muscular limitations are. We will calculate the hydrodynamic forces required to overcome an ADS operator. There is a wide range of strength and flexibility attributed to humans which are factors of age, genetics, training, and intangibles (will power). We will assume that an average young male can support up to 80 N·m moment utilizing the elbow as the origin[8]. We will use the dimensions from existing ADS that are in use today. The distance from the elbow to the beginning of the grasper is 50.5 cm. The diameter of the joints vary in size from 30 cm to 20 cm. We will assume a cylindrical arm with a 25 cm diameter and then calculate the current required to induce 80 N·m on a joint with these dimensions.

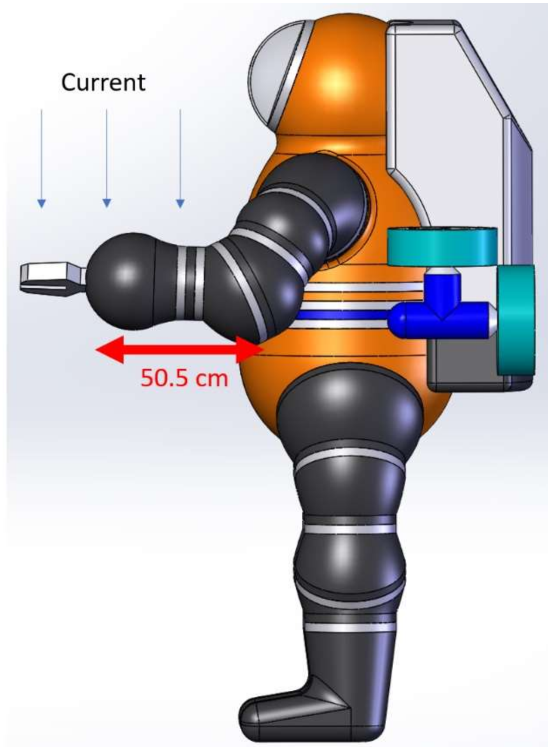


Figure 4-10 To calculate the hydrodynamic force applied by a current we assume a 50.5 cm length from elbow to beginning of grasper and a diameter of 25 cm. The current required to generate a force of 80N·m will be calculated as the force which could overcome an operator

$$F_D = \frac{1}{2}\rho U^2 \, C_D A$$

$$\rho = 1029 \; kg/m^3$$

$$C_D = 1$$

$$A = 0.505m * 0.25m = 0.126 \; m^2$$

$$F_D = {}^{80 \; N \cdot m}/_{0.505 \; m} = 158.4 \; N$$

$$U = \sqrt{\frac{2 \; F_D}{\rho \; C_D \; A}} = \; 1.56 \; \frac{m}{s} = 3 \; kt$$

Equation 2

A current of three knots could possibly cause injury to an operator in an ADS. One way to prevent this would be to design a mechanical stop which only allowed the sixty degree ROM in one direction.

4.6 Mechanical stop design

To prevent injury a mechanical stop design was explored. One possible solution is set of simple hard rubber strip that are attached to half of the support ribs which would allow flexion in only one direction. A SolidWorks drawing of the solution is below.

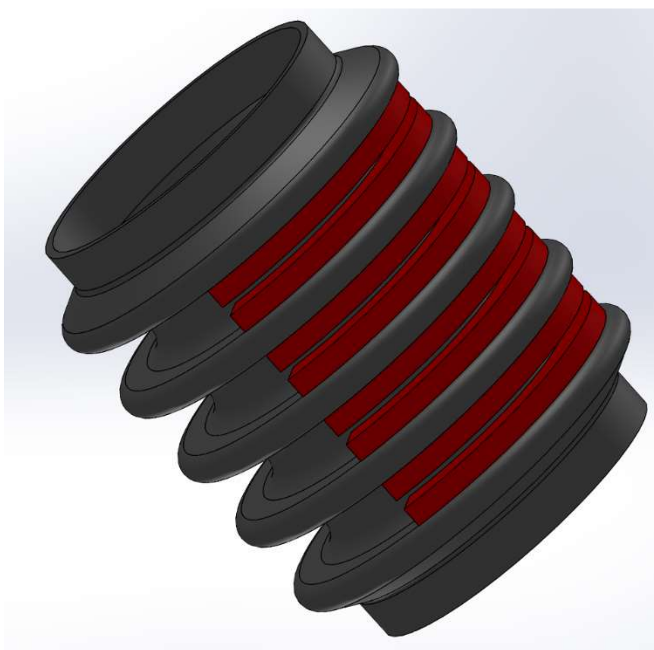


Figure 4-11 Mechanical stop design consisting of hard rubber strips which would allow flexion in only one direction protecting the operator from possible injury

4.7 Material selection

An assumption made early in the thesis was the joint membrane being perfectly inelastic and flexible. This was assumed when calculating the pivot point movement to maintain constant volume in the joint throughout its ROM. If a material is not perfectly inelastic than it will stretch when subjected to pressure at depths. At 330 m below the ocean the pressure on an ADS would be approximately 440 psi. If the membrane material stretched and lengthened at this pressure it would increase the length of the convolution and the volume would not be maintained.

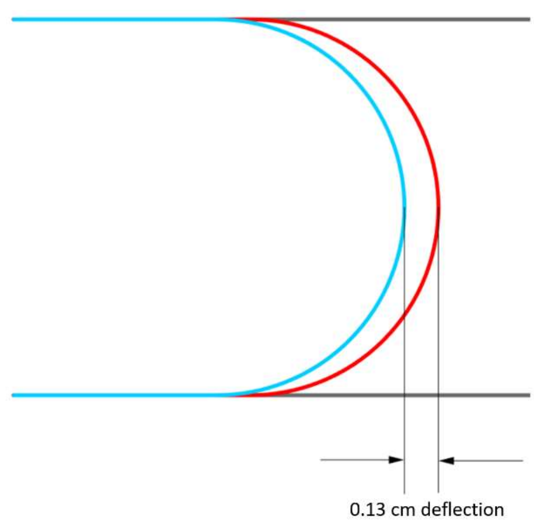


Figure 4-12 Membrane undergoing stretching due to 440 psi applied by ocean at a depth of 330m below sea level

This stretching of the membrane would cause the volume of the joint to decrease when traveling through its range of motion. This is because the joint was engineered to shift its pivot point a certain distance assuming a constant membrane length. This is illustrated with the image below which is a Matlab graphic representing the area of a joint segment which stretched 0.1 cm.

