UNDERSTANDING SPACESUIT INTERACTION USING A WEARABLE PROXIMITY SENSING SYSTEM FOR SUIT FIT OPTIMIZATION

A Thesis by

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UNDERSTANDING SPACESUIT INTERACTION USING A WEARABLE PROXIMITY SENSING SYSTEM FOR SUIT FIT OPTIMIZATION

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Biomedical Engineering.

Kim Cluff, Committee Chair

Anil Mahapatro, Committee Member

Shuang Gu, Committee Member
DEDICATION

I dedicate this thesis to my parents, brothers, grandparents, and friends.
ACKNOWLEDGEMENTS

I would like to take this opportunity to acknowledge and thank everyone who have helped me on my journey of achieving my Master of Science degree. First, I am grateful to my family for their support and encouragement throughout these two years of me receiving my M.S. degree and five years for my B.S. degree. Specifically, I would like to thank my parents for helping me stay motivated and encouraging me to keep up the hard work throughout my entire college experience. They are the ones that led me to my passion for biomedical engineering and to help push me to pursue research and receive my M.S. degree. All this knowledge and resources I have gained throughout my college career will be used in the work force to help better lives of society. I also would like to give my greatest gratitude to my grandparents for believing in me and giving me support throughout this journey. I love you all very much.

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There is currently no quantitative method of measuring space suit fit for astronauts after they have put on the spacesuit. The primary concern for spacesuit fit is the hard upper torso (HUT), which is composed of a rigid fiberglass shell with metal scye bearing joints where other suit components attach. There is a concern with how much shoulder mobility the HUT is providing for astronauts. As astronauts perform tasks in the suit, there are contact and strain injuries that come from the repeated shoulder joint movements. When the distance between the shoulder joint and the metal scye bearing joint is too small, there is higher likelihood for musculoskeletal injuries. The purpose of this research investigates the use of a wearable proximity sensor to incorporate in the spacesuit to measure distance between the shoulder joint and metal scye bearing joint of the HUT. Two electromagnetic resonant spiral sensors were created and used for proximity detection where the investigation of proximity response to a metal was used. These wearable proximity sensors were tested in various environments to resemble environments inside the spacesuit. The first environment tested two sensor designs in proximity to only metal and then expanded to test the proximity sensors resting on a cooling garment that is in the spacesuit. Next testing environment included multiple proximity sensors of the same design in proximity to a curved metal sheet to more resemble the scye bearing joint. Results indicate that addition of the cooling garment reduces accuracy, although still has reliable accuracy of less than one millimeter. Consequently, adding more proximity sensors for the same environment proves feasible with future scenarios to still be tested. This wearable proximity sensor system establishes quantitative measurements that will aid in optimization of spacesuit fit. The use of this system during fitting, donning, or training during various movements will be able to provide vital assessment of spacesuit fit to avoid shoulder joint injury.
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<tr>
<td>EMU</td>
<td>Extravehicular Mobility Unit</td>
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<td>EVA</td>
<td>Extravehicular Activity</td>
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<td>NBL</td>
<td>Neutral Buoyancy Laboratory</td>
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<td>GH</td>
<td>Glenohumeral</td>
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<tr>
<td>HUT</td>
<td>Hard Upper Torso</td>
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<td>ISS</td>
<td>International Space Station</td>
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<tr>
<td>LCVG</td>
<td>Liquid Cooling and Ventilation Garment</td>
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<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<td>RLC</td>
<td>Resistance, Inductance, Capacitance</td>
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<td>RMSE</td>
<td>Root Mean Square Error</td>
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<td>ROM</td>
<td>Range of Motion</td>
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<td>SMA</td>
<td>SubMiniature version A</td>
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<td>L</td>
<td>Inductance</td>
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<td>C</td>
<td>Capacitance</td>
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<tr>
<td>R</td>
<td>Resistance</td>
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<tr>
<td>J</td>
<td>Spatial Current Density</td>
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<tr>
<td>r</td>
<td>Length of Spiral Trace</td>
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<tr>
<td>$\mu_0$</td>
<td>Free Space Magnetic Permeability</td>
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<tr>
<td>$\mu_i$</td>
<td>Relative Magnetic Permeability</td>
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<td>I</td>
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<td>$\varepsilon_0$</td>
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<td>$\varepsilon_r$</td>
<td>Relative Permittivity</td>
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<td>$q_0$</td>
<td>Chart Density</td>
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<td>$\rho$</td>
<td>Current Density</td>
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<td>$\omega$</td>
<td>Angular Frequency</td>
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<td>Z</td>
<td>Impedance</td>
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<tr>
<td>$X_C$</td>
<td>Capacitive Reactance</td>
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<tr>
<td>$X_L$</td>
<td>Inductive Reactance</td>
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CHAPTER 1

INTRODUCTION

1.1 Motivation

Space suit fitting and design have been of serious concern for many decades in the space exploration industry. For space missions to be successful, the space suit has to fit the astronaut appropriately, although this is not always the case. With the limited sizing options and number of space suits for all astronauts of different body types to share, there is musculoskeletal injury associated with how the suit is fitting [1-10]. Appropriately sizing current space suits and new designs to alleviate these musculoskeletal injuries, specifically in the shoulder joint, must be of greatest importance to accomplish all space missions safely and successfully. Throughout the years of space missions, curiosity has led humans to discover many new aspects of our solar system that have even been observed by astronauts during space travel and space exploration. The National Aeronautics and Space Administration (NASA) has helped fill this gap in knowledge of space exploration by sending astronauts to explore outside the atmosphere of the Earth since the mid-20th century. Beyond the atmosphere of the Earth, astronauts have almost completed the building the International Space Station (ISS) as a space laboratory setting to conduct research and there have been people on board constantly for the last 15 years [11]. In order to accomplish this construction, the work on the outside of the ISS requires the current space suit, the extravehicular mobility unit (EMU), to be worn while completing vigorous tasks. These tasks require the use of heavy tools and machinery to be performed with limited shoulder mobility due to the current fit of the suit [10]. Other than trips to the ISS, humanity has set foot on the moon to collect lunar samples, which could only be executed with a pole as they could not reach down to collect the samples with their hands due to the restricted mobility [12]. Space
exploration is still in deep discovery as the main objective that society wishes see in their lifetime is for humanity to set foot on Mars. A trip to Mars will be the longest exposure a human has encountered in a microgravity environment, yet the training wearing the EMU will be immensely strenuous on the body [13]. The longest a human has spent in microgravity is 342 days, which was done by Scott Kelly from the United States and Mikhail "Misha" Korniyenko from Russia, is a space mission known as the "Year in Space" [14]. This type of space exploration study and space mission is vital to understand the human body and how biological parameters change in space. However, astronauts would not be able to perform space missions, like the "Year in Space," and future extended space missions to Mars without the vigorous and extensive training while wearing the EMU that comes along with it here on Earth.

Figure 1: Shoulder joint abduction demonstrating the contact of the clavicle bone to the scye bearing joint of the HUT (image courtesy of NASA) [10].

A study approximates that every one hour that is estimated to be spent performing an extravehicular activity (EVA) in space requires roughly 12 hours of training to be done on Earth [8]. When astronauts go through training on Earth before going into a microgravity environment, they are required to wear the entire space suit as if they were performing an EVA
space mission [10]. This training performed on Earth is primarily done at the Neutral Buoyancy Laboratory (NBL) located in Houston, Texas. This lab contains a large indoor pool filled with 6.2 million gallons of water that astronauts can submerge themselves in and enable them to feel the weightlessness that they would feel in microgravity. The NBL contains segments and components of the ISS that allow the appropriate training to be done for successful practice prior to space missions [8]. In order to fully prepare astronauts for successful EVA space missions, the amount of training done in the NBL using the necessary tools and rehearsed body orientations must be done. The EMU is not currently custom fit for every astronaut that is going into space [10]. This limitation leads to the numerous issues of musculoskeletal injuries due to the lack of full mobility, especially around the shoulder joint. The range of motion (ROM) limitations that the astronauts face while wearing the EMU has led to many new space suit designs to attempt and optimize movement [15, 16]. On the other hand, there are still many unknowns from person to person on how the suit fits prior to training and post donning that cannot be quantitatively measured. Current methods of sizing the suits are mainly based on linear and anthropometric measurements of the astronauts, while some use laser scans of the body to try and optimize fit. The major component of the EMU that causes these musculoskeletal injuries are with the hard upper torso (HUT), which is composed of a fiberglass shell and contains metallic scye bearing joints [10]. Figure 1 illustrates the limited clearance that the shoulder joint has from the HUT when moving the shoulder joint. There is limited sizing that is expected to fit all astronauts from the 99th percentile male to 5th percentile female; the universal sizing method saves money and allows multiple astronauts to share EMU components, although limited HUT sizes hinders the ROM of the shoulder joint [10]. Being able to identify how much clearance is between the surface of the body to the metal of the HUT around the
shoulder joint would be able to provide valuable information regarding how the suit is fitting after donning and before long training sessions or space missions begin. The incorporation of multiple wearable proximity sensors around the shoulder joint to detect the clearance of the scye bearing joint to the shoulder joint will greatly assist in suit fit to avoid musculoskeletal injuries.

1.2 Objectives and Specific Aims

The primary research objective of this thesis is to develop a wearable electromagnetic resonant spiral proximity sensor that enables the ability to produce real-time measurements for proximity distance between the shoulder joint and the metal component of the HUT. This objective can be achieved through a few key specific aims:

1. Development of a novel radio frequency (RF) resonant spiral proximity sensor that can be incorporated into the extravehicular mobility unit (EMU).
2. Determine a quantitative measurement of proximity detection to a metallic conductive material, which resembles the scye bearing joint of the hard upper torso (HUT).
3. Development of a liquid cooling and ventilation garment (LCVG) apparatus to rest the wearable proximity sensor on in order to measure clearance to the scye bearing joint.
4. Investigation of multiple wearable proximity sensors being used simultaneously while introducing a curved surface environment.

1.3 Thesis Outline

1. Chapter one introduces the motivation along with the primary objectives and specific aims.
2. Chapter two presents a review of relevant literature on the space suit with their major components, space training done on Earth before space missions are performed, how the space training leads to shoulder injury, countermeasures that have been addressed to
alleviate this issue, and the fabrication and operating principle of this wearable
electromagnetic resonant spiral proximity sensor.

