

Article

# Closing the wearable gap: Mobile systems for kinematic signal monitoring of the foot and ankle

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**Abstract:** Interviews from strength and conditioning coaches across all levels of athletic competition identified their two biggest concerns with the current state of wearable technology: (a) the lack of solutions that accurately capture data "from the ground up" and (b) the lack of trust due to inconsistent measurements. The purpose of this research is to investigate the use of liquid metal sensors, specifically Liquid Wire sensors, as a potential solution for accurately capturing ankle complex movements such as plantar flexion, dorsiflexion, inversion, and eversion. Sensor stretch linearity was validated using a Micro-Ohm Meter and a Wheatstone bridge circuit. Sensors made from different substrates were also tested and discovered to be linear at multiple temperatures. An ankle complex model and computing unit for measuring resistance values were developed to determine sensor output based on simulated plantar flexion movement. The sensors were found to have a significant relationship between the positional change and the resistance values for plantar flexion movement. The results of the study ultimately confirm the researchers' hypothesis that liquid metal sensors, and Liquid Wire sensors specifically, can serve as a mitigating substitute for inertial measurement unit (IMU) based solutions that attempt to capture specific joint angles and movements.

**Keywords:** Liquid metal sensors; Liquid Wire; wearables; athletic training; ankle complex; plantar flexion; resistance-based sensors; human ankle model; sensor substrate

## 1. Introduction

While improving athletic performance is a common goal of Strength and Conditioning (S&C) coaches across all levels of competition, the question of optimization of performance is still trial and error. Quantifying training protocols is one method to evaluate and validate performance programs. Traditionally, optical motion capture of biomechanical data collection is considered the gold standard for identifying kinematic and kinetic parameters [1] and is generally confined to a research laboratory or lab-like environment due to the equipment requirements. Unfortunately, high costs and limited access to these research environments reduces the opportunity for improving all athletes through technical analysis [2]. One promising technological advancement that has seen increased exposure in research and competition is wearable sensor technology and the opportunity to measure near real-time kinematics on the playing field [3]. Measuring various physiological and kinematic parameters are now accessible to the average athlete compared to the human activity recognition devices from twenty years ago [4,5]. Numerous commercially available products utilize micro electromechanical systems [6] (MEMS), accelerometers, and gyroscopes to capture biomechanical measures outside the lab [1].

One of the benefits of using MEMS devices is that they offer a lower-cost alternative to traditional motion capture solutions. Using an inertial frame, the relative orientation of limb segments can be

33 calculated from accelerometer and gyroscope data [7]. One commonly used type of MEMS is the  
34 inertial measurement unit, or IMU, and it is found in most technologies where some form of movement  
35 information is captured. However, several recurring issues are seen in IMU-based motion capture  
36 systems including distortion and drift [1], and challenges in how to consistently manage calibration  
37 [8]. The distortion and drift that affects actual sensor horizontal and vertical data are due to distortions  
38 in non-homogeneous magnetic fields, often caused by building construction materials and magnetic  
39 interference [1,9]. To reduce noise, improved anatomical models and static calibration in defined  
40 positions have been developed [1,7]. However, measurement errors still occur due to skin and segment  
41 speed of movement and axial segment rotation [10]. According to Kavanagh et al. [11], the separation  
42 of limb segment resultant acceleration could not be identified within the sensor data, resulting in the  
43 difficulty to obtain accurate measurements. Additionally, external devices are often incompatible with  
44 activities that involve contact and may require frequent adjustment and re-calibration [12] making  
45 them impractical for use in real-world environments.

46 In human movement, the neuromuscular system senses strains, positioning, and stretching of  
47 its proprioceptors and muscular system in order to coordinate limb segment movement [13]. A body  
48 network sensor system that mimics strain and stretch around the joints may offer an alternative to  
49 using stiff, circuit board-based IMUs in capturing human limb movement. Given calibration and  
50 consistency challenges that exist with IMUs used in the athletic wearable market today, a potential  
51 solution may lie in the use of a different kind of sensor, or sensors developed for a different purpose,  
52 such as soft robotic sensors. Soft robotic sensors can be identified as silicone-textile (or other soft  
53 materials) layered with liquid conductive material and generally identified as resistive or capacitive  
54 [14,15]. As these sensors are stretched, their resistive or capacitive values increase. At the beginning  
55 of this research, there were two primary soft robotic sensor solutions available to test. Liquid Wire  
56 is a resistance-based sensor and StretchSense is a capacitive-based sensor, both of which provide  
57 increased output values when stretched past their initial resting lengths. Several advantages for using  
58 soft robotic sensors such as these include (a) the ability to measure biomechanical strain without worry  
59 for occlusion errors that typically occur in optical systems and eliminate drift that can occur in MEMS  
60 sensors [2], (b) the realization of small changes in electromechanical specifications during loading  
61 and unloading, and (c) the reduction of interference as observed by the wearer [16]. In addition, soft  
62 robotic sensors inherently offer "stretchability", which allows the sensors to cover arbitrarily shaped  
63 joints that occur on the human body [17].

64 The purpose of the research described herein is to take a new type of sensor, soft robotic sensors,  
65 and determine if this solution can be re-purposed for motion capture via a customized wearable  
66 technology application. The motivation behind this idea being to mitigate or completely remove  
67 the problems described regarding IMU-based wearable solutions. But before any solution design  
68 and prototyping based around this sensor solution was initiated, the researchers identified critical  
69 questions that needed to be addressed by subject matter experts (SMEs): (a) There are known issues  
70 with data consistency and reliability with wearable technology (as previously defined) but what do  
71 actual SMEs of the technology think? (b) What are the gaps that SMEs identify as being the biggest  
72 opportunities for wearables?

### 73 1.1. Interviews – Two Concerns

74 In order to address the first question regarding wearable industry gaps, this research team sought  
75 out SMEs who were not only familiar with the intended (and actual) use of the technology but who  
76 were also knowledgeable of the "state of the art" of the wearable market. As a result of securing regional  
77 NSF I-Corporation (I-Corp) grant funding, the researchers conducted a series of nearly three-dozen,  
78 hour-long interviews with S&C coaches and athletic trainers (AT) from around the country in all  
79 sports at the collegiate and professional levels for both men and women competition. These interviews  
80 were conducted to establish the need and use of wearable technology to improve athletic performance  
81 and manage athletic activity. The primary questions posed to the interviews were (a) "What are the

82 gaps in the current generation of wearable technologies available to you today?” and (b) “If you could  
83 design a wearable solution, what information would it capture for you in order to assist in making  
84 critical decisions about health and safety?” Two primary concerns were repeated by the interviewees.  
85 The first concern was that current data from wearable sensors could not be trusted due to consistent  
86 inaccuracies and lack of transparency with generalized correlations. The second most consistently  
87 identified gap was that data captured “from the ground up” was desired but was either missing or  
88 delivered improperly in current wearable technological solutions designed for athletic competition  
89 and movement evaluation. The term “from the ground up” highlights a desire on the part of the S&C  
90 coaches and ATs to have data collected at the point where the athlete comes in contact with the ground,  
91 the foot and ankle.