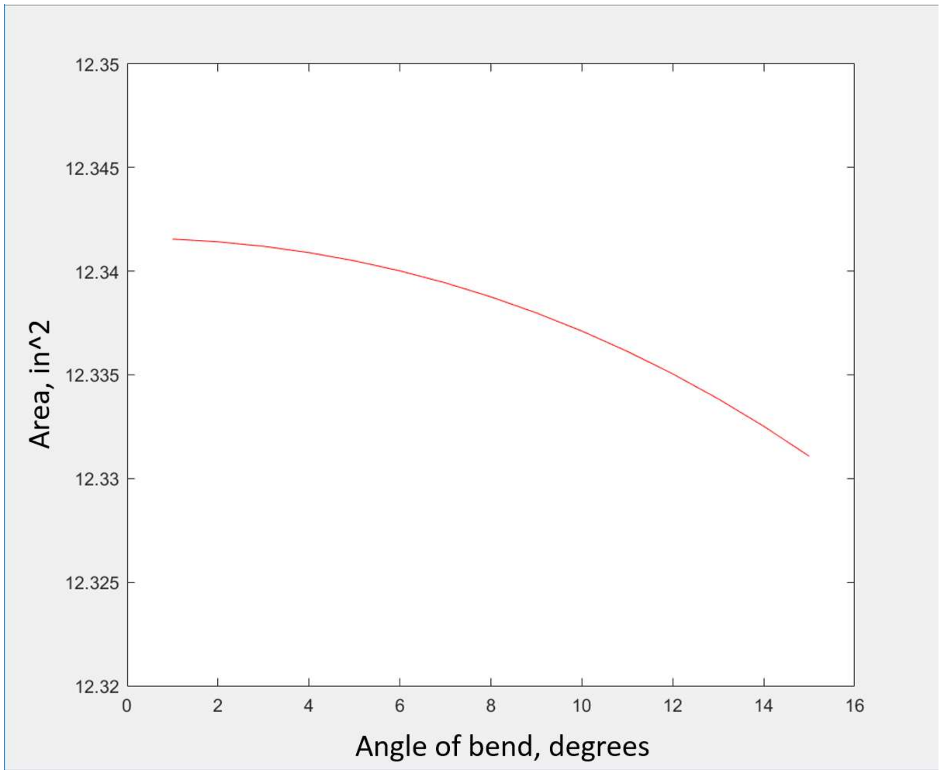


Figure 4-13 Area of joint would decrease if membrane stretched due to pressure applied by ocean. The joint would move to area of smallest volume and energy would be required to move the joint from that position making the joint difficult to use

A joint that decreases in volume as it bends would seek the smallest volume and move to that position. The following example demonstrates what the implications are if the membrane stretched by 0.25 cm and how much force would be required to move it back to the unbent position:

$$Volume\ of\ unbent\ joint\ with\ 13.5\ cm\ membrane\ length = 3228\ cm^3$$

$$Volume\ of\ bent\ joint\ with\ 13.7\ cm\ membrane\ length = 3177\ cm^3$$

$$Delta\ of\ volumes = 51\ cm^3\ or\ 5.1 * \ 10^{-5}\ m^3$$

$$440\ psi = 3.034 * 10^6\ Pa$$

$$3.034\ *\ 10^6\ Pa * 5.1 *\ 10^{-5}\ m^3 = 156\ N \cdot m$$

Equation 3

156 N · m exceeds the 80 N · m limit assigned earlier for maximum force an ADS operator could overcome. Material selection and analysis would be critical for the success of this type of joint.

Chapter 5 Conclusion

5.1 Summary

From seaweed to petroleum to fish, the ocean is an integral component to the survival and success of humankind. We will continue to work in and around the ocean and the ADS facilitates that. There have been many advances in the field of autonomy and Remote Operated Vehicles (ROVs). The US Navy's Undersea Rescue Command recently switched from ADS to ROVs. ROVs perform their mission without putting the operator at risk but the operator relies on the sensors installed for their situational awareness. With the use of multiple cameras and haptic feedback some would argue that there is no need to place an operator in harms way. Others in the community would argue that there is no substitute for having a human on scene. This thesis will not attempt to argue for one point of view or another. However, I do believe that humans are an inquisitive and adventurous species and that some will feel the need to view underwater vistas and wrecks first hand. Even with the emergence of virtual reality there will be those who will accept no substitute for the real thing. They will endure the risk to scale Mt. Everest or dive the Marianas Trench to be able to witness these majestic vistas not on a screen but through their protective viewport.

A bellows type joint could provide greater range of motion and functionality than a rotary joint in an ADS. It is conceivable to design and construct an ADS joint which maintains volume throughout its ROM. The human factors analysis proved that the joint operated as designed. Two recommendations I would suggest would be to increase the joint dimensions to accommodate a larger segment of the population. Another recommendation would be to include a mechanical stop device which would inhibit movement of the joint in one direction, reducing possible injury.

An ADS that is "swimmable", able to be propelled by the operator with fins, is a goal of the STTR stated by ONR. This bellows type joint could provide the functionality to enable that. The image below is a concept design which shows a combination of rotary and bellow type joints the author believes would provide a more functional ROM to the user.

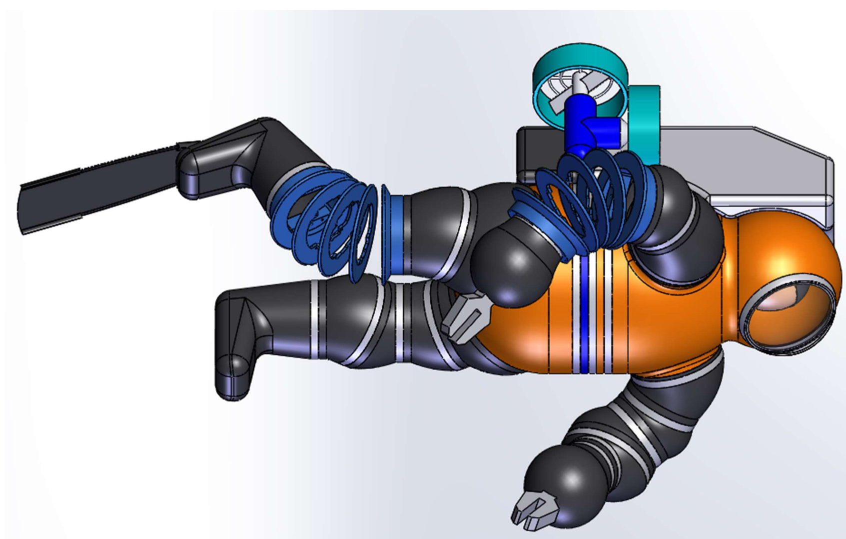


Figure 5-1 ADS that uses a combination of rotary and bellows joints. Bellows joints would be ideal for knee and elbow. Knee joint would greatly contribute to a "swimmable" suit while elbow joint could provide greater functionality

5.2 Future work

If the membrane stretches when exposed to the pressure at depths than the volume will not be maintained and the joint will seek the smallest volume. Considerable energy from the operator would be required to move the joint from this position. Further analysis on material properties of the membrane, primarily Kevlar, should be undertaken to fully define how the material will perform at depths. Possible areas of research include: Material properties as a function of repeated pressure cycles and temperature effects.

One other area of concern which Midé addressed in their preliminary findings is the survivability and durability issue. Ensuring that the membrane layer does not suffer a leak or rupture is a valid concern. Midé suggested a possible solution would be to construct the membrane with multiple layers which could provide a significant safety factor.