3. Chapter three discusses the first study that was performed which investigates proximity
detection to a metal plate using the wearable proximity sensor in the presence of the
LCVG. Two wearable proximity sensor designs are investigated to test their accuracy
and repeatability to metal with and without the presence of the LCVG. The results show
differences in the wearable proximity sensor responses and when the LCVG is included
in the environment.

4. Chapter four discusses the second study that investigates the multiple wearable proximity
sensors being used at the same time. Three wearable proximity sensors being used in an
array can give more valuable information that pertains to how the suit fits at multiple
locations. The introduction of a curved metallic environment using this array of wearable
proximity sensors is also investigated to simulate a realistic environment.

5. Chapter five is a discussion of the future work with this project and how this work can be
expanded further.

6. Chapter six provides an overall summary and conclusion of this work addressed in this
thesis.
REFERENCES


CHAPTER 2

LITERATURE REVIEW

2.1 Extravehicular Mobility Unit (EMU)

There have been thousands of hours logged from astronauts and cosmonauts for space missions to the ISS and the moon, while there will be drastically increased number of hours being logged when the trip for Mars is planned [9]. These successful space missions would not have been possible without the engineering and fabrication of a spacecraft that is able to withstand the environmental changes that arise when entering a microgravity setting. The conditions that humans live with on Earth must be maintained and carried in a spacecraft in order to keep the environment controlled with similar atmospheric conditions to that of Earth. This capability of the creation of a spacecraft has led to multiple achievements of space exploration, but became limited when astronauts needed to travel outside of the air locked spacecraft [17]. Having the capability to get out of a spacecraft and collect samples or fix exterior spacecraft components would lead to substantially more knowledge of space. This need proposed the idea to create a unique version of a spacecraft designed for a single human to contain life support known as the Extravehicular Mobility Unit (EMU). A spacecraft with the size and shape to harness a human must be able to allow mechanical movement of the limbs for necessary tasks to be performed, while also protecting the astronaut from any potential harm from the microgravity environment. Construction of the EMU has been through years of trial and error to obtain the information that is currently used today, but this suit still expresses various limitations that mostly revolve around mobility. Project Mercury was labeled as the first man-in-space program where the objectives were to orbit a manned spacecraft around the Earth, investigate human ability to function in space, and successfully recover man and spacecraft [18]. This project
proved that humans could successfully survive in space, whereas Project Gemini helped build on this knowledge to prepare for moon landings. Project Gemini was the first United States spacewalk and it used a new vehicle to send astronauts into space and discovered the knowledge that humans could safely stay in space for a few weeks [19]. Both projects were huge milestones for the construction of this gas pressurized space suit and discoveries on human spaceflight, but there had to be further modifications made that allowed for new dimensions of mobility. The Apollo program further investigated space and human characteristics in microgravity by completing 11 spaceflights and Apollo 11 involved the first landing on the moon [17, 20].

![Buzz Aldrin on the moon](image)

Figure 2: Buzz Aldrin setting foot on the moon during Apollo 11 space mission on July 21, 1969 [21].

One giant leap for mankind to successfully land on the moon in July of 1969 (Figure 2), required an EMU to withstand the exterior pressure environment without sustainment from the main spacecraft, while also allowing enough mobility to retrieve almost 50 pounds of lunar material [22]. The EMU that was used in this successful landing on the moon for the United States was created by the International Latex Corporation of Dover, Delaware, which was used for during the Apollo Program. This exact EMU that Aldrin wore is that is still holding together
in one piece to this day [23]. This suit that they generated still has similar components 40 years later, but can now be considered as the key baseline design for future space suit construction and engineering [12]. Although these suits were not custom made to fit each individual astronaut, like before in Project Mercury and Gemini, due to financial issues that arose with more astronauts coming in, the suit could no longer be directly tailored for every person [17]. Expense of the EMU became a major issue as more astronauts have been recruited and not all of them could receive a specialty sized suits for themselves [12]. This concern lead to new suit designs that have separate individual components with universal sizing methods that can be more catered for each person without sizing the entire suit for one astronaut. There are a few components of the suit are created for specific anthropometry of each astronauts where universal sizes are not satisfactory, such as the gloves; although these universal components are able to fit different sized crew-members made manufacturing easier and more cost effective. This change made the incorporation for additional astronauts to join the force to participate in space travel and space exploration that was a limitation beforehand. The key benefit to universal sizing of suit components is the amount of money that is saved, although they do introduce sizing concerns to those astronauts with different body types. For example, two astronauts could be the same height and weight, but have different body types and weight distributions that may not allow for a comfortable fit inside the suit. Current EMU suits are being designed to reduce overall size and weight with the purpose of increasing mobility for future trips to the ISS and the eventual trip to Mars. Ever since the successful Apollo mission to the moon, there has become a suit component standard that is studied and investigated throughout the years that these new suit designs will follow. As a new suit will take years or decades to develop into practical applications, incorporating biomedical sensors and monitoring systems into the current EMU is more feasible for faster application.
The Extravehicular Mobility Unit (EMU) with a few of the major separate components that the suit encompasses, such as the helmet, hard upper torso, lower torso assembly, gloves, LCVG and the arm assembly (image courtesy of NASA).

The EMU that is used in the space shuttle missions is comprised of 14 layers to protect astronauts from external thermal regulation, manage internal temperature, defend micrometeoroid garment protection, etc. that is all made with various flexible materials and blends. When the EMU is fully assembled as a spacecraft for a single crew-member, there are nine separate major items that the suit comprises of in order to provide all the necessary life support for successful space exploration [17]. Figure 3 provides an illustration of the EMU when with a few of the major components that the suit is comprised of around it. These assembly items that the EMU contains provides a baseline space suit that new suits being designed tend to follow as it has showed reliable safety and success [12]. The first separate item layer that is worn is the liquid cooling and ventilation garment (LCVG); it resembles tight fitting long underwear that has
tubes woven through it for maintaining astronaut temperature. The inner and outer lining of the LCVG are made from Nylon and spandex material to give a tight fitting form factor with this being three of the 14 layers [17]. The additional layers on top of the LCVG, which are primarily made for micro-meteorite protection, are made of Kevlar, multi-layered aluminized Mylar, and other fabrics that attribute to additional thermal protection [17]. On top of the LCVG lies the hard upper torso (HUT), which is made of a fiberglass shell that acts as the centerpiece for the major connections of other major component items. Figure 4 illustrates a crew member in the processing of donning the HUT. These two components, LCVG and HUT, is a huge area of concern for musculoskeletal injuries that limit mobility [10]. The tubing material is not extremely flexible, while the rigidity of the HUT hinders shoulder joint movement. The arm assemblies, lower torso assembly, and helmet are what attached directly to the HUT via the scye bearing joints that create the air lock seal. The other components consist of a small in-suit drink bag on the inner wall of the HUT, a communication cap under the helmet, gloves that attach to the ends of the arm assemblies, and lastly, the ancillary support is comprised of a large number of items that includes the primary life support, waste garment, and others that is worn on the back connected to the HUT [17]. Each of these suit components are vital to the astronauts for them operate tasks outside the space station without the environmental changes that microgravity will cause to their bodies. Although these are all pivotal for survival, there are still some components that need modifications to offer more mobility and monitor other aspects of their health after exposure to long durations in microgravity. Research is currently under investigation
of this issue of suit fit with new components and suit designs for specific applications being tested as well as biomedical monitoring for more quantitative assessments.

![Crew member wearing the cooling garment about to don the hard upper torso (image courtesy of NASA) [24].](image)

Future design and practical application of the spacesuits are based on the original Shuttle EMU components as mentioned before, where the majority of other suit designs modify these components for their own particular application. Enhanced spacesuits have been created along with completely refurbished suits, such as Z-series spacesuit. These suit designs provide much more mobility than the EMU suits and specifically give the shoulder joints a larger ROM [12]. Suit designs like this have been in prototyping phases for nearly a decade and in order to alleviate this issue of mobility and other limitations that the suit causes, while incorporation of biomedical monitoring sensors would take less time to come into practical application [25, 26]. The primary purpose of these new suit designs is for mobility of the arms and legs for current space mission tasks, such as research on the ISS to continue to progress and expand as well as for humans to explore unknown areas of space. When exploring unknown areas of space, there
will be some obstacles that will require more vigorous locomotive activity. New space suit designs for long duration space missions, to places like Mars, have been in the works for decades and are still currently being designed and tested. There are currently designs that greatly increase the amount of mobility that the astronauts have, such as the Biosuit that is being researched and designed at the Massachusetts Institute of Technology (MIT), which has received interest of many news articles and publications throughout their process [27-30]. This Biosuit operates on a new pressure system that relies on mechanical counter pressure compared to the current EMU that used gas pressurized suits. The biggest downside to this new design is that the project has been in the workings for over a decade, while there is still little information on the extravehicular missions with this technology for practical application [28]. The information and practical use of these new suits designs is a drastic improvement from the original EMU, although this EMU is still being used for space mission training and space exploration. There would be much more benefit for the incorporation of a wearable proximity sensor to be implemented into the suit that will give quantitative values of suit fit. Space mission training is the primary use of these suits today with countless hours wearing the suit that does not provide the necessary mobility of the shoulder that lead to musculoskeletal injuries.