#### 92 1.1.1. Rebuilding Trust

93 The first gap identified through the I-Corp interviews, the issue of trust, is a major concern as  
94 these S&C coaches and AT’s are responsible for making decisions about the health and safety of athletes.  
95 Training and rehabilitation protocols directly influence athletes’ functional health beyond competition.  
96 Backing the concerns identified by the interviewees, multiple researchers have expressed concerns  
97 about the efficacy of sensors in rehabilitation use due to inaccuracies [18,19], and the inability of users  
98 to successfully manage the number of false positives that can occur through wearable sensor use often  
99 results in poor compliance [18]. To overcome inaccuracies found in wearable technology, researchers  
100 have used a variety of different and frequent calibration procedure methods [20], extra sensors, and  
101 substituted ultra-wide band for magnetometers [8]. As seen in a study of three commercially available  
102 Altitude and Heading Reference Systems (AHRS) [20], relative accuracy, which can be related to human  
103 joint angle measurement, deviated from one degree in a 30 second time segment to over 16 degrees  
104 in repeated two minute dynamic segments compared to the gold standard of optical motion capture.  
105 Resetting of the reference points for the sensors during the trials did improve accuracy; however,  
106 constant re-calibration can occur in the lab and be tolerated but this frequent level of adjustment  
107 is neither practical nor acceptable for practitioners who would need to stop training or practice to  
108 re-calibrate wearable devices.

109 From the corroborated output amassed during the I-Corp interviews, the number of step counts  
110 by Mississippi State University (MSU) men’s and women’s basketball teams captured during the  
111 2016–2017 season recorded higher than normal step activity during practices. Further investigation  
112 into the data revealed that the dribbling motion of the basketball by the player’s arms and hands were  
113 being counted as steps and work performed. Other inaccuracies also occurred with the MSU football  
114 team. During a spring training practice in 2017, one player registered as taking a few hundred steps  
115 and traveling 10 miles, which is obviously not physically possible. At most, average football players  
116 in an average practice will travel between one and two miles depending on the position played, but  
117 not 10 miles. Additional evidence of inaccuracies has led S&C coaches at universities of similar sizes  
118 and athletic budgets as MSU to completely stop using any type of wearable technology. These peer  
119 institutions are recommending that other university athletic programs do the same and terminate  
120 wearable use for health and safety assessments associated with practice and training events.

#### 121 1.1.2. From the Ground Up

122 The second piece of valuable information gained from the S&C coaches and AT interviews  
123 regarding wearable gaps revealed the need for information to be captured “from the ground up”.  
124 According to responses from the I-Corp interviewees, current wearable technology does not provide  
125 accurate ground reaction force and ankle complex movement data. Determining ankle complex  
126 movement (especially in near real-time to aid in health and safety-based decision making) has many  
127 benefits to both the athletic and rehabilitation industries, as the foot and ankle mobility influence total  
128 human movement [21]. Repeated lateral movement or excessive movement beyond normal range of  
129 motion of inversion can lead to ankle sprains [22]. In addition, high and repeated forces occurring

130 at the foot and ankle can be used to infer what happens at the knee and hip, which can lead to early  
 131 fatigue and negatively alter postural control, resulting in biomechanical compensations that may  
 132 cause injury [23]. A review of currently available wearable solutions further accentuates this ankle  
 133 data gap. While a few solutions capture some information at the foot and ankle level, none of them  
 134 capture absolute joint angles—meaning, no solution can give exact ankle movement values. In fact, few,  
 135 if any, wearable solutions provide more than inferred joint angle data (ankle or otherwise) because  
 136 angles are assumed based on limb segments. Devices proven to be inaccurate due to drift and other  
 137 inconsistencies are also using inferences to make assumptions about generalized joint movements.  
 138 The interviewees' concerns about both trust and a lack of data captured "from the ground up" come  
 139 full circle based on information shown in Table 1. Thus, the need to develop wearable technology  
 140 differently is clear and further emphasizes the need to utilize a technology capable of consistently  
 141 capturing the strains and stressors at the ankle complex in order to provide data that may not be  
 142 visually noticed by the S&C coaches.

**Table 1.** Wearable solution capability comparison.

R = RFID Tags. T = Total Distance. Z = Z-axis only. A = Average Value. DP = Developmental Platform.  
 H = Hydrocell Technology. CF = Conductive Fibers. GPS = Global Positioning System.

		Kinematic Measures					Kinetic Measures				Hardware				
		Symmetry	Step/ Jump Count	Inferred Joint Angles	Absolute Joint Angles	Limb Segments	Intensity & Load	Ground Reaction Force	Shock/ Impact Force	Pressure	Accelerometers	Magnetometers	Gyroscopes	GPS	Dielectric Elastomers
Catapult [24–26]	IMU	×	×				×	×		×	×	×	×		
Zephyr [27–31]	IMU		×				×	×		×			×		
IMeasureU [32]	IMU	×	×	×	×		×	×		×	×	×			
Zebra [33–39]	RFID		T				×			R					
STATSport [40,41]	IMU		×				×	×		×	×	×	×		
ADPM [42]	IMU	×	×	×	×		×	×		×	×	×			
TekScan[43]	Insole		×				×	×	×					×	
Shimmer Sense [44]	DP		×	×	×		×	×		×	×	×			
zFlo-Motion [45]	Insole		×				×	Z	×	×	×			×	
Novel Pedar [46]	Insole & DP		×				×	×	×					×	
DorsaVi [47]	IMU			×	×		A	×		×	×	×			
BioStamp [48]	IMU & Research		×	×	×			×		×		×			
Heddoko [49]	IMU Garment		×	×	×					×	×	×		×	
GaitUP [50]	IMU		×	×	×			×		×	×	×			
Motus [51]	IMU		×	×	×	×				×		×			
Notch [52]	IMU & DP			×	×					×	×	×			
Noitom [53]	IMU & DP			×	×					×		×			
Xsens[54]	IMU	×	×	×	×		×	×		×	×	×			
G-Vert [55]	IMU	×	×				×	×		×		×	×		
LegSys [56]	IMU		×	×	×					×	×	×			
paroTec [57]	Insole	×	×				×	×	×					H	
Sensoria [58–61]	CF	×	×					×	×	×	×				

143 Table 1 is an analysis of many of the movement-calculating wearable solutions available identified  
 144 in the I-Corps interviews by S&C coaches as either having been used in the past, in use today by their  
 145 institution or, at a minimum, of interest for potential consideration. Since many of these wearable  
 146 technologies are new solutions and have not been validated in literature, much of the information had  
 147 to be extracted from manufacturer websites as well as news and sports-related articles. In some cases,

148 true capability and functionality were not clear; therefore, the authors had to default to promotional  
149 material claims and intellectual property definitions via patents. Much of the information about the  
150 devices' true functionality and data capturing granularity is vague at best, which is one of the reasons  
151 highlighted in the interviews for why a lack of trust among the users of the technology exists. While  
152 compiling Table 1 further emphasized the lack of trust gap, the completed version of the table also  
153 highlights the second gap, a lack of absolute measurements for any joint, including the ankle complex.