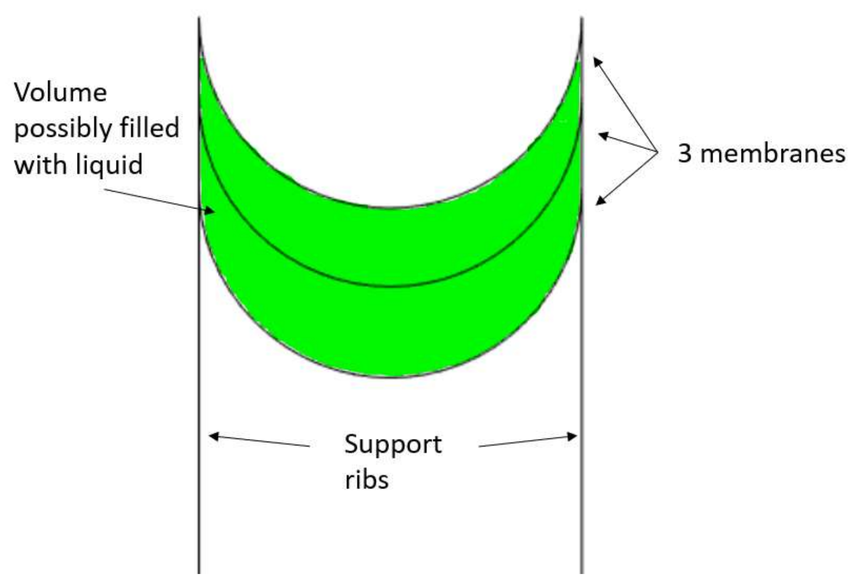


Figure 5-2 Bellows type joint that utilizes multiple membrane layers to provide redundancy and reduction in risk to puncturing. This concept would need to address the issue of maintaining volume in between each membrane layer

Further research of this proof of concept is recommended. The volume in between the membranes in this approach would have to be designed to be maintained throughout its movement.

Defining and measuring functionality is a difficult task in regards to an ADS. There is a wide variety of work an operator in an ADS could be expected to do ranging from welding to performing inspections. My colleagues, Wilkins and Colgary, who performed research into this field, measured the effort of an operator in an ADS to bolt and unbolt a flange. Performing the identical experiment with a suit constructed of rotary and bellow joints might favor the traditional ADS because of the movements required. On the other hand, it might favor the bellows joint because of the allowed movements in plane. The point being is that measuring effort required, or "functionality", is and will be subjective based on feedback from the operators and the task at hand.

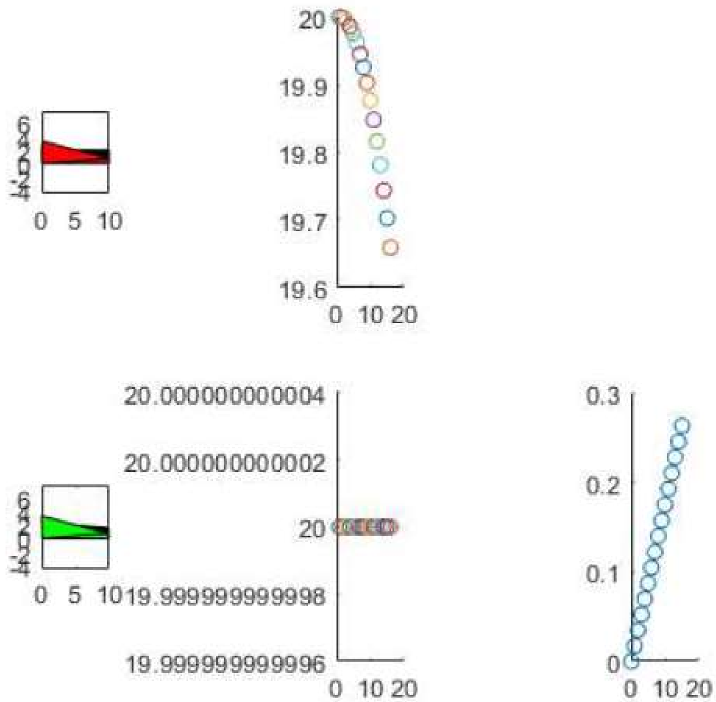
Appendices

Appendix A

```
%David Ingraham
%Determination of required change in pivot location to maintain zero change
%in volume as joint manuevers through 15 degrees
%2/22/2018
%Area of a joint
clear all;
clear fig;

A=0; %A,B,C,D are initial locations of ends of bars in cartesian coordinates
B=0;
C=10; %length of bars
D=0;
E=2;  %Vertical separation of bars
n=0;  %angle of rotation
f=1;  %counter
f1=figure;
subplot(2,3,1)
title('Plot_of_area');
xlabel('xaxis');
ylabel('yaxis');

while n<16
x1=5-5*cosd(n); %cartesian coordinate of left side of bar
y1=2+5*sind(n);   %cartesian coordinate of left side of bar
x2=5+5*cosd(n); %cartesian coordinate of right side of bar
y2=2 - 5*sind(n);   %cartesian coordinate of right side of bar
P=[A,B;C,D;x2,y2;x1,y1];   %draws shape of polygon
shp=alphaShape(P);
plot(shp,'FaceColor','red')
hold on
n=n+1;
end

hold off
n=0;
f=1;
subplot(2,3,2)
title('Plot_of_area');
xlabel('xaxis');
ylabel('yaxis');

while n<16
x1=5-5*cosd(n); %cartesian coordinate of left side of bar
y1=2+5*sind(n);   %cartesian coordinate of left side of bar
```

```
x2=5+5*cosd(n); %cartesian coordinate of right side of bar
y2=2 - 5*sind(n);   %cartesian coordinate of right side of bar
P=[A,B;C,D;x2,y2;x1,y1];
shp=alphaShape(P);
m=area(shp);
list(f,1)=m;
list(f,2)=n;
scatter (f,m)
hold on
f=f+1;
n=n+1;
end
hold off
n=5;
f=1;
p = polyfit(list(:,2),list(:,1),2);  %used to determine the curve to calculate how the are
a of polygon changes due to angle
subplot(2,3,4)
title('Plot_of_area');
xlabel('xaxis');
ylabel('yaxis');
syms F                               %required to be able to utilize solver function
while n<16
x1=5 - (5+F) * cosd(n);
y1=2+(5+F)*sind(n);
x2=5+(5-F)*cosd(n);
y2=2-(5-F)*sind(n);
xcoord = [A, x1, x2, C];
ycoord = [A, y1, y2, B];
S = solve(polyarea(xcoord,ycoord)==20,F);  %determines distance pivot needs to shift to ma
intain zero change in volume
S=double(S);
solution(f,1) = S;
x1=5 - (5+S) * cosd(n);
y1=2+(5+S)*sind(n);
x2=5+(5-S)*cosd(n);
y2=2-(5-S)*sind(n);
P=[A,B;C,D;x2,y2;x1,y1];
rhp=alphaShape(P);
plot(rhp,'FaceColor','green')
t = area(rhp);
list1(f,1)=t;
list1(f,2)=n;
hold on
n=n+1;
f=f+1;
end
hold off
subplot(2,3,5);
title('Plot_of_area');
xlabel('xaxis');
ylabel('yaxis');
n=0;
f=1;
p = polyfit(list(:,2),list(:,1),2);
while n<16
x1=5 - (5+F) * cosd(n);
```