2.2 Extravehicular Activity (EVA) Training

For every space mission to be successful, there must be extensive amounts of training done for astronauts on Earth before leaving the atmosphere. It has been estimated that for every hour of planned in-space-flight mission, the astronaut has to undergo approximately 12 hours of training [8]. The primary focus for EVA training is for research studies and exploration while on the ISS, but these missions can still last from weeks to months long [11]. According to the estimated space flight to training ratio, this accounts for hundreds of hours training that must be
completed for these types of space missions. Once the trips for extreme duration space flights to Mars become more feasibility, the number of hours spent performing EVA training will dramatically increase. With the frequency of EVA hours increasing, there is a demanding need to improve the full body space suit for mobility "by a factor of four" to account for future planetary exploration [31]. This becomes a major issue as the vast majority of spacesuit related musculoskeletal injuries come from the hours spent during EVA training on Earth, rather than during actual EVA missions to space. When conducting an EVA space mission, the astronaut is not exposed to as much time in the EMU as they do when they are training in the NBL. Before training even begins and the EMU suit it put on, sizing and fitting for each of the space suit components is done that is done through anthropometric measurements and laser scanning. This alludes to the issue that there is no objective or quantitative value of how the suit is fitting after the astronaut puts on the suit other than them giving their subjective opinion [10, 32]. When suit designers are evaluating the dimensions of the astronaut, they need to know the amount of adjustability the suits need to be usable without the higher risk of injury. This is where the wearable proximity sensor will have the prospective application. After the suit is sized, the EVA training begins with putting on the space suit, known as donning, which takes approximately 15-30 minutes [17]. Once the donning process is complete, the astronaut can then begin their training that is primarily done in the NBL. The Johnson Space Center in Houston, Texas houses the NBL which is a large indoor pool of 202 feet in length, 102 feet wide, and 40 feet deep that contains replicas of distinct components of the ISS [1, 8]. This large pool allows for life size ISS replicas to be used as well as the astronauts wearing the EMU to experience a microgravity environment by fully submerging themselves which gives them a feeling of weightlessness. The tasks that astronauts perform during the EVA training in the NBL varies from person to person
depending on the planned space mission, while some only need small training sessions with experience of different momentum and force exertions and others needing hands on with heavy tools [33]. Others that require more extensive training sessions are at higher risk for injury, not only due to more training sessions, but they also must go through use of all different types of heavy tools and machinery in varying orientations of the body [8]. Figure 5 demonstrates an astronaut performing NBL training practicing using the EMU in a microgravity environment. This type of extensive training leads to the greatest amount of musculoskeletal injuries around the shoulder joint due to the continuous repetitive movements and contact with the HUT. After training is complete, injuries are assessed, and recovery is done for the aide of prevention for future injuries [8].

![Figure 5: NASA astronaut doing underwater training in the NBL (image courtesy of NASA).](image)

In order to prepare each astronaut for a successful space mission, EVA training can begin 12 months prior to the EVA flight depending on the expense, difficulty, and duration of the mission. The amount of training that can come from long duration missions to the ISS is an expensive cost for physical and mental ability of the astronaut to face [34]. When some astronauts are going through the basic training in the NBL to become suit qualified, this requires approximately 12 hours in the NBL [8]. Even with this minimal amount of training to get suit
qualified, this can still a cause for concern in terms of musculoskeletal injuries around the shoulder joint. Therefore, from the more advanced and trained astronauts to the ones in the beginnings of training, there are still hundreds of hours recorded training in the NBL throughout their careers[25]. Throughout training, there are some limitations that are faced during EVA training in the NBL that hardly anyone would realize was an issue. The most significant example is the act of gravity when training in the NBL. When the astronaut is wearing the EMU and fully submerged under water, the suit is considered weightless, although the person inside the pressurized suit is not weightless. The astronaut inside the suit still experiences the forces of gravity when underwater, whereas this occurrence would not take place outside the atmosphere of the Earth [25]. Additionally, there must be extra weight added to the EMU during underwater training as the suits still tend to float and does not mimic a truly microgravity environment [1]. Due to these issues, when the more advanced training is taking place with heavy tools and they are performing inverted body positioning, there are shifts of the body inside the suit. These shifts of the person wearing the suit encounter one key component of the suit, the HUT. Constant and repetitive contact between the shoulder joint and the metal of the HUT is a significant cause of discomfort and musculoskeletal injury [8, 10, 25]. Astronauts will likely perform approximately 24 hours a week of EVAs to train for exploration, construction, and maintenance for future space missions to other bodies of land [1]. As the number of EVAs training hours increase with the current expectations for trips to Mars, it is vital that there is a firm understanding of the EMU suit system designs. The key design parameters of the EMU that need further understanding from person to person includes the pressure of the suit, weight, mass, center-of-gravity location, ROM, and overall safety [1]. There have been a total of over 100 EVA missions to the ISS for mostly construction and research which where there has been nearly
1,000 hours spent for construction for over the last decade, **Figure 6** demonstrates an example of this construction [11, 34, 35]. Since there has been a human in space for more than 5,000 days, the living quarters are expanding to become more comfortable and extensive research is being done to learn more of what space has to offer [11]. All of these successful missions would not be possible without the proper training and skills gained that lead up to the missions at months in advance [34]. As trips to the moon, Mars, and other asteroid exploration hopes to continue, along with the construction and maintenance of the ISS ongoing, there will be a significant increase in EVA hours [2]. With EVA hours increasing in number and the amount of crew members performing training also increasing, these musculoskeletal injuries that have been continuing to happen need further investigation and evaluation for adjustments to be made. The introduction of a wearable proximity sensor will significantly aide in the overall decrease in quantity of shoulder joint injuries that have been occurring for decades. There have been many noteworthy studies done to understand why this issue is occurring, with statistical evidence and research with their own approaches [36].

![Figure 6: Astronaut performing a spacewalk to fix a faulty pump on the exterior of the ISS (image courtesy of NASA) [35].](image-url)
2.3 Astronaut Shoulder Joint Injury

It has been demonstrated that training in the space suit underwater in the NBL is the highest cause of musculoskeletal injuries and the amount of hours training is only increasing [34]. One of first studies done to examine this issue was in 2002 by creating a shoulder injury tiger team to evaluate the risk of shoulder injury that is associated with EVA training in the NBL. The tiger team discovered that two of the 22 astronauts they surveyed needed surgical intervention [10]. Reports have also been made that 25 shoulder surgeries have been performed since 1995 as it relates to EVA training and spacesuit design. Of these astronauts who had to get the shoulder surgery, half of them attributed an event or mechanism of their injury relates to training with the planar HUT [5]. These statistics address the significance of the complication that pertains to mobility of the shoulder joint in the suit; this surgical intervention leads to months of time they could have been preparing for a space mission and instead are going through rehabilitation. The rehabilitation of the shoulder joint takes longer than a hinge joint, such as the elbow, as the shoulder joint provides the greatest amount of mobile capability [37]. The shoulder joint is considered a ball and socket joint that gives an indefinite number of axes for motion that makes the anatomy and physiology more complex than other musculoskeletal joints. The complexity of the shoulder joint that is comprised of multiple bones, ligaments, and muscles, give the necessary mobility and stability. There are three major bones of the shoulder joint that consist of the humerus, scapula, and the clavicle. The humerus is the bone of the upper arm between the elbow joint and the shoulder joint, the scapula that is commonly known as the shoulder blade in which the humerus fits into. This joint between the humerus and scapula is a ball-and-socket joint called the glenohumeral (GH) joint or commonly known as the shoulder joint where the head of the humerus fits into the socket of the scapula [37, 38]. Above the part of
the scapula that lies inferior to the humerus is the clavicle or also known as the collarbone. This bone lies horizontally from the sternum (center of the chest) to the scapula which holds the arm away from the trunk of the body. This gliding joint between the scapula and the collarbone is the acromioclavicular joint, while the sternoclavicular joint is between the clavicle and the sternum. The GH joint provides the most mobility out of every joint in the body, this allows for the muscles to exhibit flexion, extension, abduction, adduction, external rotation, internal rotation, etc. Although with the great mobility causes a higher likelihood of injury that can lead to dislocation or stress and strain of the complex arrangement of ligaments and muscles that hold all these bones together. There are four major muscle-tendon groups that attach the humerus to the scapula is known as the rotator cuff. The muscles of the rotator cuff include supraspinous, infraspinatus, teres minor muscles, and the subscapularis. In between these muscle groups of the rotator cuff is the bursa, which is a fluid sac that allows for lubrication of the muscles to easily slide past one another [37, 38]. Figure 7 illustrates the anatomy of the GH joint with the major bones and muscles that make up the rotator cuff. This area of the body is at the highest risk for concern when astronauts are training in the NBL as their repeated movements in various body orientations with the use of heavy tools can cause contact and strain injuries with the HUT. These repeated movements and overuse of the rotator cuff is due to the astronaut compensating for the lack of mobility.
There has been evidence of shoulder related injuries during training in the NBL since the late 1990s with suit designers, medical personnel, and engineers inspecting preventative factors to mitigate this concern [10, 39, 40]. The EMU shoulder injury tiger team was created in 2002 to evaluate the relationship between shoulder injury and EVA training in the NBL. Some of the major risk factors investigated were limited ROM, tasks during inverted positions, overhead tasks, repetitive motions, heavy tool use, and training frequency that were compiled into a report [10]. Dave Williams conducted this survey to evaluate the concerns of shoulder injuries during EVAs as there was a clear relationship between the two, although no previous evidence and data of the matter existed at the time. Williams was able to recruit 22 astronauts to participate in his shoulder injury survey during their EVA training exercises. This group of participants averaged 43 year of age and almost every person described themselves as athletic. Three of these participants were female and one of the three reported minor shoulder pain during training in the EMU. While overall, 14 of the 22 that were surveyed experienced some degree of pain to the
shoulder joint with two of them needed rotator cuff surgery. Prior to the survey and experiment, there were ten astronauts that had mentioned preexisting shoulder injury. These shoulder injuries that occurred during the experiment were classified into minor and major injuries. Classification of minor injuries were seen to contribute to preforming tasks in an inverted body position, frequency of runs in the NBL, suboptimal suit fit, and lack of appropriate padding in the locations of most impingement [10]. The major injuries that were seen were due to the limitations of normal shoulder mobility using the HUT in the EMU, inverted body positions, overhead tasks, repetitive motion, use of heavy tools, and frequent runs in the NBL. These minor injuries required minimal medical attention, while the major injuries required extensive medical attention and possible surgical intervention [10]. As these findings suggest, it is evident that the rigidity of the HUT around the shoulder joint can be attributed as a main cause for concern of musculoskeletal injuries. Figure 8 demonstrates the irritation that HUT causes when performing EVA training in the NBL.

Figure 8: Demonstration of injury caused by the HUT after training in the NBL. A. Anterior view B. Lateral view C. Posterior view (image courtesy of NASA) [10].