### 154 1.2. Dynamic Range of Motion and Sensor Placement

155 Due to the intricacy of the ankle complex, precise placement of sensors are required to obtain  
156 accurate kinematic data during movement. Ankle complex rotational components can be found within  
157 the talocrural, subtalar, and inferior tibiofibular joints [22]. Given the anatomical design of the ankle  
158 joints, movement of the foot during open kinetic chain in plantar flexion and dorsiflexion do not  
159 occur in a single sagittal plane [62]. During plantar flexion, the foot moves 28 degrees in the sagittal  
160 plane, one degree in the transverse plane, and four degrees in the frontal plane [22]. Likewise during  
161 dorsiflexion, there are 23 degrees of movement in the sagittal plane, nine degrees in the transverse  
162 plane, and two degrees in the frontal plane [22]. Unlike previous research on comparisons of IMUs for  
163 optimal motion capture which both ignore internal and external rotations and inversion and eversion  
164 [63], this study looks at the viability in using soft robotic sensors to capture all movement in all three  
165 planes.

166 An important aspect of this investigation is the consideration for placement of these sensors in  
167 order to optimize measurements of complex ankle movements. Previous work by Mengüç et al. [2] has  
168 evaluated the sensor placement at the posterior part of the ankle and heel, extending from the distal  
169 aspect of the gastrocnemius muscle complex down to the calcaneous, which has shown positive results  
170 in sagittal plane movements (coefficient of determination 0.9680). To capture tri-planar ankle joint  
171 movement, one sensor was placed parallel to the distal 1/3 aspect of the fibula, overlaying the lateral  
172 malleolus to capture inversion and eversion. Second, vertically in-line with the distal 1/3 aspect of  
173 the tibia onto the superior aspect of the talus and a third sensor was positioned perpendicular to the  
174 23 degree axis of inversion [22]. This research provides a starting point for where sensors should be  
175 placed in order to effectively capture full range of ankle motion.

176 With a clear goal identified (capture data "from the ground up") and a potential replacement IMU  
177 sensor direction found, the aim of this study is to evaluate the use of resistive soft robotic sensors at  
178 the ankle complex movement level. Determining ankle complex movement in near real-time has many  
179 benefits to both the athletic and rehabilitation industries, as the foot and ankle mobility influence total  
180 human movement [21]. As repeated lateral movement or excessive movement beyond normal range  
181 of motion of inversion can lead to ankle sprains [22], applying resistive soft robotic sensors at the ankle  
182 complex may provide information to coaches, trainers, and therapists in preventing over-use injuries  
183 and validate proper ankle rehabilitation training exercises. The goal of this paper is to show that soft  
184 robotic sensors have the potential to usher in a new type of wearable that is not limited by the difficult  
185 challenges created by IMUs such as drift. Liquid Wire sensors were selected for this study given their  
186 resistive properties, the researcher's access to different substrate types, and the ability to custom order  
187 sensors with specific resting resistances and lengths. Based on the goals and limitations above, the  
188 contributions of this paper are as follows:

- 189 • Liquid metal sensors (specifically those manufactured by Liquid Wire [64]), which are designed  
190 for soft-robotics applications, are experimentally shown to be suitable for capturing ankle  
191 complex movements for dorsiflexion, plantar flexion, inversion, and eversion.
- 192
- 193 • A simple microprocessor-based computing unit prototype designed to accurately measure the  
194 Liquid Wire sensors resistances is provided.

195

- 196 • Liquid Wire sensors, which vary their resistance under stretching, are experimentally shown to  
197 provide a linear relationship versus stretching distance and temperature.
- 198
- 199 • Linear regression models were used to relate the resistance measurements into ankle angle  
200 measurements.
- 201
- 202 • A detailed summary of the state-of-the-art in wearable solutions is provided which shows that  
203 there currently is not another wearable solution capable of making ankle measurements (Table  
204 1).

205 The remainder of this paper is organized as follows. Section 2 provides information on  
206 experimental materials and methods. Section 3 discusses experimental results. Section 4 draws  
207 conclusions and lists the researchers' future work pursuits.

## 208 2. Materials and Methods

209 This section discusses materials and methods for (a) testing the Liquid Wire sensors, (b) testing  
210 the dynamic range of motion, and (c) estimating angles from the Liquid Wire sensors. Results and  
211 conclusions from these tests are discussed in sections 3 and 4, respectively.

### 212 2.1. Liquid Wire testing

213 In order to prove that the Liquid Wire sensors are a viable tracking solution, the researchers  
214 conducted several experiments to verify that the sensor output changed linearly with stretched length,  
215 regardless of temperature, and that the sensor could be feasibly utilized in a microcontroller-based  
216 system.

#### 217 2.1.1. Testing Goals

218 The goals of the Liquid Wire testing were to (a) validate that the Liquid Wire sensor is linear in  
219 resistance versus stretched length, (b) validate that the Liquid Wire sensor is linear in resistance versus  
220 stretched length at various temperatures, and to (c) validate that the Liquid Wire sensor's resistance  
221 could be accurately measured in a microprocessor-based solution.

#### 222 2.1.2. Equipment

223 Test equipment is shown in Table 2. Table 3 lists the bill-of-materials for the computing unit.

**Table 2.** Test Equipment for Liquid Wire Testing.

Component/Purpose	Manufacturer	Model
Clamps – hold test article	Irwin	Quick-Grip 3" clamps
Drill Press – stretch test article	Irwin	4" Drill Press Vise
Micro-Ohm meter – validate computing unit	Agilent/Keysight	34420A
Digital multimeter – validate computing unit	Fluke	179
Liquid Wire sensors – test articles	Liquid Wire	Various
Hand-held temperature sensor – monitor test article temperature	Etekcity	1080
Ankle complex model – test sensor linearity	Custom	Ankle test fixture
Blow dryer – heat test article	Conair	146RX
Digital Caliper – measure test article stretch	Tritan	0344621
DC Benchtop Power Supply – power circuit for testing	Extech	382213