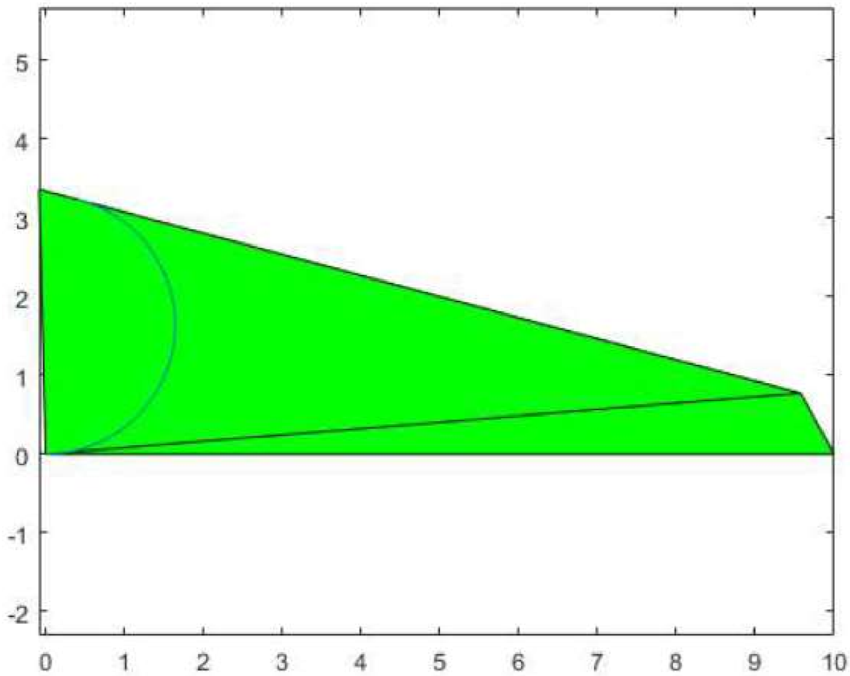
```
y1=2+(5+F)*sind(n);
x2=5+(5-F)*cosd(n);
y2=2-(5-F)*sind(n);
xcoord = [A, x1, x2, C];
ycoord = [A, y1, y2, B];
S = solve(polyarea(xcoord,ycoord)==20,F);  %determines distance pivot needs to shift to ma
intain zero change in volume
S=double(S);
solution(f,1) = S;
x1=5 - (5+S) * cosd(n);
y1=2+(5+S)*sind(n);
x2=5+(5-S)*cosd(n);
y2=2-(5-S)*sind(n);
P=[A,B;C,D;x2,y2;x1,y1];
rhp=alphaShape(P);
t = area(rhp);
list1(f,1)=t;
list1(f,2)=n;
scatter(f,t)
hold on
n=n+1;
f=f+1;
end
n=0;
l=1;
subplot(2,3,6);
title('Plot_of_area');
xlabel('pivot location');
ylabel('angle');
while n<16
    xaxis(l,1)=n;
    n=n+1;
    l=l+1;
end
scatter(xaxis,solution(:,1))         %displays graph showing pivot location versus angle
q = polyfit(xaxis,solution(:,1),2);   %displays equation showing linear change required to
 maintain constant volume
```



Determine radius and location of largest circle which will be inscribed in joint

```
mem_length = 5.3;
M = (y2-y1)/(x2-x1);
y0 = y1 - M*x1;
ZeroX = -y0/M;
theta = atand(M);
d = ZeroX/cosd(theta/2);
r = sind(-theta/2) * d;
% Now we will compare the triange to see if b = c
c = sqrt((ZeroX - x1)^2 + y1^2);
% If c is greater than b the circle will not fit in joint wedge.
CtoB = gt(c,ZeroX);
% How much bigger is c to b
delta = c - ZeroX;
% Calculate shortest membrane required to form arc at max bend and calculate
% lay down
% Subtract delta from x1,y1 and verify it's same location as e
e = [ZeroX - ZeroX*cosd(-theta), ZeroX * sind(-theta)];
% verify b = c
c = sqrt((ZeroX - e(1,1))^2 + e(1,2)^2);
b = ZeroX;
th = linspace(pi/2 + theta * pi / 180, -pi/2, 1000);
x5 = r*cos(th);
y5 = r*sin(th) + r;
figure
plot(rhp,'FaceColor','green')
hold on
plot(x5,y5); axis equal;
```

```
hold on
```



Calculate the length of the membrane and area

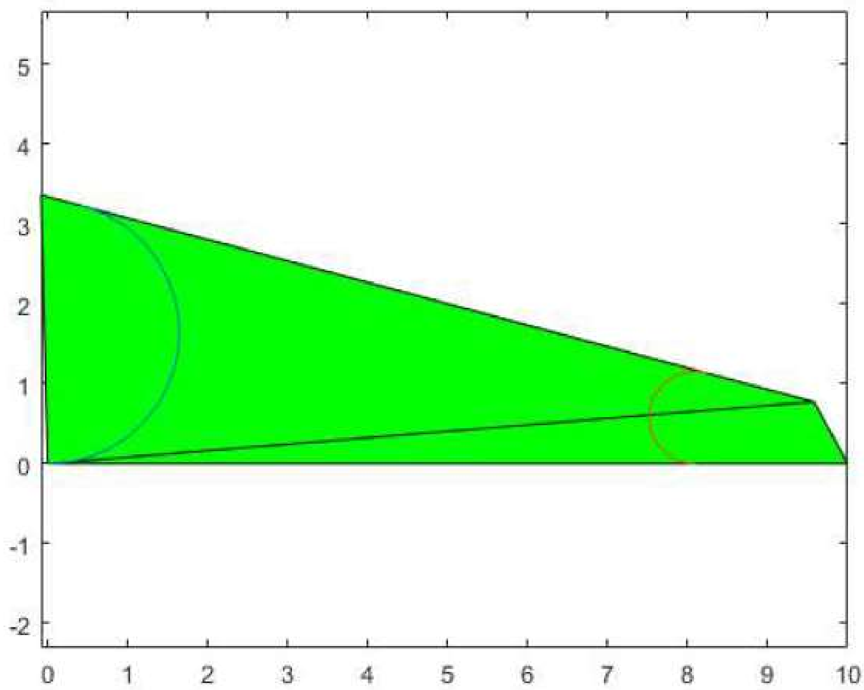
```
delta = sqrt((x1 - e(1,1))^2 + (y1 - e(1,2))^2);
mem_length = delta + r * (180 + theta) * pi / 180;
area_arc = r^2/2 * (((180 + theta) * pi /180) - sind(180+theta));
poly_x = [x1, e(1,1), 0, 0];
poly_y = [y1, e(1,2), r, 0];
area = polyarea(poly_x,poly_y);
area_total_larger_side = area + area_arc;
```

Calculate the position and membrane lay down on smaller radius segment

```
syms F;
theta = -theta
d = F * cosd(theta/2);
rr = F * sind(theta/2);
g = [ZeroX - F*cosd(theta/2), rr];
gtop = [g(1,1) + rr*sind(theta) , rr*cosd(theta)+rr];
S = solve(rr * (180+theta)*pi/180 + sqrt((gtop(1,1)-x2)^2 + (gtop(1,2) - y2)^2) + C - g(1,
1)==mem_length,F);
S = double(S);
d = F * cosd(theta/2);
rr = S * sind(theta/2);
g = [ZeroX - S * cosd(theta/2), rr];
gtop = [g(1,1) + rr*sind(theta) , rr*cosd(theta)+rr];
```

```
gbot = [ZeroX - S * cosd(theta/2), 0];
mem_length_opp_side = rr * (180+theta)*pi/180+sqrt((gtop(1,1)-x2)^2+(gtop(1,2)-y2)^2) + C
- gbot(1,1);
area_arc = rr^2/2 * (((180 + theta) * pi /180) - sind(180+theta));
poly_x = [gbot(1,1), gbot(1,1), gtop(1,1), x2, C];
poly_y = [gbot(1,2), g(1,2), gtop(1,2), y2, D];
area1 = polyarea(poly_x,poly_y);
area_total_smaller_side = area + area_arc;
area_total_15_deg_angle = area_total_smaller_side + area_total_larger_side
th = linspace(pi/2 - theta * pi / 180, 3*pi/2, 1000);
x3 = (rr*cos(th)+g(1,1));
y3 = (rr*sin(th) + rr);
plot(x3,y3); axis equal;
```