Findings from the tiger team report indicated that from 64% of them had experienced some degree of shoulder pain during EVA training in the EMU and with 14% of those needing surgical treatment, they recommended that appropriate action for a study to evaluate all types of injury associated with EVA was needed [10]. One of the key parameters to investigate to
alleviate this shoulder joint problem is how the suit is designed and how it fits from astronaut to astronaut. When examining the findings of suit fit measurements in the survey, they found that when taking measurements to choose the appropriate suit size, they base it on anthropometric linear distance measurements that are taken between landmarks on the body. An example of this is taking distance measurement from shoulder to tip of the finger or from shoulder to shoulder as illustrated in Figure 9. Although the determination of where these landmarks are can be subjective from person to person that is taking the measurements with human error being a contributing factor as well [10]. From this finding, they recommended to create a database for EMU sizing for all these anthropometric measurements and implementing a full-body laser scan for all those astronauts performing EVA training. This suggestion seemed to be logical and could potentially prevent sizing issues, although after the size of the suit components is determined, one of the major issues with suit sizing is the changes to the shape of the body over time. Measurement for suit sizing could be weeks to months before they get their suit on for training in the NBL and these body changes could result in higher likelihood of shoulder injury. Additionally, when training is complete and the astronaut enters a microgravity environment, there are changes that happen to the body that could influence suit fit, such as elongation of the spinal column and fluid shifts in the body [10]. This poses the issue that there is no objective and quantitative method to assess how the suit fits on the crew member after the suit is on. Moreover, there is not even suit fit quantification during NBL training or during a space mission when wearing EMU. They wrote as a recommendation for a fit check procedure to be implemented which includes an objective assessment of functional mobility in the EMU [10]. This addresses the motivation for this study, that there is a lack of knowledge of suit fit for the engineers and space suit designers after suit donning is complete.
Figure 9: Suit designers taking measurements of the astronaut after donning the EMU (image courtesy of NASA) [10].

2.4 Countermeasures to Astronaut Injury

NASA understands that this is a current issue and has been undergoing numerous tests and discovering new findings since before the Apollo space mission. There have been numerous papers and documents from NASA addressing this issue [1, 6, 7, 10, 41], while one contributing author even writes a letter of support for this project as an objective application to help resolve the problem [1]. This apparent issue has led to multiple prototypes of space suits designed with different improvements in mind. Soft suits, such as the Modified ACES, Demonstrator Suit, and Mobility Mockup, are designed with the concept of increased mobility, although are not designed for longer term missions. ILC in Dover has designed the REI-Suit and Z-1 suit, while other universities have designed the MX-2 and Biosuit from the University of Maryland and MIT respectively [24, 25]. Some concepts work on all aspect changes for overall improvement advancing design and operations, while others only focus on specific applications and capabilities. New suit types are still ongoing and can give human capabilities within the environment, although may not directly account for the movement within the suit that the wearer
faces. While a whole new suit design or components redesigned for person to person is ideal, but it is not realistic or feasible. If the development and replacement of one component of the EMU, the HUT, would be priced between 5-15 million dollars with at least 5 years to implement into practical use [10, 12]. Therefore, a solution to keep the design of the current system with other approaches to be investigated to objectively measure suit fit to avoid future injuries to the shoulder joint.

There have been further studies that have investigated this issue pertaining the musculoskeletal injuries of the shoulder joint not only with NASA, but with various research institutes as well. For example, Dava Newman and her research team at MIT have taken interest in human performance in terms of bioastronautics and engineering for over a decade with primary work addressing space suit mobility [25-29, 31, 33, 36, 42-47]. One example inspects the statistical analysis that has been quantified to explore the underlying cause of these musculoskeletal shoulder joint injuries [36]. Bideltoid breadth, expanded chest depth, and shoulder circumference were the most important measurements that attributed to these injuries in the shoulder joints with predictor variables being percent time in the HUT, training frequency, and recovery. They found that the time of training inside the HUT attributed to the most incidents of injury even if the astronauts previous records did not show any history of shoulder injury [36]. Musculoskeletal modeling has also been done to analyze suit mobility for injuries that the EMU causes. Diaz at MIT conducted a human-spacesuit interaction analysis between the Shuttle EMU and a later iteration of suit, the MK-III spacesuit, to establish an understanding of mobility that attributes to these common musculoskeletal injuries [43]. This MK-III is an advanced hybrid space suit that is intended to pressurize at higher pressures compared to the Shuttle EMU can with similar components, but this suit allows for more mobility of the upper
extremities [24]. These types of analysis are excellent for understanding the problem to try and further understand how to mitigate shoulder joint injury, however none of these methods can objectively measure suit fit after donning. A study at MIT has been the first to do this with a pressure sensor array [25, 26].

![Polipo pressure sensing device worn on the arm with a total of 12 pressure sensors located on hot spots for impingement from the EMU [42].](image)

The Polipo is a pressure sensing system that was designed at MIT to measure real time movement inside the EMU. This wearable device consists of a network of 12 pressure sensors that are dispersed around the shoulder joint and down the arm, as seen in Figure 10. There were three movements done by three subjects to determine the force that was acted on each pressure sensor while wearing the MK-III space suit [42]. A pressure sensing device such as the Polipo has shown great promise to help identify location of impingement from the suit and how much pressure the suit is placing on specific locations. Although there is still an unknown quantitative value of how much clearance the shoulder has before encountering the scye bearing joints of the HUT. By incorporating a wearable proximity sensing system will add to this quantitative
evaluation of suit fit post donning, although wearable proximity sensors are not common. There are many types of proximity sensors such as ultrasonic, inductive, capacitive, and photoelectric [48]. Ultrasonic sensors are the primary type used for proximity application and work by sending sound waves at a target and the sound waves reflect, the device then measures the echo and can compute the distance away the target is [49]. These types of ultrasonic sensors have reliability to detect distance for proximity detection [50]. One study uses an ultrasonic sensor to measure respiration rate, this has a 0.3mm resolution and detection distance from 100-1000 mm [51]. As this is a great resolution for long distances, these ultrasonic proximity sensors have more difficulty with short distances that would be needed inside the EMU. Additionally, the size of the device itself measures 20x42x15mm and is too large to fit inside the suit [51]. These types of proximity sensors do not have the wearable form factor that would enable a wearable device. For the wearable proximity sensor to be incorporated into the suit, it must be an extremely thin design and be able to form to a curved environment. This gap can be filled with the use of radio-frequency based sensors that can achieve flexibility while maintaining a paper-thin design. Although the major issue with these devices that use electromagnetic fields is the presence of metallic components [52-61]. As the scye bearing joint of the HUT is made of metal, this type of proximity sensor using RF would generally be avoided, but this wearable electromagnetic resonant spiral proximity sensor presented in this thesis will address this concern.

2.5 Wearable Electromagnetic Resonant Spiral Proximity Sensor

2.5.1 Fabrication

These electromagnetic resonant spiral sensors are designed and manufactured in house. The first step in production is the design of the spiral where number of turns and geometrical shape must be determined. This process is done using a lab-built MatLab function to generate the
spiral pattern. After the spiral is generated, the corresponding trace can be adjusted as well as the gap width between the traces; all parameters can be modified to give alternate resonant frequency responses which will be addressed later in Section 2.5.1 and 2.5.2. Once the spiral is designed to the desired specifications, the loop antenna is created to surround the spiral. The spiral and the antenna are on the same plane in this case, although can be separated if the antenna is capable of coupling to the spiral. After the design process, the electromagnetic resonator can be printed. The printing process is done on a copper sheet that is backed with polyimide. The polyimide is a neutral dielectric material that will not influence the response of the resonator [62], although other materials can be used for other applications. For example, this type of resonator was backed with polyvinylidene fluoride for one application that relates to a temperature detection sensor whereas the temperature of the material changes, the permittivity also changes [63]. All other studies using this technology have used polyimide as a backing material [64, 65]. The resonator can then be chemically etched to remove the copper that is not part of the spiral or the surrounding loop antenna. Etching is done using ferric chloride in an etch tank as seen in Figure 11. After all the copper is etched, the copper trace and antenna are revealed and then covered by a layer of Kapton to protect the copper from any scratches, oxidation, or damage. Lead wires are then soldered to the antenna with a SubMiniature version A (SMA) adapter which will connect to a vector network analyzer (VNA) to produce the electromagnetic response.
2.5.2 Operating Principles

Figure 11: Etching of an electromagnetic resonant spiral sensor in ferric chloride.

Figure 12: RF waves inducing a current through the spiral trace, an oscillating electromagnetic field is formulated around it.

The theory and operating principles of spiral RF resonators and their expressions to calculate complex impedance, inductance, capacitance, and resonant frequency response have been well
established in the literature [66-71]. When sweeps from the incident RF waves, that originate from the loop antenna, interrogate the inner spiral trace, a current is induced through the copper trace [70]. This results in an oscillating magnetic and electric field (following Maxwell's equations and right-hand rule) that are generated around the spiral resonator [68, 69]. This electromagnetic field phenomena around the spiral trace can be seen in Figure 12. As the loop antenna electromagnetically couples to the spiral within, an electromotive force is induced which drives free electrons through the conductive copper trace to move back and forth that produces a resonant frequency response. This resonant frequency response is based on inductance (L), capacitance (C), and resistance (R), where movement of electrons in the geometrical design of the spiral trace cause inductance, resistance comes from the ohmic loss along the trace width, and capacitance comes from the gap between the traces [72]. Figure 13 illustrates a side view of the resonant spiral sensor and how the electric and magnetic field formulate around it to detect an object in its proximity. The magnitude of the magnetic field depends on the inductance that is calculated using Equation (1) [68, 69].

\[
L = \frac{\mu_0}{4\pi I^2} \int \int \int \frac{J(r_i) \mu_0 J(r_j) \mu_0}{|r_i - r_j|} d^3r_i d^3r_j
\]

where \(L\) is the total inductance, \(J(r_i)\) is the spatial current density as a function of \(r_i\) is the length of the spiral trace is, \(\mu_0\) is the free space magnetic permeability, \(\mu_r\) is the relative magnetic permeability, and \(I\) is the total current in the circuit. Whereas Equation (2) represents the calculation for the magnitude of the capacitance [68, 69].

\[
C^{-1} = \frac{1}{4\pi \varepsilon_\epsilon} \int \int \int \frac{\rho(r) \rho(r')}{|r - r'|} d^3r d^3r'
\]
where $C$ is the capacitance, $\varepsilon_0$ is the free space relative permittivity $\varepsilon_r$ is the relative permittivity, $q_0$ is the charge density, $\rho$ is the current density, and $r$ is the conductive trace length. From equations (1) and (2), there is dependency of the inductance of the relative permeability and capacitance of the relative permittivity of the material. When the design of the trace in the resonant spiral sensor is altered, including the geometrical shape, size, amount of turns in the spiral, trace width, gap width, all can result in distinct electromagnetic field [65]. As this electromagnetic field changes from the permeability and permittivity of the surrounding environment, the resonant frequency will also induce a change in response that can be quantitatively measured. Resonance occurs at specific frequencies where energy is stored in the electromagnetic field, where the first principle resonant frequency can be calculated using Equation (3) [67, 69].