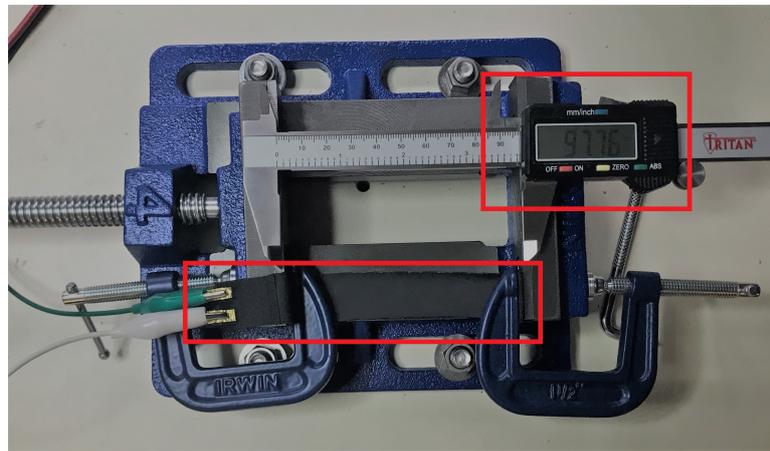
#### 224 2.1.3. Test Procedure

225 An apparatus was constructed to take measurements from the Liquid Wire sensors at various  
226 stretched lengths. In order to stretch the sensor in a stable and consistent manner, an IRWIN four-inch  
227 drill press vise was mounted on top of a table. Two IRWIN QUICK-GRIP three-inch clamps held

**Table 3.** Equipment bill of materials for the prototype computing unit.

Manufacturer	Model	Description
Arduino	Uno R3	Microprocessor
RexQuails	RQ-RK-001	Resistors
CTYRZCH	4330118083	16 Bit I2C ADS1115 4-channel Analog-to-Digital Converter Module
Jameco ValuePro	20812	Solderless Breadboard
Elenco	JW-350	Pre-formed Jumper Wire Kit
Elegoo	EL-CP-004	Breadboard wire set for Arduino
Cable Matters	200001-BLK-10x3	USB 2.0 A-to-B Printer Cable, 10 feet

228 down each end of the Liquid Wire sensor to an end of the vise. Care was taken to not over-tighten  
 229 the clamps so as to not damage the test article. A digital caliper was used to measure the length of  
 230 the segment of sensor being stretched. A screw located on one side of the vise was used for adjusting  
 231 one side of the vise and was used to consistently stretch the Liquid Wire sensor. Fig. 1 shows the test  
 232 fixture in the Sensor Analysis and Intelligence Laboratory (SAIL) facility. The Liquid Wire sensor is the  
 233 dark band highlighted near the bottom of the figure. The caliper measuring the sensor length is also  
 234 highlighted. By turning the vice screw, the sensor length can be carefully adjusted.

**Figure 1.** Picture of Liquid Wire test fixture. Liquid Wire sensor and digital caliper highlighted.

### 235 Linearity Testing

236 For the first experiment, two benchmark methods for measuring resistance were used to determine  
 237 if there is a linear relationship between resistance and stretch length. The methods used were: (a) a  
 238 Micro-Ohm Meter, which is the lab standard in measuring resistance, and (b) a Wheatstone bridge  
 239 circuit, which is a very accurate and common circuit used for measuring resistance. These two methods  
 240 were evaluated and compared against each other to decide which one would be used for the remaining  
 241 experiments. For the first method, an Agilent Micro-Ohm Meter was connected directly to the Liquid  
 242 Wire sensor to measure its resistance. The Liquid Wire sensor was mounted on the testing apparatus,  
 243 and the screw was turned in 180° intervals. At each interval, the resistance and length of the sensor  
 244 was measured. This was done until the sensor was stretched to approximately 20 mm longer than its  
 245 original length.

246 The same process was then repeated for the Wheatstone bridge circuit. For this method, three  
 247 10 Ω resistors were soldered together. Care was taken to identify these resistors as  $R_1$ ,  $R_2$ ,  $R_3$ , similar  
 248 to the schematic shown in Fig. 2. The Micro-Ohm meter was used to record precise measurements  
 249 of the three resistors to be used in calculations. Alligator clamps were used to connect the Liquid  
 250 Wire sensor to  $R_2$  and  $R_3$ . A power supply ( $V_{supply}$ ) was connected and set to 0.5 V to reduce current  
 251 draw through the resistors. The positive end was connected to the node between  $R_1$  and  $R_3$ , and the

252 negative end was connected to the node between  $R_2$  and the Liquid Wire sensor. A multimeter was  
 253 then connected at the node between  $R_1$  and  $R_2$  and the node between  $R_3$  and the Liquid Wire sensor,  
 254 and these nodes are labeled as  $V_{12}$  and  $V_{34}$  in Fig. 2, respectively. A voltage measurement ( $V_{measured}$ )  
 255 was taken from the multimeter to determine the difference between these two nodes. These values  
 256 were used to determine the resistance with Equations 1 and 2, where all resistances have units of Ohms.  
 257 The complete derivation for these equations can be found in Appendix A.

$$\alpha = \frac{V_{measured}}{V_{supply}} + \frac{R_2}{R_1 + R_2} \quad (1)$$

$$R_{LiquidWire} = \frac{R_3 * \alpha}{1 - \alpha} \quad (2)$$

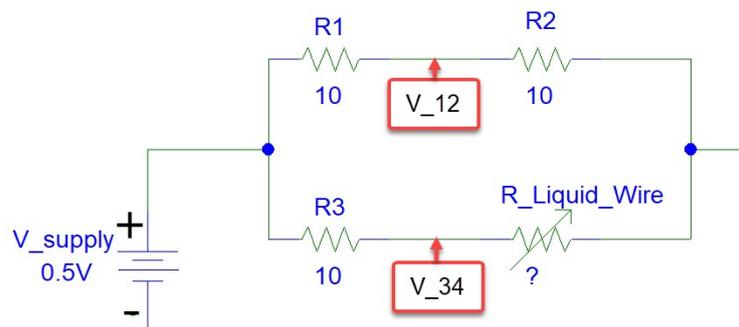


Figure 2. Schematic diagram of Wheatstone bridge circuit. Resistances are in  $\Omega$ .

258 The benefits of using the Micro-Ohm Meter is its level of precision and the ease of setup as circuit  
 259 construction was not required to get sensor measurements. Moreover, measurements from this very  
 260 accurate device were used to validate the prototype computing unit's measurements. However, this  
 261 method was not without issue. Due to the way the device calculated the sensor's resistance, there was  
 262 inherent drift in the measurements. Also, the resistance was updated about once a second, therefore,  
 263 measuring with this method would not work in a real-time application. The change in resistance  
 264 was still linear, but it was difficult to get a consistent measurement, since the Micro-Ohm Meter  
 265 would slightly change the value displayed soon after stretching the sensor. While the multimeter  
 266 output for the Wheatstone bridge circuit did not provide the same level of precision as the Micro-Ohm  
 267 Meter, it still provided a more consistent reading for the researcher to record. This was important for  
 268 consistently collecting data in the remaining experiments.