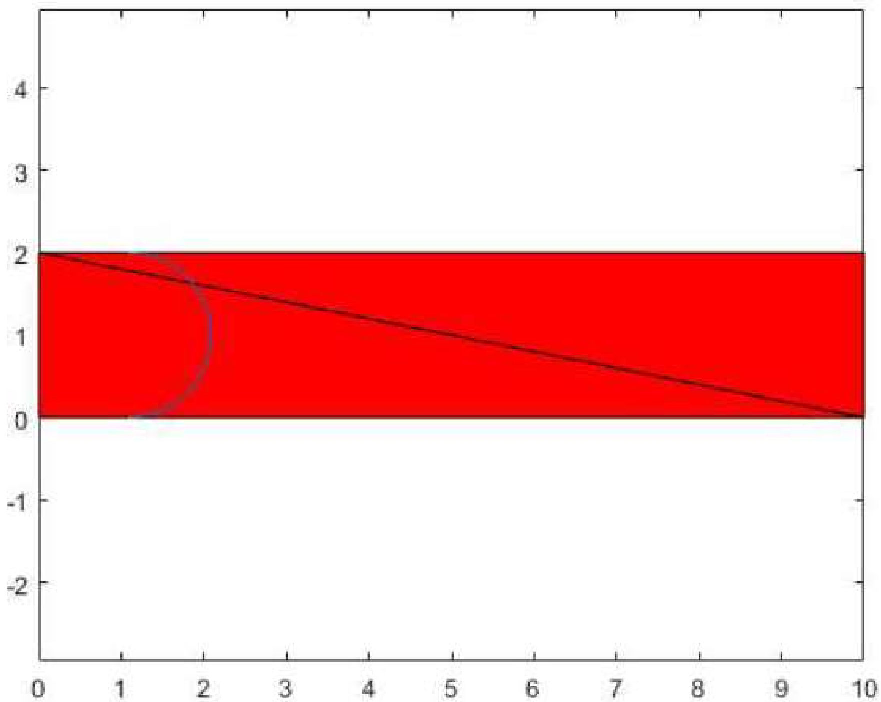
```
theta =

   15.0000


area_total_15_deg_angle =

    5.1377
```



Analyze unbent joint

```
figure
```

```
n=0;
mem_length = 5.3;
x1=C/2-C/2*cosd(n); %cartesian coordinate of left side of bar
y1=E+C/2*sind(n);   %cartesian coordinate of left side of bar
x2=C/2+C/2*cosd(n); %cartesian coordinate of right side of bar
y2=E - C/2*sind(n);   %cartesian coordinate of right side of bar
P=[A,B;C,D;x2,y2;x1,y1];   %draws shape of polygon
shp=alphaShape(P);
plot(shp,'FaceColor','red')
hold on
h = F;
rrr = E/2;
g = [h,rrr];
gtop = [g(1,1), E];
gbot = [g(1,1), 0];
S = solve(pi  + 2 * F == mem_length, F);
S=double(S);
h = S;
g = [h,rrr];
gtop = [g(1,1), E];
gbot = [g(1,1),0];
mem_length_unbent_side = rrr * pi + 2 * h;
area_arc = pi * rrr^2 / 2;
poly_x = [gbot(1,1), A, A, gtop(1,1)];
poly_y = [gbot(1,2), A, E, E];
area2 = polyarea(poly_x,poly_y);
area_total_unbent_side = 2 * (area2 + area_arc);
th = linspace(pi/2, -pi/2, 1000);
x3 = rrr*cos(th)+g(1,1);
y3 = rrr*sin(th) + rrr;
plot(x3,y3); axis equal;
area_internal = 20 - area_total_unbent_side;
```



Due to symmetry the other side of unbent joint will be same. Now we will compare the areas

of unbent joint to bent joints and see if further modifications to pivot location are required to maintain constant volume during movement.

```
%Comparing internal areas of different bend angles of joints we see that at
% unbent 12.6373 < bent 17.0701 which means the joint would oppose being moved
% because it would lead to an increase in volume
```