$$\omega = \frac{1}{\sqrt{LC}}$$

(3)

where $\omega$ is equal to $2\pi f$ where $f$ is the frequency, $L$ is the inductance, and $C$ is the capacitance. This equation is a property of a lumped RLC circuit network that gives the electromagnetic spiral sensor resonant frequency characteristics that can be used to quantify proximity distance.
2.5.3 Resonant Frequency Characteristics

Resonant frequency is a specific frequency value that is determined by the resistance, inductance, and capacitance (RLC) of the circuit, or in this case, the conductive spiral. This behaves similarly to a LC circuit although the resistance influences the sharpness, deepness, and quality factor of the resonant peak [73]. Resonance occurs due to the energy that is stored in the magnetic field from the inductance and in the electric field from the capacitance. Scattering parameters can be used to describe this electromagnetic behavior by evaluating the reflection coefficient. The reflection coefficient describes the amount of electromagnetic energy is reflected or transmitted from the object that is impinging upon the electromagnetic field. One of the common types of scattering parameters is $S_{11}$, which represents how much power is reflected to and from the antenna where if the $S_{11} = 0$, then all the power is being reflected [73]. When all the power is being transmitted from the antenna, the scattering parameter creates a peak, where the minimum value is known as the resonant frequency. This phenomenon is illustrated in Figure 14 where the resonant frequency is indicated with a circle on the Cartesian coordinate system and Smith chart. The Smith chart is generated using polar coordinates that gives
impedance characteristics of the scattering parameters. Impedance \((Z)\) is a complex parameter that incorporates the resistance \((R)\) and the reactance \((X)\) as demonstrated in Equation (4).

\[
Z = R + Xj
\]  

(4)

The resistive component is represented as the horizontal line on the Smith chart, while the reactance can be characterized as inductive \((X_L)\) or capacitive \((X_C)\). When the resistance is at 0.0 then it is represented as a short circuit, while when at \(\infty\) as an open circuit. If the reactance is positive, then it is represented as inductive reactance and is located on the top half of the Smith Chart, while capacitive reactance is the opposite. Quality factor is another parameter that is measured through the reflection coefficient. This parameter is inversely proportional to the reactance and the resistance from the impedance. When the power is fully transmitted and produces the resonant frequency peak, this corresponds to the impedance being matched to the circuit, as indicated by 1.0 on the Smith chart in Figure 14. These spiral resonators produce multiple resonant frequencies that produce harmonics and other resonant frequencies. The current VNA being used can measure a frequency bandwidth between 9 kHz and 3 GHz [74]. Resonance is not always matched the load impedance of the circuit and therefore may not transmit all power to reach the ideal resonant frequency but will still allow for scattering parameters to be evaluated for proximity analysis.
Figure 14: Identification of the resonant frequency on a Cartesian coordinate graph and the corresponding resonant frequency location on a Smith Chart. The resonant frequency is 185.2 kHz, $S_{11}$ magnitude is -29.02 dB, impedance magnitude is 53.7 $\Omega$, and the quality factor is 0.00234.
REFERENCES


CHAPTER 3

IDENTIFICATION OF SHOULDER JOINT CLEARANCE IN EXTRAVEHICULAR MOBILITY UNIT USING ELECTROMAGNETIC RESONANT SPIRAL PROXIMITY SENSOR

3.1 Abstract

Shoulder injury is one of the most common phenomena that occurs for astronauts when they are training for space flight with the requirement of wearing the full space suit. The two major components of the space suit include the hard upper torso (HUT) that is primarily composed of a fiberglass shell which lays on top of the liquid cooling and ventilation garment (LCVG) that has water continuously circulating through a tubing mechanism throughout the body. These two components are the contributing factors that can limit the range of motion in the shoulders, potentially causing rotator cuff tears. The space suit currently does not contain any provision to account for this biomechanical interference to adjust for optimum range of motion. The objective of this paper is to propose a novel detection scheme using a wearable electromagnetic resonant spiral sensor that could allow a real-time quantitative value for proximity between the shoulder and the metallic component of the HUT in the presence of the LCVG. The first study investigated the ability of the wearable proximity sensor to detect the proximity of aluminum with no LCVG present, while the second study incorporated the wearable proximity sensor on top of the LCVG for a simulated suit environment. Results: Four scenarios were performed with two wearable proximity sensors resonating at different frequencies placed in an environment with and without the LCVG, where 10 repeated tests were used to train and an additional 10 to validate a regression learning algorithm. The experimental results indicated that the wearable proximity sensors in both open air and with the LCVG have repeatability to provide
a root mean square error (RMSE) of approximately 1 mm or less. This significant accuracy from when the wearable proximity sensors are touching the metal to 1 cm air gap distance is achieved allowing application into the space suit to provide valuable information for suit fit optimization.

3.2 Introduction

Common injuries that astronauts face during spaceflight and training are the result of interactions with the rigid components of the space suit that cause contact and strain injuries from hard impacts or repeated movements [1, 7, 8, 10]. Shoulders are highly vulnerable to these types of injuries and can be severe enough to require surgical attention that may prolong a space mission. When the mobility of the shoulder is compromised, this creates more strain on the rotator cuff muscles to compensate for these limitations [10]. Rotator cuff tears are one the most frequent types of shoulder injury amongst astronauts from these types of musculoskeletal injuries with a recovery time of up to four to six months [75]. There are currently several ergonomic suit designs that are being researched to address this issue along with 3-D scans of the entire body, although with these new designs and modifications, there is still an unknown quantitative parameter when the suit is worn [4, 27, 41]. Incorporation of a suit fit measurement will provide the necessary knowledge to properly adjust the suit after the suit has been donned to provide more optimal shoulder mobility. Until now, little information is known on human movement that fully interacts with the rigid inner workings of a spacesuit. The individual wearing the suit can identify that there is some discomfort, but does not know the underlying reason why or how the suit can be properly adjusted.

National Aeronautics and Space Administration (NASA) currently uses the extravehicular mobility unit (EMU) as their primary space suit for space flight missions to the international space station (ISS) and for extravehicular activity (EVA) training [8]. The base layer of the
EMU is composed of the liquid cooling and ventilation garment (LCVG) that contains a tubing mechanism woven throughout nylon and spandex lining materials that is able to aide in the maintenance of a healthy body temperature in extreme environments [10, 24, 76]. Components of the suit around the torso are made of rigid material can cause unnecessary rubbing and irritation on the skin, especially in certain types of movements of the shoulders or inverted body positioning [10, 76]. This rigid component is known as the hard upper torso (HUT), that is worn as the component of the EMU on the layer above the LCVG, is a rigid fiberglass shell that connects and seals the other portions of the suit together that contains metal scye bearing joints at the openings [76]. **Figure 15** illustrates a skeletal model of the shoulder with the metal scye bearing joint of the HUT from the EMU that shows little to no space between the clavicle and the metal. This metal scye bearing joint is one of the main underlying components that is causing the skin irritation, rotator cuff injuries, and other musculoskeletal shoulder joint injuries to the astronauts [1, 10, 24, 36, 43]. A proper clearance between the body and the scye bearing joint needs to be at least one centimeter around the shoulder joint to allow for sufficient range of motion for the shoulder [10].

![Figure 15: HUT model with indication of major components causing limited range of motion for the shoulders due to the scye bearing joints.](image-url)
The current technology that is being used to resolve this issue is limited, but stays mostly reliant on laser scanning with new biomedical sensor technology being introduced. Pressure sensors have been designed to determine the pressure that the suit is putting on the crewmember, however, this type of sensor does not provide insight on the clearance that shoulder has after donning [25, 42]. This knowledge presents a need for a new biomedical proximity sensor for a quantitative space suit fitting parameter. Other sensors that detect proximity distance, such as ultrasonic and infrared sensors, do not have a suitable form factor that enables placement in the EMU, have difficulty forming to the skin, and generally begin measuring distances at 0.4-0.5 meters. These types of proximity sensors can also have limiting factors when it pertains to being worn directly for an extended period of time [50, 77, 78]. Additionally, there are capacitive based sensors that can achieve this wearable form factor and can provide reliable reading in the millimeter to centimeter range, which this sensor has most resemblance to, although are generally not used in metallic environments. This electromagnetic resonant spiral sensor can be simply designed to provide what all these proximity based sensors can achieve with more reliability and accuracy. Radio-frequency (RF) antenna-based sensors can achieve this wearable form factor with a thin design and detect measurements from micrometer to meter detection range with both conductive and nonconductive material [79]. The wearable form factor of antenna-based skin patch sensors have been implemented in our previous work to measure limp hemodynamics, detection of volume changes, and measurements of changes in intraventricular stroke volume [64, 65, 72]. Most radio frequency identification sensors that rely on use of electromagnetic fields avoid the proximity to a metal environment as it weakens the intensity of the magnetic field that leads to inaccurate readings and alterations to the frequency response [52-55, 57, 61]. Metal in contact with an antenna can result in a dampened frequency response or
lead an inconsistent shift in resonance, whereas this current work will investigate a novel method to analyze this scenario.

This paper focuses on the use of an electromagnetic RF resonant spiral proximity sensor to determine the clearance between the suit and the astronaut wearing the suit. Measurement of proximity distance between the suit and the astronaut will provide vital information for proper suit adjustment and be useful as new HUT or suit components are designed. The HUT contains a metal component that drastically alters the response of the sensor, while the LCVG that is worn beneath, has water that circulates throughout the suit that will initiate a response detected by the sensor. Both of these will be implemented into the setup to analyze the response of the wearable proximity sensor. The objective of this paper is to propose a novel detection scheme using an electromagnetic resonant spiral sensor that could allow a real-time quantitative value for proximity between the shoulder and the metal component of the HUT in the presence of the LCVG.

3.3 Materials and Methods

3.3.1 Sensor Design

Proximity detection to metal was determined in two separate scenarios with two separate electromagnetic resonant spiral proximity sensors. The use of both wearable proximity sensors allows for future optimization of sensor designs and geometries of the copper trace for a suitable application with both seen in Figure 16. Wearable proximity sensor one uses a square planar spiral design with a loop antenna that surrounds a 15 turn copper spiral trace with width of 0.38 mm and a gap width of 0.65 mm. The second wearable proximity sensor uses a circular planar spiral with 30 turns with trace width and gap width of 0.35 mm and 0.18 mm respectively. The use of more turns and smaller gap width allows for more capacitive properties compared to the
first wearable proximity sensor, which is the reasoning for these two different designs. Both of the wearable proximity sensors are surrounded by a solid line loop antenna also made from a copper trace that interrogates the spiral. The two environments that are tested with both wearable sensors in proximity to metal are in open air as well as on the outside of an LCVG apparatus in proximity to an aluminum sheet that represents the scye bearing joint of the HUT. Applying a wearable proximity sensor on the outside of the LCVG allows for only air to be between the sensor and the metal, rather than placing the sensor directly on the surface of the skin, which will introduce more materials between the object that is wanted to be detected.