269 Results for both of these methods are discussed in section 3.1.1. Based on the issues described  
 270 related to taking measurements with the Micro-Ohm Meter, the Wheatstone bridge circuit was selected  
 271 as the method of measurement to be used for the remaining experiments described in this section as  
 272 well as the static model testing described in section 2.2. During this experiment, the researchers noted  
 273 that the connections to the sensor leads were getting damaged. After consulting with Liquid Wire, the  
 274 company stated that a sensor would not work reliably and could potentially be damaged if stretched  
 275 20% beyond the sensor's original length.

## 276 Temperature Testing

277 In order to verify that the Liquid Wire sensor output remained linear against stretched length  
 278 regardless of temperature, the same testing apparatus was arranged as described in section 2.1.3 using  
 279 the Wheatstone bridge circuit. Two types of Liquid Wire sensors were used, each with a different  
 280 substrate: one with a TPU (thermoplastic polyurethane) coated proprietary liquid metal, and one  
 281 with a silicone covering. The different types were chosen for this particular experiment to evaluate  
 282 whether or not substrate had an effect on resistance at different temperatures. Data was collected for

283 four different stretched lengths of the sensor. This data was first collected with the sensor at room  
 284 temperature. Afterwards, a heat gun was used to heat the sensor up to 80°F. A hand-held temperature  
 285 sensor was used to monitor sensor temperature and make sure that it was maintained at the same  
 286 temperature. Data was then collected, and the temperature was verified and corrected at each stretched  
 287 length. This process was completed one last time at 98°F, to simulate the surface temperature of the  
 288 human body's skin. Results from this experiment are discussed in section 3.1.2.

### 289 Microprocessor Testing

290 A microprocessor-based prototype, also known as the computing unit, was constructed to validate  
 291 the potential for the sensor data to be collected in real-time. This prototype was designed to take  
 292 measurements from the various types of sensors that were supplied by Liquid Wire, which would  
 293 also be used for future research experiments (See Future Work in section 4.2). Table 4 provides several  
 294 examples of sensors that were tested, which are also pictured in Fig. 3. The researchers first designed  
 295 the prototype using an Arduino Uno R3, an ADS1115 16-bit Analog-to-Digital Converter (ADC)  
 296 Module, and the previously described Wheatstone bridge circuit. The ADC module was able to pick  
 297 up small changes in voltage due to its high precision voltage reading, which was useful for increasing  
 298 sensitivity to changes in stretched length of the Liquid Wire sensor. This module was able to collect  
 299 even more precise data through the use of its built-in programmable gain amplifier (PGA), which could  
 300 amplify small signals to provide even more sensitivity to sensor output changes. It essentially replaced  
 301 the multimeter used in the previous experiments, as it took the difference in voltage measurements  
 302 between nodes  $V_{34}$  and  $V_{12}$  and transmitted a corresponding analog value to the microprocessor over  
 303 I<sup>2</sup>C. The Wheatstone bridge circuit and ADC module were powered by the 3.3 V source from the  
 304 Arduino Uno. Due to the higher voltage supply, the 10  $\Omega$  resistors were replaced with 100  $\Omega$  resistors  
 305 to reduce current flow through the circuit. An extra 100  $\Omega$  resistor was placed in series with the leg of  
 306 the Liquid Wire sensor to keep the bridge closer to being balanced. The microprocessor communicated  
 307 with a laptop over a serial connection and provided output that indicated the current resistance of the  
 308 Liquid Wire sensor.

Table 4. Liquid Wire Testing Article Specifications.

ID	Substrate	Length (mm)	Resting Resistance ( $\Omega$ )
A	Thermoplastic Polyurethane	202	30.0
B	Thermoplastic Polyurethane	209	44.1
C	Silicone	165	6.0
D	Thermoplastic Polyurethane	107	13.6

309 While testing the prototype with different sensors, the researchers encountered an issue with  
 310 reaching a peak amplified voltage due to the differences in resting resistances (resistance measured  
 311 without stretching) between the Liquid Wire sensors. These resting resistances ranged from roughly 5  
 312  $\Omega$  to 45  $\Omega$ . To prevent this issue, either the gain of the amplifier had to be reduced or the values of the  
 313 resistors in the Wheatstone bridge had to be increased. Furthermore, this would come at the expense  
 314 of losing levels of voltage measurements, also known as bins. In practical terms, when correlating  
 315 sensor readings to joint angles, the prototype would lose precision when estimating angles in future  
 316 experiments if the circuit was not physically changed. Due to this issue, the researchers investigated  
 317 replacing the Wheatstone bridge circuit with a voltage divider circuit, which was determined to be a  
 318 simpler and more flexible method for measuring sensors of varying resistance. An added benefit to  
 319 the voltage divider circuit was that four sensors could be measured at the same time instead of two,  
 320 since the ADC module would only need to measure the voltage measured at one node ( $V_1$  in Fig. 5).

321 The data shown in Fig. 4 taken from Personal Simulation Program with Integrated Circuit  
 322 Emphasis (pSPICE) provides further justification for this design choice. The simulation performed  
 323 shows the range of bins that correlate to the given range of resistances that was stated previously. The  
 324 simulated Wheatstone bridge circuit used 100  $\Omega$  resistors at each leg with a variable resistor in series

325 with one of the legs to emulate the Liquid Wire sensor. An instrumentation amplifier was connected  
 326 to nodes  $V_{34}$  and  $V_{12}$  to emulate the PGA functionality of the ADC module taking a differential  
 327 measurement. The simulated voltage divider circuit used a  $150\ \Omega$  resistor in series with a variable  
 328 resistor. A non-inverting operational amplifier was connected at node  $V_1$  between the  $150\ \Omega$  resistor  
 329 and the variable resistor to emulate the PGA functionality of the ADC module taking a single-ended  
 330 measurement. In simulation, the gain was set to 4 volts per volt (V/V) for both circuits. At a range of 5  
 331  $\Omega$  to 40  $\Omega$  for the variable resistor, the voltage divider circuit provided 74,421 bins for measurements,  
 332 while the Wheatstone bridge circuit provided 57,856 bins. When factoring in that the Wheatstone  
 333 bridge loses linearity in measuring voltage around 32  $\Omega$ , the realistic amount of resolution provided  
 334 is closer to 50,390 bins. The fact that the circuit provides less resolution and still fails to take reliable  
 335 measurements after a certain threshold indicates that the voltage divider circuit is the better choice for  
 336 the prototype. A picture of the computing unit and a block diagram describing the design are shown  
 337 in Fig. 3. The design change for the computing unit's circuit design is depicted in Fig. 5.