Run through F values and calculate area for each one

```
clc
clear all
clear fig
A = [0,0];
B = [0,2];
C = [10,2];
D = [10,0];
n=0;
mem_length = 5.3
i = 1;
%while i < 16
%    F[1,i] =  -0.0005*i^2 - 0.0064*i + 0.0003;
%   i = i + 1;
%end
syms F
if n ==0
```

```
    figure
       h = F;
       rr = 1;
       e = [h,rr];
       etop = [F, B(1,2)];
       ebot = F;
       S = solve(pi  + 2 * F == mem_length, F);
       S=double(S);
       h = S;
       e = [h,rr];
       etop = [h, B(1,2)];
       ebot = h;
       mem_length_unbent_side = rr * pi + 2 * h;
       area_arc = pi / 2;
       poly_x = [ebot, A(1,1), A(1,1), etop(1,1)];
       poly_y = [A(1,2), A(1,2), B(1,2), B(1,2)];
       area_unbent = polyarea(poly_x,poly_y);
       area_total_unbent_side = 2 * (area_unbent + area_arc);
       th = linspace(pi/2, -pi/2, 1000);
       x3 = rr*cos(th)+e(1,1);
       y3 = rr*sin(th) + rr;
       plot(x3,y3); axis equal;
       area_internal = 20 - area_total_unbent_side;
       integral_area = (10 - (2 * h))*2 - pi;
       ebot_tracker(1,n+1) = ebot;
       etop_tracker(1,n+1) = etop(1,1);
       n=n+1;
end
syms G H
while n < 16
    figure
    pivot = -0.5437/15*n;
    BB = [5-(5+pivot) * cosd(n), 2+(5+pivot)*sind(n)];
    CC = [5+(5-pivot) * cosd(n), 2-(5-pivot)*sind(n)];
    slope = (CC(1,2)-BB(1,2))/(CC(1,1)-BB(1,1));
    Z = CC(1,2)/(-1*slope)+CC(1,1);
    y0 = slope * (-1*Z)
    ebot = Z - G * cosd(n/2);
    rr = G * sind(n/2);
    etop = [ebot + rr*sind(n), rr+rr*cosd(n)];
    fbot = Z - H*cosd(n/2);
    r = H*sind(n/2);
    ftop = [fbot+r*sind(n), r+r*cosd(n)];
    S = solve(sqrt((BB(1,1)-etop(1,1))^2+(BB(1,2)-etop(1,2))^2)+ebot+(180-n)*pi*rr/180==me
m_length,G);
    S = double(S(1,1));
    ebot = Z - S * cosd(n/2);
    rr = S * sind(n/2);
    etop = [ebot + rr*sind(n), rr+rr*cosd(n)];
    T = solve(sqrt((CC(1,1)-ftop(1,1))^2+(CC(1,2)-ftop(1,2))^2)+C(1,1)-fbot+(180+n)*pi*r/1
80==mem_length,H);
    T = double(T);
    fbot = Z - T*cosd(n/2);
    r = T*sind(n/2);
    ftop = [fbot+r*sind(n) , r+r*cosd(n)];
    poly_x = [A(1,1), BB(1,1), CC(1,1), D(1,1)];
    poly_y = [A(1,2), BB(1,2), CC(1,2), D(1,2)];
```

```
    area1 = polyarea(poly_x,poly_y);
    poly_x_left = [ebot,A(1,1),BB(1,1),etop(1,1), ebot];
    poly_y_left = [A(1,2),A(1,2),BB(1,2),etop(1,2),rr];
    poly_x_right = [fbot,fbot,ftop(1,1),CC(1,1),D(1,1)];
    poly_y_right = [D(1,2),r,ftop(1,2),CC(1,2),D(1,2)];
    areapolyleft(1,n) = polyarea(poly_x_left,poly_y_left);
    areapolyright(1,n) = polyarea(poly_x_right,poly_y_right);
    arc_area_left(1,n) = rr^2*pi*(180-n)/360;
    arc_area_right(1,n) = r^2*pi*(180+n)/360;
    area_polygon_method(1,n) = area1 - areapolyleft(1,n)-areapolyright(1,n)-arc_area_left(
1,n)-arc_area_right(1,n);
    area_left_integral = rr*etop(1,2) - 0.5*(etop(1,2)-rr)*(etop(1,1)-ebot)-0.5*(ebot+rr-e
top(1,1))*slope*(-1)*(ebot+rr-etop(1,1))-(180-n)*pi*rr^2/360;
    area_right_integral = ((slope*ftop(1,1)^2/2+y0*ftop(1,1))-(slope*(ebot+rr)^2/2+y0*(ebo
t+rr))) - 0.5*(ftop(1,2)-r)*(ftop(1,1)-fbot)-r*(ftop(1,1)-fbot)-(180+n)*pi*r^2/360;
    area_integral_method(1,n) = area_left_integral + area_right_integral;
    P=[A;BB;CC;D];
    rhp=alphaShape(P);
    plot(rhp,'FaceColor','green')
    hold on
    th = linspace(pi/2 - n * pi / 180, -pi/2, 1000);
    x5 = ebot + rr*cos(th);
    y5 = rr*sin(th) + rr;
    plot(x5,y5); axis equal;
    hold on
    th = linspace(pi/2 - n * pi / 180, 3*pi/2, 1000);
    x5 = fbot + r*cos(th);
    y5 = r*sin(th) + r;
    plot(x5,y5); axis equal;
    hold on
    left_side_x = [ebot,ebot,etop(1,1)];
    left_side_y = [0,rr,etop(1,2)];
    plot(left_side_x,left_side_y)
    hold on
    right_side_x = [fbot,fbot,ftop(1,1)];
    right_side_y = [0,r, ftop(1,2)];
    plot(right_side_x,right_side_y)
    distance(1,n)=sqrt((CC(1,1)-BB(1,1))^2+(CC(1,2)-BB(1,2))^2);
    fbot_tracker(1,n+1) = fbot;
    ebot_tracker(1,n+1) = ebot;
    mem_left = 2*pi*rr*((180-n)/360)+ebot+sqrt((BB(1,1)-etop(1,1))^2+(BB(1,2)-etop(1,2))^2
);
    mem_right = 2*pi*r*((180+n)/360)+(10-fbot)+sqrt((CC(1,1)-ftop(1,1))^2+(CC(1,2)-ftop(1,
2))^2);
    mem_left_tracker(1,n+1) = mem_left;
    mem_right_tracker(1,n+1) = mem_right;
    n=n+1;
end
figure
plot(1:15,area_integral_method,'r')
ylim([12.32 12.35])
xlim([0 16])
```

Appendix B

P1000 - Beam Loading *(metric)*

Span	Max Allowable Uniform Load	Defl. at Uniform Load	Uniform Loading at Deflection		
			Span/180	Span/240	Span/360
mm	kN	mm	kN	kN	kN
600	7.6	1	7.6	7.6	7.6
750	6.1	2	6.1	6.1	5.9
1,000	4.6	4	4.6	4.6	3.3
1,250	3.6	6	3.6	3.2	2.1
1,500	3.1	9	3.0	2.2	1.5
1,750	2.6	12	2.2	1.6	1.1
2,000	2.3	15	1.6	1.2	0.8
2,500	1.8	24	1.1	0.8	0.5
3,000	1.5	34	0.8	0.5	0.4
3,500	1.3	46	0.5	0.4	0.3
4,000	1.2	62	0.4	0.3	0.2
4,500	1.0	78	0.3	0.3	0.2
5,000	0.9	97	0.3	0.2	NR
6,000	0.8	136	0.2	NR	NR

P1001 - Beam Loading *(metric)*

Span	Max Allowable Uniform Load	Defl. at Uniform Load	Uniform Loading at Deflection		
			Span/180	Span/240	Span/360
mm	kN	mm	kN	kN	kN
600	15.6 *	1	15.6 *	15.6 *	15.6 *
750	15.6 *	1	15.6 *	15.6 *	15.6 *
1,000	13.0	2	13.0	13.0	13.0
1,250	10.4	3	10.4	10.4	10.4
1,500	8.7	5	8.7	8.7	7.4
1,750	7.4	7	7.4	7.4	5.5
2,000	6.5	9	6.5	6.3	4.2
2,500	5.2	13	5.2	4.0	2.7
3,000	4.3	19	3.7	2.8	1.9
3,500	3.7	26	2.8	2.0	1.4
4,000	3.2	34	2.1	1.6	1.1
4,500	2.9	44	1.6	1.2	0.8
5,000	2.6	53	1.3	1.0	0.7
6,000	2.2	78	0.9	0.7	0.4

P1000 - Column Loading *(metric)*

Unbraced Height	Maximum Allowable Load at Slot Face	Maximum Column Load Applied at C.G.			
		K = 0.65	K = 0.80	K = 1.0	K = 1.2
mm	*kN*	*kN*	*kN*	*kN*	*kN*
600	15.8	48.0	44.3	39.4	34.8
750	15.2	44.0	39.4	33.8	28.9
1,000	13.7	37.5	32.0	26.1	21.3
1,250	12.1	31.6	26.1	20.3	16.5
1,500	10.7	26.7	21.3	16.5	13.4
1,750	9.6	22.7	17.8	13.8	11.3
2,000	8.7	19.3	15.3	11.9	9.6
2,250	7.9	16.9	13.4	10.4	8.2
2,500	7.2	15.0	11.9	9.1	**
2,750	6.7	13.5	10.6	8.1	**