Figure 16: Sensor design of two sensors with different resonant frequency responses. A. Sensor one consisting of 15 turns in a square pattern with spiral trace of 0.38 mm and gap width of 0.65 mm with resonant frequency ~260 MHz. B. Sensor two consisting of 30 turns in a circular geometry with copper trace with of 0.35 mm and gap width of 0.18 mm with resonant frequency ~150 MHz.

3.3.2 Experimental Setup

The use of the wearable proximity sensors to be tested in the open air established a baseline reading of proximity detection with the setup shown in Figure 17. The wearable proximity sensor was adhered to a polystyrene foam block, due to its dielectric properties are similar to air, with little to no electromagnetic field interference [80]. The material under test, in this case an aluminum sheet that was adhered to another polystyrene foam block, was positioned parallel to the wearable proximity sensor with the air gap distance increased by steps of 0.5 mm up to 10
mm for a total of 21 distances measured. Data was recorded and collected at each of the 21
distances with 10 sweeps taken at each distance. After both wearable proximity sensors are
tested with this scenario, an LCVG apparatus that was made with elastic net dressing with 1/16
inch latex tubing threaded between. This LCVG was placed flat against the polystyrene foam
block with the wearable proximity sensor placed on top of the LCVG, therefore, allowed only a
medium of air between the sensor and the metal. This setup with the wearable proximity sensor
on the outside of the LCVG allows for future application inside the EMU as seen in Figure 18
with this self-made cooling garment. In order to create an environment with the LCVG, a
continuous flow of room temperature water was flowing through the LCVG tubing during each
test.

![Diagram](image.png)

Figure 17: Experimental setup that tested the response to the wearable sensor in proximity to the
MUT, in this case aluminum, with air as a medium. The wearable proximity sensor was powered
with an interrogation device by an external radiofrequency wave.

In order to test repeatability and accuracy of each wearable proximity sensor in both
environments, 20 total tests were performed for each of the sensors with and without the
incorporation of the LCVG. The first scenario was the use of the first wearable proximity sensor in air, scenario two was the second sensor two in air, scenario three was the first sensor one on the outside of the LCVG, and scenario four with the second sensor on the outside of the LCVG. Half of the 20 tests were used to train a machine learning algorithm and the other half was used to predict and validate the proximity distance response. The 10 trials that were used to train the algorithm were done with a 25% holdout validation. A fine regression tree learning algorithm was used to determine root mean square error (RMSE) values of the prediction tests. Scattering parameters for each distance was taken with 5001 data points and 10 sweeps at all 21 distances. All sweeps from every distance in all 20 tests were used for prediction and validation testing.

Figure 18: Wearable proximity sensor on the outside of the LCVG apparatus with air as a medium between the wearable proximity sensor and the metal component of the HUT. A. Wearable proximity sensor 1 on the cooling garment. B. Wearable proximity sensor 2 on the cooling garment.

3.4 Theory & Calculation

The operating principle of the RF resonant spiral sensors are described in detail in the prior arts of our previous work where the incident RF waves that originate from the loop antenna interrogate the spiral that induces a current in the copper trace [64, 65, 68, 72]. This causes an
oscillating magnetic and electric field to formulate around the resonant spiral sensor that shifts the resonant frequency when impinged upon. Current analysis with these resonant spiral sensors, which can be considered as a lumped RLC network, involves the use of tracking different electrical signatures at resonance, i.e. shift in resonant frequency, reflection coefficient, impedance, and reactance as the time-varying electromagnetic field is imposed upon. Although in this study, conductive materials come into play and the resonant frequency patterns are not as easily intuitive like in the prior work with these resonant spiral sensors. Data is collected and recorded through the R&S ZNC-3 vector network analyzer, which provides the real and imaginary reflection coefficient along the $S_{11}$ magnitude extracting the frequency and scalar magnitude of the reflection coefficient that is unit-less. Hence, it was necessary to deduce the relationship between load impedance and complex reflection coefficient for further processing and determination of the resonant frequency characteristics of the wearable proximity sensor near a conductive material. As the electrical load changes from inductive to capacitive or vice versa, the complex impedance of the sensor also varies based on the incident radio-frequency. Tracking the impedance response of the resonant spiral sensor provides further clarification of the electromagnetic interaction of the wearable proximity sensor with the metal component in the electromagnetic field. The calculation of the impedance can be expressed as a function of scattering parameters, $S_{11}$, and can be distilled into real and imaginary components through the following mathematical deduction:

$$\frac{Z_L}{Z_0} = \frac{1 + \Gamma}{1 - \Gamma} \quad (5)$$

Reflection coefficient can be interpreted as a complex quantity as it contains both the magnitude and phase information. The correlation between load impedance ($Z_L$), the characteristic
impedance \((Z_0)\), and the reflection coefficient \((\Gamma)\), can be expressed by equation 1, where the complex reflection coefficient can be written as equation 2. By incorporating equation 2 into equation 1, the load impedance can be further rewritten as equation 3.

\[
\Gamma = x + iy
\]  

(6) therefore, can be solved as:

\[
\frac{Z_L}{Z_0} = \frac{1-x^2-y^2 + j \frac{2y}{(1-x)^2 + y^2}}{(1-x)^2 + y^2}
\]  

(7)

where \(Z_L\) is the load impedance and \(Z_0\) is the characteristic impedance. It can be recalled that \(x\) is the real component of the reflection coefficient and \(y\) is the imaginary part of the reflection coefficient and from this, the real and imaginary components of the impedance can be represented as functions of the reflection by:

\[
\text{Re} \left( \frac{Z_L}{Z_0} \right) = \frac{1 - \text{Re}(\Gamma)^2 - \text{Im}(\Gamma)^2}{(1 - \text{Re}(\Gamma))^2 + \text{Im}(\Gamma)^2}
\]  

(8)

\[
\text{Im} \left( \frac{Z_L}{Z_0} \right) = \frac{2 \text{Im}(\Gamma)}{(1 - \text{Re}(\Gamma))^2 + \text{Im}(\Gamma)^2}
\]  

(9)

The right side of each equation can be multiplied by the source impedance that leaves the load impedance with its real and imaginary components [74]. These two components can be used to calculate the impedance magnitude and phase. The load impedance can be represented by the following equation:

\[
Z = R + jX
\]  

(10)

where \(Z\) is the impedance, \(R\) is the resistance, and \(X\) is the reactance. From these components, the quality factor can be calculated by taking the imaginary component of the impedance divided by
the real component of the impedance. This parameter is unit-less and characterizes the sharpness of the resonant frequency response which further signifies the quality of transmitted power from the resonant spiral sensor. The transmitted power from the resonant spiral sensor is an important parameter, because it also determines the sensitivity of the resonator as a wearable proximity sensor. Some of the transmitted power from the wearable proximity sensor gets reflected back to the sensing instrument when it detects an object with different permittivity in its sensing field.

3.5 Results

The tests for each wearable proximity sensor in all the experimental cases was done over multiple days. Repeatable readings between each test while data was collected appeared promising based on statistical accuracy and the sensitivity test from the regression learning.

3.5.1 Scattering Parameters

$S_{11}$ scattering parameters for all 21 distances with 10 sweeps per distance over 20 tests was taken. Each wearable proximity sensor had similar resonant frequency responses in both scenarios with and without an LCVG. The scattering parameters of the first test of each scenario can be seen in Figure 19 in a Cartesian graph, with all resonant frequencies shifting lower as distance is increased. As impedance plays a large factor at the resonant frequency, a Smith chart for the first test of each scenario is shown in Figure 20. It can be seen that when the wearable proximity sensor is in direct contact with the metal, the resonant frequency lies closer to the edge of the Smith chart. The resonant frequency response from the Cartesian and Smith graphs give valuable information that can determine predictor variables in the regression learning algorithm.
Figure 19: Scattering parameters for each distance that shifts downward from the wearable proximity sensor touching the metal (0 mm dashed line) to the wearable proximity sensor furthest away (10 mm dotted line) from the metal for both scenarios. A. Wearable proximity sensor 1 with no LCVG; B. Wearable proximity sensor 2 with no LCVG; C. Wearable proximity sensor 1 on the outside of the LCVG; D. Wearable proximity sensor 2 on the outside of the LCVG.

Figure 20: Smith chart for each distance that tracks the resonant frequency with bold circles with dot dashed line for each wearable proximity sensor in both scenarios. A. Wearable proximity sensor 1 with no LCVG; B. Wearable proximity sensor 2 with no LCVG; C. Wearable proximity sensor 1 on the outside of the LCVG; D. Wearable proximity sensor 2 on the outside of the LCVG.

3.5.2 Predictor Variables

There were six predictors chosen from the resonant frequency response information to potentially use for the regression learning algorithm which include, resonant frequency, $S_{11}$
magnitude, change in resonant frequency from the initial, impedance magnitude, change in impedance magnitude from the initial, and quality factor. Each of the six predictors were plotted against distance for all sweeps and all 20 tests as illustrated in Figure 21, which only shows the scenario with wearable proximity sensor two (circular planar spiral) on the outside of the LCVG as it shows most promise for application. Some predictors were more repeatable than others, although in order to give the most parsimonious data, a correlation matrix between each of the predictors was done to eliminate predictors that had strong correlation as seen in Figure 22 for the second wearable proximity sensor with the LCVG included. Correlation between each predictors for wearable proximity sensor two on the outside of the LCVG shows strong correlation (R>0.90) between impedance magnitude and the change in impedance magnitude. In this case, the change in impedance magnitude was removed as a predictor. Each wearable proximity sensor in both scenarios gave different correlations between each predictor, which was evaluated and predictors were chosen individually before using the regression learner.
Figure 21: Each predictor variable against distance for wearable proximity sensor two on the outside of the LCVG. A. Resonant frequency response; B. S11 magnitude at the resonant frequency; C. Change in resonant frequency from the initial starting frequency; D. Impedance magnitude at the resonant frequency; E. Change in impedance magnitude from the initial starting impedance magnitude at the resonant frequency; F. Quality factor at the resonant frequency.