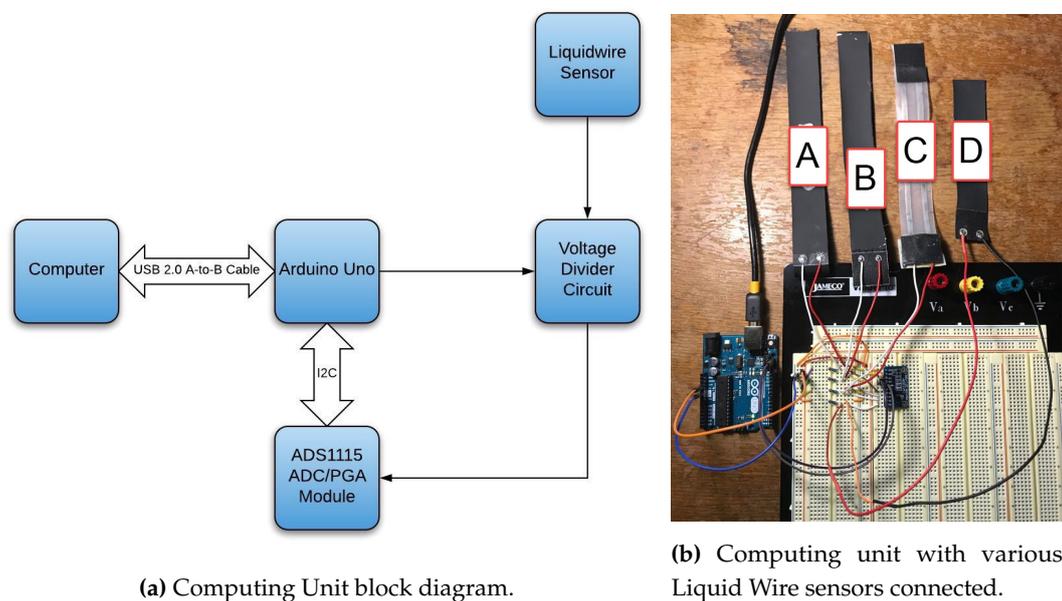
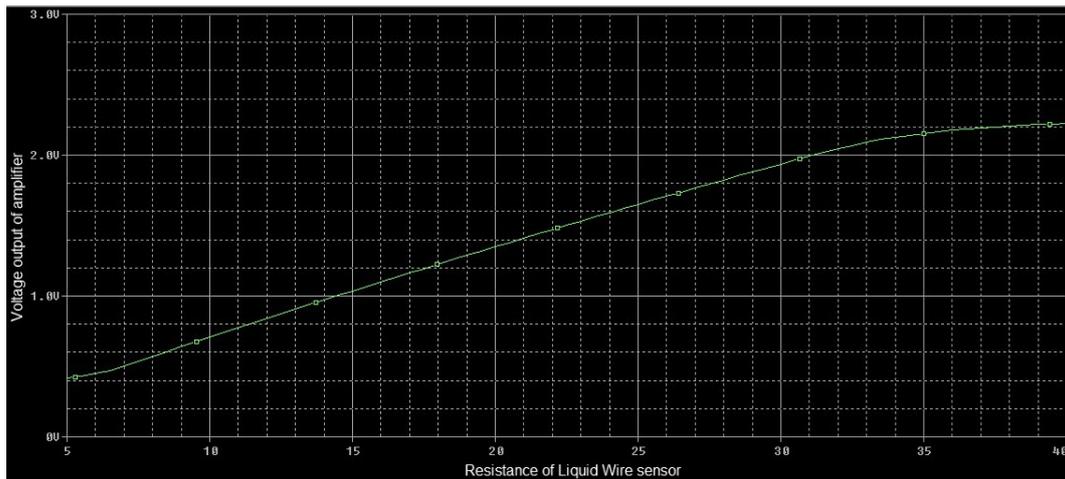
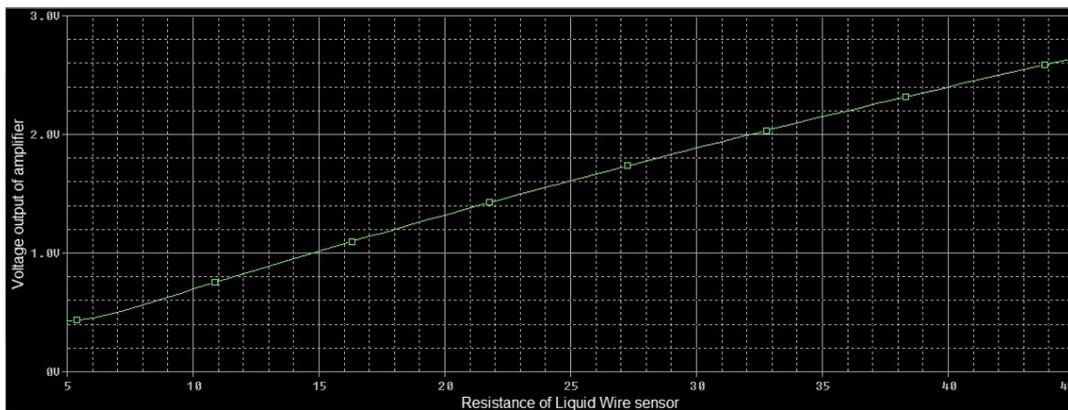


Figure 3. Microprocessor prototype.

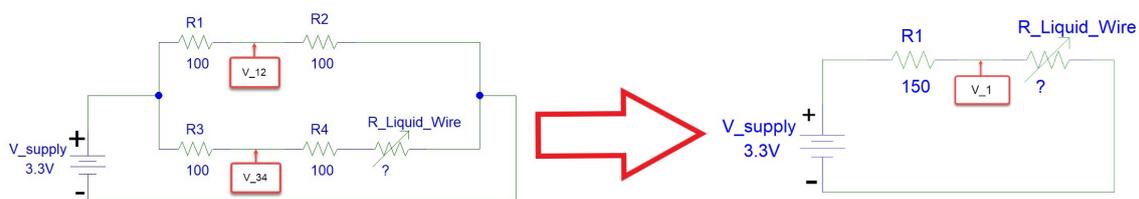


(a) Wheatstone bridge measurement range.



(b) Voltage divider measurement range.

**Figure 4.** Comparison of range of voltage levels (bins) that can be used for taking measurements at various sensor values. Note that sensitivity of change decreases for the Wheatstone bridge at about 32  $\Omega$ .



**Figure 5.** Computing unit circuit design change from Wheatstone bridge to voltage divider.

338 After re-designing the prototype, the voltage divider circuit replaced the Wheatstone bridge circuit  
 339 to validate the accuracy of the computing unit. The same test procedure described in section 2.1.3  
 340 that was used for validating linearity of the Liquid Wire sensor was conducted using the computing  
 341 unit as a method of measurement. The data collected from the computing unit was compared to data  
 342 collected with the Micro-Ohm meter to validate accuracy. Results are discussed in section 3.1.3.