P1001 - Column Loading *(metric)*

Unbraced Height	Maximum Allowable Load at Slot Face	Maximum Column Load Applied at C.G.			
		K = 0.65	K = 0.80	K = 1.0	K = 1.2
mm	*kN*	*kN*	*kN*	*kN*	*kN*
600	28.6	108.2	105.3	101.3	97.4
750	28.3	105.0	101.3	96.5	92.2
1,000	27.8	99.6	95.0	89.7	83.9
1,250	27.3	94.7	89.7	81.7	70.1
1,500	26.8	90.3	83.9	70.1	56.4
1,750	25.4	86.7	74.8	58.6	43.5
2,000	23.9	79.4	65.5	47.7	33.3
2,250	22.2	71.9	56.4	37.9	26.3
2,500	20.4	64.4	47.7	30.7	21.3
2,750	18.5	56.9	39.6	25.4	17.6

P1000/P1001 - Elements of Section (metric)

Parameter	P1000		P1001	
Area of Section	3.58	cm^2	7.16	cm^2
Axis 1-1				
Moment of Inertia (I)	7.68	cm^4	38.62	cm^4
Section Modulus (S)	3.30	cm^3	9.36	cm^3
Radius of Gyration (r)	1.46	cm	2.32	cm
Axis 2-2				
Moment of Inertia (I)	9.80	cm^4	19.60	cm^4
Section Modulus (S)	4.75	cm^3	9.50	cm^3
Radius of Gyration (r)	1.65	cm	1.65	cm

Notes:

* Load limited by spot weld shear.

** KL/r > 200

NR = Not Recommended.

1. Beam loads are given in *total* uniform load (W Lbs) not uniform load (w lbs/ft or w lbs/in).
2. Beam loads are based on a simple span and assumed to be adequately laterally braced. Unbraced spans can reduce beam load carrying capacity. Refer to Page 62 for reduction factors for unbraced lengths.
3. For pierced channel, multiply beam loads by the following factor:

"KO" Series.......95%	**"T" Series 85%**
"HS" Series 90%	**"SL" Series........85%**
"H3" Series........90%	**"DS" Series........70%**
"WT" Series.......85%	

4. Deduct channel weight from the beam loads.
5. For concentrated midspan point loads, multiply beam loads by 50% and the corresponding deflection by 80%. For other load conditions refer to page 18.
6. All beam loads are for bending about Axis 1-1.

Columns are structural members that are loaded parallel to their length. Most columns are vertical and are used to carry loads from a higher level to a lower level. However any member subjected to compression loads, such as a diagonal or prop brace, is a column.

A column fails by "buckling", which is a sudden loss of straightness and subsequent collapse. Allowable column load is dependent on:

(a) the length of column,
(b) the type of loading,
(c) the support conditions, and
(d) the column's cross-sectional shape and material.

COLUMN LENGTH

The column length is measured from braced point to braced point. A braced point is where the column is restrained from lateral movement (translation) in all directions.

COLUMN LOADING – CONCENTRIC LOADING

Loads applied to the center of gravity of the column cross-section are considered concentric. A beam that passes over and rests on the top of a column is an example of concentric loading.

COLUMN LOADING – ECCENTRIC LOADING

Any load which is not concentric is eccentric. The amount of eccentricity (in inches) has a major effect on the load-carrying capacity of any particular column. A load that is transmitted to a Unistrut Metal Framing column using a standard fitting bolted to the slot face is considered eccentric.

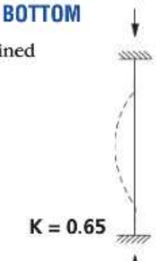
The load tables give allowable loads for both concentric (loaded at C.G.) and certain eccentric (loaded at slot face) loading. Allowable loads for other eccentric loading must be determined by a qualified design professional.

SUPPORT CONDITIONS

Based on the support conditions, an appropriate "K" value is selected. This "K" value, which mathematically describes the column end conditions, is used in the column design equations. The most common support condition combinations are as follows:

SUPPORT CONDITIONS - FIXED TOP – FIXED BOTTOM

Both ends are restrained against rotation and lateral movement (translation).



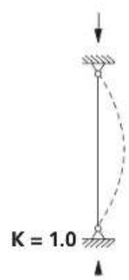
SUPPORT CONDITIONS - PINNED TOP – FIXED BOTTOM

The top is restrained against lateral movement (translation) but is allowed to rotate. The bottom is restrained against rotation and lateral movement.

This is a common support condition and is used to construct the allowable column load applied at the Slot Face tables.

SUPPORT CONDITIONS - PINNED TOP – PINNED BOTTOM

Both ends are restrained against lateral movement (translation) but, are allowed to rotate.



SUPPORT CONDITIONS - FIXED / FREE TOP – FIXED BOTTOM

The top is restrained against rotation but is allowed to move laterally. The bottom is restrained against rotation and lateral movement (translation).

CROSS-SECTIONAL SHAPE

The cross-sectional shape of a column member determines the value of its "Radius of Gyration" or "r". In general, a member with a large "r" makes a better column than a member with a small "r". Each axis of a column has a different "r". Typically the axis with the smallest "r" determines the final design.

BOLT TORQUE

Bolt torque values are given to ensure the proper connection between Unistrut Metal Framing components. It is important to understand that there is a direct, but not necessarily consistent, relationship between bolt torque and tension in the bolt. Too much tension in the bolt can cause it to break or crush the component parts. Too little tension in the bolt can prevent the connection from developing its full load capacity. The torque values given have been developed over many years of experience and testing.

Bolt Torque						
BOLT SIZE	**¼"-20**	**5/16"-18**	**⅜"-16**	**½"-13**	**⅝"-11**	**¾"-10**
Rec.Torque Ft/Lbs *(N•m)*	6 *(8)*	11 *(15)*	19 *(26)*	50 *(68)*	100 *(136)*	125 *(170)*
Max Torque Ft/Lbs *(N•m)*	7 *(9)*	15 *(20)*	25 *(34)*	70 *(95)*	125 *(170)*	135 *(183)*

These are based on using a properly calibrated torque wrench with a clean dry (non-lubricated) Unistrut fitting, bolt and nut. A lubricated bolt or nut can cause extremely high tension in the connection and may lead to bolt failure. It must be noted that the accuracy of commercial torque wrenches varies widely and it is the responsibility of the installer to ensure that proper bolt torque has been achieved.

Appendix C

MIT Committee On the Use of Humans as Experimental Subjects

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue
Cambridge, Massachusetts 02139
Building E 25-143B
(617) 253-6787

To:	Alexandra Techet 5-230
From:	Leigh Firn, Chair COUHES
Date:	09/06/2017
Committee Action:	Amendment to Approved Protocol
COUHES Protocol #:	1608661454A002
Study Title:	Human - Atmospheric Dive Suit (ADS) New Arm Interaction
Expiration Date:	09/07/2017

The amendment to the above-referenced protocol has been APPROVED following expedited review by the Committee on the Use of Humans as Experimental Subjects (COUHES).

This approval covers the following change(s)/modification(s):

-David Ingraham has been added to the protocol and will be conducting experiments with human subjects.

If the research involves collaboration with another institution, then the research cannot commence until COUHES receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date. Please allow sufficient time for continued approval. You may not continue any research activity beyond the expiration date without COUHES approval. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the study and related research grants.

Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please submit Final Report Closure Form.

Unless informed consent is waived by the IRB, use only the most recent, IRB approved and stamped copies of the consent form(s).