Figure 22: Correlation plot for all six predictors for wearable proximity sensor two on the outside of the LCVG. The only predictors with a strong correlation (R>0.90) are predictor four and five being impedance magnitude and change in impedance magnitude.
3.5.3 Regression Learning

A fine regression tree learning algorithm was used for both wearable proximity sensors with and without the LCVG environment with 10 repeated tests to train and 10 tests to validate. The only predictors that were used in each environment were ones that had no strong correlation, where both wearable proximity sensors with no LCVG had four predictors, wearable proximity sensor one (square planar spiral) with the LCVG had three predictors, and wearable proximity sensor two (circular planar spiral) with the LCVG had five predictors. Each scenario had their own fine tree regression learning algorithms to predict the response. Data for the predictor variable from the regression learner are plotted against the actual values in Figure 23. This data indicated that the use of each wearable proximity sensor with no LCVG has the lower RMSE value of 0.72 mm and 0.57 mm for wearable proximity sensor one and two respectively for a range from 0-10 mm. Therefore when the LCVG is added to the environment, the RMSE for wearable proximity sensor one increases to 1.05 mm and wearable proximity sensor two increases to 0.93 mm for the same distance range. The coefficient of determination was used to show the strength of fit with each wearable proximity sensor with no LCVG had $R^2=0.95$ and $R^2=0.87$ respectively, while on the outside of the LCVG, wearable proximity sensor one had $R^2=0.83$ and wearable proximity sensor two had $R^2=0.93$. 
Figure 23: Distance prediction against actual distance using a fine regression tree learning algorithm with all predictors with no strong correlation. A. Wearable proximity sensor 1 with no LCVG (RMSE=0.72 mm, R²=0.95); B. Wearable proximity sensor 2 with no LCVG (RMSE=0.57 mm, R²=0.87); C. Wearable proximity sensor 1 on the outside of the LCVG (RMSE=1.05 mm, R²=0.83); D. Wearable proximity sensor 2 on the outside of the LCVG (RMSE=0.93 mm, R²=0.93).

3.6 Discussion

These results show novel application with an electromagnetic resonant spiral sensor to determine proximity distance to metal for space suit fitting application. This information and future use inside the EMU will provide insightful knowledge for space suit fitting parameters that will decrease likelihood of musculoskeletal injury that astronauts face. Sensing applications inside the space suit using this type of wearable proximity sensor allows for no change in astronaut performance, but will provide quantitative suit fit values for proper adjustment. These types of wearable proximity sensors can be easily woven into fabric of the LCVG in multiple locations that are in the hot spots for contact and strain injuries. Different wearable proximity sensor designs can be fabricated to fit proximity detection needs for different locations inside the suit that can be optimized for resolution at each placement. This type of technology will add
useful information to suit fit for astronauts after donning after the current methodologies of anthropometric measurements and laser scanning are performed. As the body changes in space and adjusts in microgravity environments, the use of this technology will be able to additionally provide quantitative parameters of suit fit after training or space mission has been completed. New iterations and designs for space suits could use this biomedical monitoring system as well for enabling proper clearance for shoulder mobility for their proposed designs.

This electromagnetic resonant spiral proximity sensor is working as both a parallel-plate capacitor and fringe capacitor as both conductors and non-conductors can be detected as this sensor produces both electric and magnetic fields. Both of these oscillating fields are impinged upon from materials under test that contain different dielectric properties that relate to their permittivity and permeability. More precise and sensitive measurements may be further investigated by looking upon the capacitance of the wearable proximity sensor taken from the impedance information to detect micrometer resolution. This electromagnetic resonant spiral proximity sensor is able to achieve a flexible design and thin form factor that other proximity sensors alike cannot with this capability of millimeter resolution. Designing and fabricating new geometrical parameters for these wearable proximity sensors with varying gap and trace width, along with number of turns, will change the electromagnetic field size and strength to gain more detection distance and keep the millimeter and micrometer resolution. This wearable form factor gives the technology multiple proximity applications that can be easily modified for proposed resolution and detection distances. For the two wearable proximity sensors used in this study, both show similar results in terms of accuracy and total distance detection, although wearable proximity sensor two (planar circular spiral) had better RMSE values than wearable proximity sensor one (planar square spiral) when testing with and without the LCVG. Resonant frequencies operating at lower frequencies theoretically provide this further detection distance,
while with the conductor in the electromagnetic field limits this proximity detection distance due to absorbing the field and production of opposing fields. The size of the metal plate used in this study may have been the result of this smaller proximity detection as the conductor absorbs the electromagnetic field whereas a different size and shape could produce a different response. Conductors in the presence of the electromagnetic field gives these resonant spiral sensors limitations on furthest distance that can be detected, but this study proves it is possible for accurate readings.

Future application inside the space suit will allow for more simulated environmental measurements to be taken and studied. Tests performed with these wearable RF resonant spiral proximity sensors inside the EMU environment will explore options of human trials in specific shoulder movements. Application inside the EMU will indicate which movements are the highest cause of contact with the HUT. These wearable proximity sensors will be able to give continuous quantitative results throughout the training or space mission and it will provide proper sizing to be determined as well as placement of the HUT beforehand. As training is the major cause of these shoulder joint injuries, proper suit fit and adjustment will be useful for all astronauts to avoid this type of musculoskeletal injury. This leads to the major limitation of the study that does not involve a perfect simulated environment with a curved surface of the metal scye bearing joint or the proximity sensor woven into the fabric of the LCVG. The next study with this wearable proximity sensor will integrate a simulated environment close to a HUT model with skin dielectrics introduced in the wearing an LCVG apparatus to determine locations of multiple wearable proximity sensors to be tested in a simulated environment.
3.7 Conclusion

This paper is able to present a new method of analyzing S-parameter data to determine proximity distance between an RF resonant wearable proximity sensor and a metal component, while incorporating a real life space suit setting with an LCVG apparatus. Using this method allows for the possibility to incorporate this wearable biomedical technology into a spacesuit. This data to be then used to locate where and at what distance the metal component of the EMU is to the wearable proximity sensor that is placed inside the suit. Using resonant frequency response values to train a regression learning algorithm provides an accurate detection and better insight on how the wearable proximity sensor is reacting to the metal in its proximity. The use of this study can then allow for astronauts using the EMU, for space flight or training, to be able to easily identify how to readjust the suit for comfortability and minimize the risk of injury.

3.8 Acknowledgements

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CHAPTER 4

DETERMINATION OF PROXIMITY DISTANCE TO A METALLIC SURFACE USING AN ARRAY OF ELECTROMAGNETIC RESONANT SPIRAL PROXIMITY SENSORS FOR ASTROANT SUIT FIT

4.1 Abstract

There is a quantitative measurement of suit fit that is needed after the suit is on in order to evaluate that there is proper clearance for the shoulder joint of the astronaut. If there is insufficient clearance for the shoulder joint, there is higher likelihood of astronauts to get shoulder injury. When the shoulder joint continuously comes into contact with the rigid metal components of the suit, injuries can be significant enough where surgery may be required. The purpose of this study is to investigate how an array of electromagnetic resonant spiral proximity sensors can determine proximity distance to metal. This array of wearable proximity sensors will be evaluated in a simple parallel environment and two curved environments. The two curved environments will test how the wearable proximity sensors react to different sized curved surfaces in proximity to a larger metal curved surface. Results indicated that the wearable proximity sensor that has exhibited primary contact with the metal is clearly apparent and the adjacent sensor can detect a response as well. As the size of the curved surface that the wearable proximity sensors rest on becomes closer in size to the curved metal surface, the adjacent sensors display greater responses. The use of multiple wearable proximity sensors in curved environment similar to the inside of a space suit will give more quantitative assessment of where clearance needs to increase around the shoulder joint.
4.2 Introduction

Astronauts currently working for the National Aeronautics and Space Administration (NASA) only have a limited number of space suits available that used for extravehicular activity (EVA) [12]. The primary use for these suits is for EVA training on Earth and working on the exterior components of the International Space Station (ISS) [34]. These space suits, known as the extravehicular mobility unit (EMU), are made up of various components that attach to a center rigid component, called the hard upper torso (HUT) [4, 8, 10, 34, 81]. This specific component is not sized for each specific astronaut, but they have general sizes that all astronauts have to share [24]. When there are only limited sizes of HUT components available, they do not always fit appropriately and limit the amount of movement the shoulder joint has [10]. The cost of producing new ones would cost millions of dollars and would take years to implement, therefore incorporating a sensing system inside the suit would plead beneficial for suit fit [12]. This issue of how the HUT fits leads to improper fitting and causes limited mobility if the HUT is not placed properly when donning. With this problem, NASA has even had to change their personnel for a planned space mission due to the inappropriately sized suits or limited amounts of them available [82]. The limited mobility becomes even more of a concern due to the musculoskeletal injuries that occur when the shoulder joint comes into contact with the HUT. The incorporation of a medical device to determine quantitative values of how the suit is fitting would dramatically benefit astronauts to make sure there is proper clearance the shoulder joint has.
Integrating a wearable proximity sensing device to determine the amount of clearance that the shoulder joint has would help determine suit fitting parameters. Proximity effects are most reliable and predominantly used when locating an object that is directly parallel to the system that is detecting proximity distance. This is primarily done with just one proximity detection system that is usually ultrasonic or capacitive based [50, 77, 79, 83-88]. On the other hand, when a curved surface is introduced as the object under test then the use of one proximity detection instrument may not be able to given reliable information. This is the case when only one proximity detection system is being used, although more information can be gathered when multiple proximity sensors are used. When multiple proximity sensors are surrounding an object, they typically can produce an image of what that object on the inside looks like and how far away it is. An example of this is a noncontact wrist location device where multiple sensing angle are surrounding the wrist proximity values are produced from what the sensors pick up [89, 90]. Medical devices serve as a detection scheme to determine what happens on the inside of the body, but not what is surrounding the outside. From the exterior, the body can be exposed to contact injuries of objects that cannot be seen. The use of a proximity detection array with a
wearable form factor will be able to determine how close an object could be from coming into contact with the body at multiple locations. This type of application for a wearable proximity sensor array is vital for astronauts when fitting their space suits. When the astronaut dons the suit, they have no quantitative value of how far away the suit is from their body to determine how the suit fits. If the suit does not fit appropriately, there is more likelihood of the body around the shoulder joint coming into contact with the rigid inner components of the suit, referring to the hard upper torso (HUT) [3-5, 7, 8, 10, 25, 26, 29, 34, 39, 43]. With limited amount of sizes of space suits, there is not always guarantee that one of these sizes is going to fit a given astronaut. The use of multiple proximity sensors placed around the shoulder joint inside the suit will give valuable information of where the suit may be more likely to come into contact with the shoulder joint, as demonstrated in Figure 24. Applying these proximity sensors that are able to flexible form to the curved portion around the shoulder joint will enable that there is sufficient clearance for optimal shoulder mobility. This paper introduces a group of electromagnetic resonant spiral sensors placed side by side on a curved surface that is detecting proximity to a curved object around it. The purpose of this study is to establish how multiple electromagnetic resonant spiral sensors in an array react when detecting proximity to a metal curved object, which represents the scye bearing joints of the HUT. The objective of this study is to quantitatively measure proximity distance of a curved surface at multiple locations to use to determine suit fitting parameters.
4.3 Materials and Methods