## 343 2.2. Static Model Testing

344 The human ankle complex is comprised of three joints: the talocrural joint, the subtalar joint, and  
345 the distal tibiofibular joint, which is a syndesmosis joint [22]. This allows the foot and ankle to move  
346 in multiple planes of motion as needed for walking, running, and athletic movements. Modeling of  
347 the ankle complex has provided basic descriptions of foot movement in plantar flexion, a downward  
348 movement of the foot; dorsiflexion, an upward movement of the foot; eversion, an outward movement  
349 of the bottom of the foot; and inversion, an inward movement of the bottom of the foot. Using these  
350 four measures of ankle complex movement has been shown to be effective in studying the differences  
351 in passive and active joint movement [21].

352 To understand the sensor output's relationship to the ankle joint movement, a model of the human  
353 ankle was constructed of 2" × 4" pine and 3/8" rubber flooring material securely screwed into the  
354 wood, allowing for angular rotation in the sagittal and frontal planes as derived from a previous  
355 model used in the literature [65]. The sensor was then attached to the model using toupee double  
356 sided tape and reinforced with an overlapping elastic band to secure and create two anchor points.  
357 Upon attachment, the sensor was stretched slightly. To measure the degrees of plantar flexion and  
358 rotation, two smartphones were calibrated using a carpenter's bubble level running the RIDGID Level  
359 iOS application. The smartphones were securely attached to the model via elastic bands and phone  
360 mount. An electronic goniometer was used to validate the measurements from the smartphone. Using  
361 smartphones allowed for validation of accurate measure for the degrees of movement compared to the  
362 hand placement of the electronic goniometer on the model for each change in position. The movement  
363 of the model foot was performed by one experimenter while a second experimenter read and recorded  
364 the voltage output from a multimeter. A TPU-based sensor and a silicone-based sensor were used  
365 for this study. Markings on the model allowed for consistent placement of the different Liquid Wire  
366 sensors.

### 367 2.2.1. Testing Goals

368 The goals of the model testing were twofold: (a) to capture changes in resistance of the Liquid  
369 Wire sensors relative to simulated ankle complex movement and (b) to evaluate the different substrates  
370 in capturing simulated ankle complex movement. Previous bench testing provided insight into the  
371 linearity of the Liquid Wire sensors; the focus of this portion of the study is on consistent linearity  
372 occurring in simulated joint rotation.

### 373 2.2.2. Equipment



(a) Measurements taken with goniometer.

(b) Measurements taken with smartphone levels.

**Figure 6.** Pictures of the ankle model mockup.

374 The ankle model was constructed of a 1/2" wooden base with a vertical wooden 2" × 4" spine  
 375 screwed to the base. Two additional 2" × 4"s were used, allowing for the flexible flooring to be  
 376 securely screwed to the bottom 2" × 4". The additional 2" × 4" was placed on top of the flooring  
 377 material and secured by screws into the 2" × 4" spine. Another 2" × 4" was attached to the top of the  
 378 flooring material which represented the foot. Images of the model are shown in Fig. 6. The sensor  
 379 was connected to a Wheatstone bridge circuit that was arranged as described in the Linearity Testing  
 380 portion of section 2.1.3.

### 381 2.2.3. Test Procedure

382 Two researchers compiled the data onto a Microsoft Excel formatted sheet. After properly applying  
 383 and securing the sensor with toupee tape and an anchor strap, and mounting the smartphones onto  
 384 the model, one researcher moved the model's foot and called out the number of degrees of movement.  
 385 The second researcher then recorded the multimeter output onto the Excel sheet. After recordings  
 386 were taken, calculations were run based on the previously given Equations 1 and 2 to determine the  
 387 resistance of the Liquid Wire sensor.

## 388 3. Results and Discussion

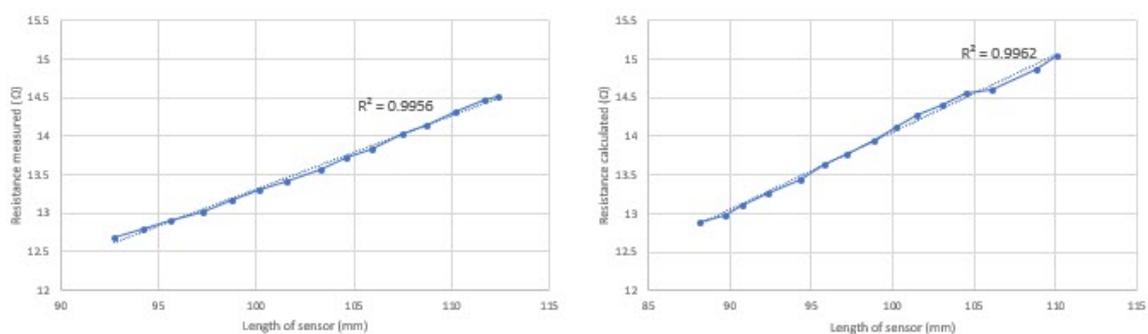
389 This section discusses the results of the Liquid Wire TPU and Silicone sensors conducted in section  
 390 (2) (a) the bench testing on linearity, (b) temperature testing, and (c) changes in resistance during a  
 391 static positioning representing plantar flexion, inversion, and eversion on the ankle model.

### 392 3.1. Liquid Wire Testing Results

393 The following three subsections discuss the results gathered and their relevance to the testing  
 394 goals (a), (b), and (c) as defined in section 2.1.1.

#### 395 3.1.1. Linearity Testing Results

396 The results in Fig. 7 address testing goal (a) of section 2.1.1, which was to validate that the Liquid  
 397 Wire sensor was linear in resistance versus stretched length. Linearity in stretched length was evident  
 398 for both the Micro-Ohm Meter and the Wheatstone bridge circuit. Fig. 7 depicts linearity test data  
 399 collected for each method as well as their coefficient of determination values.



(a) Micro-Ohm Meter results.

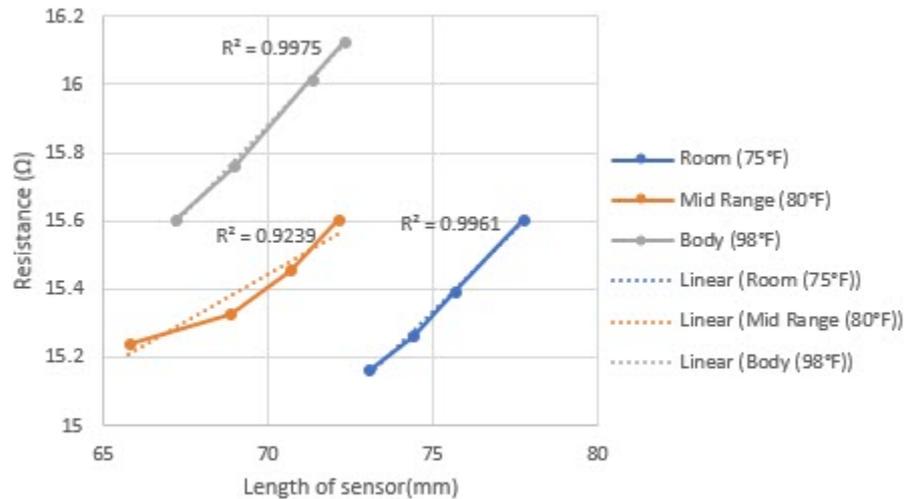
(b) Wheatstone bridge results.