Adverse Events: Any serious or unexpected adverse event must be reported to COUHES within 48 hours. All other adverse events should be reported in writing within 10 working days.

Amendments: Any changes to the protocol, including changes in experimental design, equipment, personnel or funding, must be approved by COUHES before they can be initiated, except when necessary to eliminate apparent immediate hazards to the subject.

Human subjects training is required for all study personnel and must be updated every 3 years.

You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with COUHES, original signed consent forms, and study data.

MIT Committee On the Use of Humans as Experimental Subjects

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To:	Alexandra Techet 5-230
From:	Leigh Firn, Chair COUHES
Date:	09/06/2017
Committee Action:	Renewal
COUHES Protocol #:	1608661454R001
Study Title:	Human - Atmospheric Dive Suit (ADS) New Arm Interaction
Expiration Date:	09/05/2018

The above-referenced protocol was given renewed approval following Expedited Review by the Committee on the Use of Humans as Experimental Subjects (COUHES).

If the research involves collaboration with another institution, then the research cannot commence until COUHES receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date. Please allow sufficient time for continued approval. You may not continue any research activity beyond the expiration date without COUHES approval. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the study and related research grants.

Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please submit Final Report Closure Form.

Unless informed consent is waived by the IRB, use only the most recent, IRB approved and stamped copies of the consent form(s).

Adverse Events: Any serious or unexpected adverse event must be reported to COUHES within 48 hours. All other adverse events should be reported in writing within 10 working days.

Amendments: Any changes to the protocol, including changes in experimental design, equipment, personnel or funding, must be approved by COUHES before they can be initiated, except when necessary to eliminate apparent immediate hazards to the subject.

Human subjects training is required for all study personnel and must be updated every 3 years.

You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with COUHES, original signed consent forms, and study data.

CONSENT TO PARTICIPATE IN
BIOMEDICAL RESEARCH

Human-ADS (Atmospheric Dive Suit) New Arm Interaction

You are asked to participate in a research study conducted by Prof Alexandra Techet, and her associated investigators from the Department of Mechanical Engineering at the Massachusetts Institute of Technology (M.I.T.). You have been asked to participate in this study because of your voluntary interest in doing so and your healthy medical condition. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- **PARTICIPATION AND WITHDRAWAL**

Your participation in this research is completely VOLUNTARY. If you choose to participate you may subsequently withdraw from the study at any time without penalty or consequences of any kind. If you choose not to participate, that will not affect your relationship with M.I.T. or your right to health care or other services to which you are otherwise entitled.

- **PURPOSE OF THE STUDY**

The purpose of this research is to develop an understanding of how the human interacts with the new ADS arm, and to use that information to assess and inform future design. In order to quantify this accurately, it is necessary to test in an underwater environment.

- **PROCEDURES**

If you volunteer to participate in this study, we would ask you to do the following things:

Tests:

- You will insert one arm in the ADS arm which will be mounted inside a tank of water but accessible from a side of the tank.
- You will notify the test supervisor if any discomfort or pain is experienced, in which case feedback will be collected and you will decide whether or not to abort the study.
- You will be asked to make a series of movements, which will each be repeated no more than 20 times. After each session, assuming the successful completion of the previous session, you will be asked to perform a new series of movements. At all times the test supervisor will watch over the subject, ensuring their safety.
- You are free to terminate the experiment immediately, at any time, for any reason.

The entire duration of the test will not be more than 45 minutes.

- **POTENTIAL RISKS AND DISCOMFORTS**

There is negligible risk from participation in this experiment. Safety precautions will always be the primary consideration. The ADS arm might inhibit human mobility, so you may feel minor discomfort as you bend the joints of the suit. It is expected to be minimal and have no long term effects.

You will be inspected immediately before and after test sessions. As minor risks associated with this study are all immediately evident, these inspections should suffice. You will contact the MIT Medical Department as well as the test director immediately if any prolonged pain occurs.

The treatment or procedure may involve risks that are currently unforeseeable.

- **ANTICIPATED BENEFITS TO SUBJECTS**

There are no known benefits to the subject for participation in this study.

- **ANTICIPATED BENEFITS TO SOCIETY**

The US Navy, Commercial, and Civilian diving industry may benefit from the evaluation of human-ADS interaction as it will be used to develop an ADS that will enable humans to explore the deep ocean without the risk of diving related illness.

- **ALTERNATIVES TO PARTICIPATION**

You may choose not to participate in this research experiment.

- **PAYMENT FOR PARTICIPATION**

You will not receive payment for participation in this study.

- **FINANCIAL OBLIGATION**

Neither you nor your insurance company will be billed for your participation in this research.

- **PRIVACY AND CONFIDENTIALITY**

The only people who will know that you are a research subject are members of the research team and, if appropriate, your physicians and nurses. No information about you,

Volunteer Request Email / Flyer

SUBJ: Study on Human Interaction with new ADS Arm – Request for Volunteers

Greetings,

We are looking for volunteers to participate in a study to collect data on human interaction with a newly designed ADS (Atmospheric Dive Suit) arm.

Participation will involve using the test ADS arm by inserting an arm into ADS arm which will be mounted in a water tank in a such a way that the arm will be submerged in water but a subject will be able to use it from the outside of the tank. In addition, video and audio of the actual test might be recorded.

Participation is strictly voluntary. Participants' personal information will not be recorded or reported. There is no expectation for recipients of this email to participate. There will be no monetary or other compensation for participation. The benefit of participating in this study is the advancement of diving technology.

If you are interested in participating in this research during your upcoming scheduled training dive, please reply to this email. Prior to the study, all participants will be fully informed of the processes and risks, and proper consent will be documented and collected. Response to this email does not in any way indicate commitment or consent for participation.

Thank you,
MIT ADS Testing Personnel

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Bibliography

[1] N. O. and A. A. US Department of Commerce, "How much of the ocean have we explored?" [Online]. Available: https://oceanservice.noaa.gov/facts/exploration.html. [Accessed: 18-Jan-2018].

[2] T. Bissett, "ADS Hardsuits – Phoenix International." .

[3] C. Wilkins, "An Experimental Study of the Human Interface with One Atmosphere Diving Suit Appendages," MIT, 2016.

[4] J. Colgary, "An Experimental Study of the One Atmosphere Diving Suit and Data Analysis of Military Diving," MIT, 2016.

[5] G. Harris, *Ironsuit: the history of the atmospheric diving suit*. Best Publishing Company, 1994.

[6] O. A. R. P. Webb Associates (Yellow Springs, *Anthropometric source book.* [Washington] : National Aeronautics and Space Administration, Scientific and Technical Information Office ; [Springfield, Va. : for sale by the National Technical Information Service], 1978., 1978.

[7] "Range of Joint Motion Evaluation Chart, Washington State Department of Health and Social Services, Rev (3/2014)." .

[8] "Introductory Biomechanics - From Cells to Organisms - 8. Muscles and Movement - Knovel." [Online]. Available: https://app.knovel.com/web/view/pdf/show.v/rcid:kpIBFCO008/cid:kt006B52U2/viewerType:pdf/root_slug:introductory-biomechanics--from-cells-to-organisms/url_slug:muscles-and-movement?cid=kt006B52U2. [Accessed: 13-Nov-2017].