Three wearable proximity sensors with their own separate loop antennas were created with the same geometrical pattern and design. The wearable proximity sensors were circular planar spirals with 30 turns with a trace and gap width of 0.38mm and 0.18mm respectively, as seen in Figure 25. They were firstly placed next to one another on a flat surface and each were tested simultaneously in proximity to a metal plate in parallel to the wearable proximity sensors. This setup will be referred to as Experiment 1. The metal plate was made of aluminum, the same material as the scye bearing joint of the HUT, and was able to cover the entirety of each resonant spiral as to avoid any fringing electromagnetic fields around the metal. Proximity was done between zero millimeters to one centimeter with sweeps taken at every 0.5 millimeters (or 500 micrometers) to give a total of 21 distances measured. There was a total of 210 sweeps taken for the duration of the study for each of the three wearable proximity sensors with 10 sweeps taken at each distance. This parallel proximity test using three separate wearable proximity sensors was done to establish that there was a similar response from each, as the printing and etching between each varies.

Figure 25: Circular planar electromagnetic resonant spiral sensor with 30 turns of a copper with trace width of 0.38 mm and gap width between the traces of 0.18 mm.
Figure 26: Three wearable proximity sensors on a curved cylindrical surface in proximity to a metal plate placed on a polystyrene foam block.

The next study uses these same three wearable proximity sensors, although introduces a curved environment. When these wearable proximity sensors are placed inside the suit, they will not be on a flat surface or be in proximity to a flat metal plate. These wearable proximity sensors will be placed side by side on two different curved surfaces with different diameters (13.2cm and 11cm) and be in proximity to a larger diameter metal sheet (30.1cm). Larger diameter surface will be referred to as Experiment 2 and the smaller diameter surface as Experiment 3. The use of two diameter sized surfaces, for the wearable proximity sensors to rest upon, will simulate two different sized astronauts with the same curved metallic surface used as representative of the same sized HUT. The same distances and number of sweeps will be used as in Experiment 1. As the distance is increasing from the curved surfaces, the distance is referring to the proximity away from the center of the curved metal plate. Each of the three wearable proximity sensors are placed in this location to determine how each will respond. Figure 26 illustrates the setup for Experiment 2 & 3 demonstrating the wearable proximity
sensor at the bottom of the setup located in the center of the metal plate. Additionally, both other wearable proximity sensors are put in this position at the center of the metal to determine the response for both Experiment 2 & 3.

4.4 Results

The results indicate that in Experiment 1, all three of the wearable proximity sensors respond very similar with a total shift of 10.9 MHz, 11.9 MHz, and 10.4 MHz for spiral 1, 2, and 3 respectively with a standard deviation of 0.76 MHz. They all have a resonant frequency in the same bandwidth between 140 to 180 MHz for all 21 distances. Figure 27 illustrates the $S_{11}$ response for each wearable proximity sensor as they are placed side by side in parallel to the metal plate. Using this information that all three spirals have similar responses, the response on curved environments can then be determined.

![Figure 27: Three wearable proximity sensors with the same design parameters in proximity to a metal plate with $S_{11}$ scattering parameters below their respective spiral.](image)
The introduction of a curved environment for Experiment 2 & 3 show promising results with wearable proximity sensors adjacent to the primary target in the middle of the curved metal showing small reflection coefficient response. Figure 28 illustrates the scattering parameters of Experiment 2 for the scenarios when the three wearable proximity sensors are in the center of the curved metal surface. This additionally demonstrates the responses from the other two wearable proximity sensors that were not the primary target in the center of the metal. Experiment 3 also illustrates similar results as seen in Figure 29. The exact reflection coefficient parameters can be seen in Table 1, where the change in resonant frequency and change in impedance magnitude is determined for Experiment 2 & 3 for all the wearable proximity sensors. All wearable proximity sensors were placed in the center of the metal with responses from all the sensors determined.

Figure 28: Each spiral on the larger diameter cylinder with each on touching the curved metal with their corresponding response of each other spiral sensor.
Figure 29: Each spiral on the small diameter cylinder with each on touching the curved metal with their corresponding response of each other spiral sensor.

### TABLE 1:
RESONANT FREQUENCY DATA ANALYSIS

<table>
<thead>
<tr>
<th></th>
<th>Large Cylinder (Experiment 2)</th>
<th>Small Cylinder (Experiment 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spiral 1 Touching</td>
<td>Spiral 2 Touching</td>
</tr>
<tr>
<td>Spiral 1</td>
<td>Resonant Frequency</td>
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<td></td>
<td>Impedance Magnitude</td>
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</tr>
<tr>
<td>Spiral 2</td>
<td>Resonant Frequency</td>
<td>0.3 MHz</td>
</tr>
<tr>
<td></td>
<td>Impedance Magnitude</td>
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</tr>
<tr>
<td>Spiral 3</td>
<td>Resonant Frequency</td>
<td>0 MHz</td>
</tr>
<tr>
<td></td>
<td>Impedance Magnitude</td>
<td>0.28 Ω</td>
</tr>
</tbody>
</table>
4.5 Discussion

As the whole shoulder joint is compromised for astronauts when wearing the suit, this array of wearable proximity sensors would be able to identify where the metal scye bearing joint is touching, or in close proximity to the shoulder joint. This data that is gathered can distinguish which wearable proximity sensor in the array is in closest contact and determine proximity distance from that sensor. In both sized cylinders with the three wearable proximity sensors, the sensor that is the primary target for impingement produced similar response to that for the parallel testing, while the wearable proximity sensor directly next to that primary target got a response as well. The larger cylinder, in Experiment 2 that was tested, initiated more of a response from the adjacent wearable proximity sensor to the primary one. This relationship is due to the fact that since this cylinder in Experiment 2 is closer in size to the size of the metal scye bearing joint, the adjacent wearable proximity sensors are closer than when on the smaller sized cylinder. Having multiple of these wearable proximity sensors surrounding the shoulder joint that could exhibit contact from the HUT would ensure that there is proper clearance.

The amount of clearance that for optimal suit fit is one centimeter completely around the shoulder joint [10]. As the results indicated, these wearable proximity sensors can be strategically placed around the shoulder joint to confirm this clearance is there. When there is insufficient amount of clearance around the shoulder joint, there would be definitive quantitative values that the suit is fitting properly and would contribute to less likelihood of musculoskeletal injury. As this controlled curved environment provides promising insight to proximity detection in multiple locations, there is still the limitation that was faced due to a human participant not being used. Further testing with this environment could also evaluate more wearable proximity sensors and possibly less of a gap between the two. Although this area between them was not evaluated in this study, there is evidence that this area may not be able to clearly show proximity
distance without further investigation. Although using these paper-thin wearable proximity sensors, a quantitative evaluation that proper clearance that the shoulder has from the metal scye bearing joint of the HUT can be achieved.

4.6 Conclusion

With astronaut suit fitting being such a prominent issue due to the amount of musculoskeletal injuries, the use of wearable proximity sensors implemented in the suit will determine there is proper clearance. If there is proper clearance around the entirety of the shoulder joint, there will be better suit fit, better range of motion, and less injuries. The use of multiple wearable proximity sensors provides more valuable information that could help validate appropriate suit fit for every astronaut performing EVA training or trips to the ISS.
REFERENCES


CHAPTER 5

CONCLUSION

Proximity detection was successfully achieved with the use of a wearable proximity sensing system. The use of this system will provide quantitative assessment of astronaut spacesuit fitting that was not previously known. When the fit of the spacesuit is optimized, there is less likelihood of musculoskeletal injury to occur. Findings from this research establishes that when this wearable proximity sensor is detecting a metal surface, such as the scye bearing joints of the HUT, the response of the reflection coefficient can be directly correlated to distance. This correlation can be easily trained for the system to predict proximity distance with millimeter accuracy. Incorporation of new materials into the environment of the sensing system still demonstrates strong accuracy. For example, introducing a cooling garment with continuous flow of water in the environment changes the permittivity and electromagnetic properties. Although this does introduce more variability, there can be calibration and training associated with this environment for future implementation into the space suit. Results also demonstrate that when introducing a more complex environment with a curved surface that would be reminiscent of the human body, this wearable proximity sensing system would still produce quantitative information. As more tests and environments of the suit is introduced, this wearable sensing system will be able to accurately provide measurements to aide in suit fit optimization.

Future work using these wearable proximity sensors would address the use of human participants and more realistic models of the spacesuit components. Performing shoulder joint movements with these wearable proximity sensors would evaluate suit fit during various actions. By statically testing different angles of shoulder movements with the proximity sensors worn,
distance measurements trained for each sensor would illustrate a higher representation of suit fit. As different movements of the shoulder may have impingement in different locations for all astronauts, the integration of this wearable proximity sensing system would establish use. Incorporation of multiple wearable proximity sensors into the suit could pose some difficulties, although use of one antenna with one sensing device that is coupling to multiple spirals would reduce complexity. These wearable proximity sensors would ideally be placed in hot spots for contact between the shoulder joint and the HUT. Each of these sensors would initiate a different response that would be correlated to distance to provide valuable information for how to properly adjust the suit for maximum shoulder mobility. Using this sensing system would also provide use for future spacesuit designs, exchanging for new sizes, implementation of padding in specific areas, or provide highest area of contact during training. The use of a proximity sensing system has shown application that would assist in the prevention of shoulder joint injuries due to spacesuit fit.
REFERENCES
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