Figure 7. Data collected for linearity testing for resistance versus the stretch length.

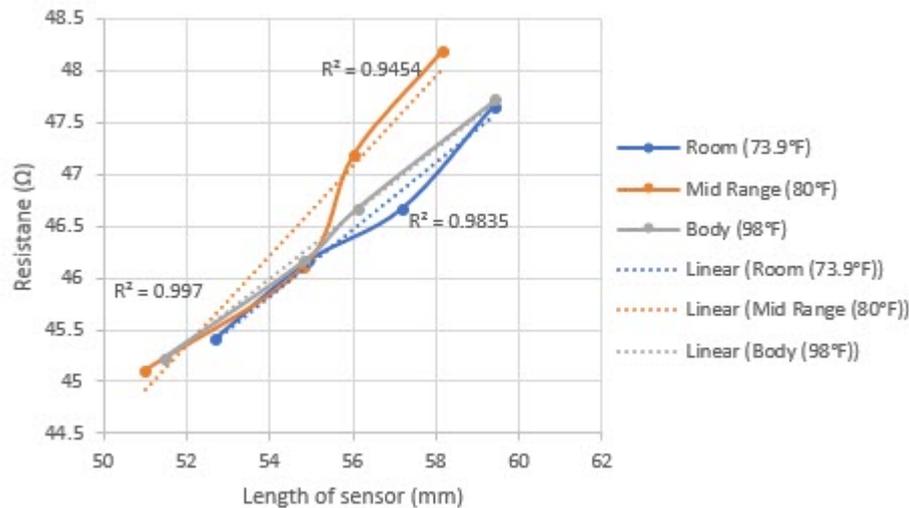
#### 400 3.1.2. Temperature Testing Results

401 Next, testing goal (b) of section 2.1.1 was addressed, which was to validate that the Liquid Wire  
 402 sensor was linear in resistance versus temperature. Based on the data gathered, temperature did not  
 403 have a drastic affect on the linearity of strain on the Liquid Wire sensors. However, one interesting  
 404 result was that temperature did appear to have an affect on the TPU sensor's resistance overall, as

405 the values measured increased with temperature. Based on the data collected from the silicone sensor,  
 406 there appeared to be minimal correlation with resistance and temperature. This finding is important  
 407 when considering tying resistive values to the tracking of movement on the human body. If the TPU  
 408 sensor is used, extra temperature sensing may be needed to correct an increase in resistance value if  
 409 the sensor's temperature is affected by the human's surface body temperature. Results are shown in  
 410 Fig. 8.



(a) TPU



(b) Silicone

Figure 8. Data collected for temperature testing for resistance vs length stretched.

### 411 3.1.3. Computing Unit Testing Results

412 Finally, the computing unit prototype was compared against a Micro-Ohm meter to satisfy  
 413 testing goal (c). The prototype constructed for taking measurements of the Liquid Wire sensor  
 414 proved to be a viable solution. An average percent error of 1.55% was calculated between the  
 415 measurements taken from the computing unit and the Micro-Ohm meter. This could have been  
 416 due to the calculations performed by the microprocessor, or from researcher error when resetting the

417 linearity testing apparatus. Results are shown in Fig. 9. These results show that the computing unit is  
 418 very close to measurements of a high-accuracy, laboratory unit.

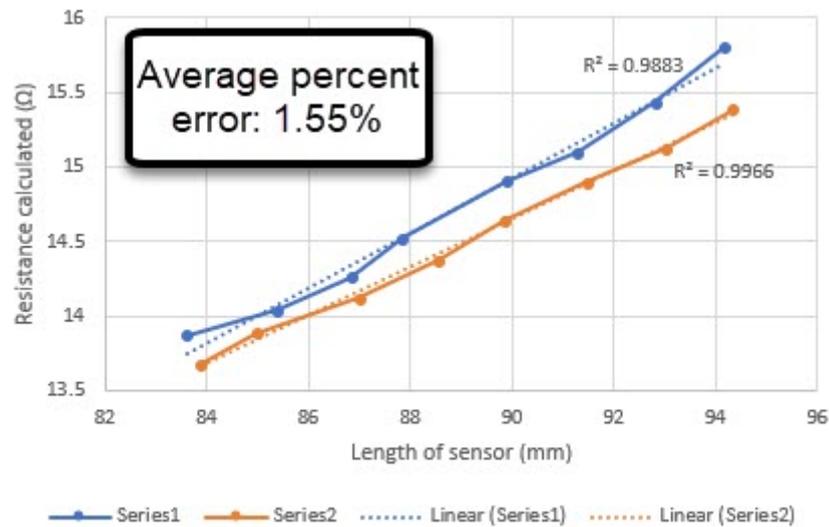


Figure 9. Comparison of Computing Unit and Micro-Ohm meter measurements collected.

### 419 3.2. Estimating Angles from Liquid Wire Measurements Testing Results

420 To test the linearity of both the Liquid Wire TPU and Silicone sensors, the model was moved and  
 421 held at specific, static degrees representing human ankle complex plantar flexion. This resulted in the  
 422 degree of plantar flexion as the independent variable and sensor resistance as the dependent variable.  
 423 Using a regression analysis comparing the change in sensor resistance when stretched due to changes  
 424 in increasing ankle model's plantar flexion resulted in the development of two mathematical models.  
 425 The significance level was set at  $\alpha = 0.05$  for all of the analyses. The Fit Regression Model analysis  
 426 (MiniTab18 Statistical Software, USA), revealed the regression models for the Liquid Wire TPU (Eq.  
 427 3) and Liquid Wire silicone sensor (Eq. 4), which produced linear models with coefficients (P-value  
 428  $< 0.001$ ). Thus, the model provides the expected value of sensor resistance in Ohms when varying  
 429 degrees of  $D$ , which is angle of plantar flexion in degrees.  $R_{TPU}$  is the resistance estimate for the TPU  
 430 sensor, and  $R_{SIL}$  is the resistance estimate for the silicone sensor, respectively. The rotational aspect of  
 431 the model resulted in almost equal changes in resistance of the sensors. This provided insight into the  
 432 requirement of using multiple sensors to assess ankle inversion and eversion. Due to the symmetry of  
 433 the change (Fig. 9b & 9d), it would not be possible for the software to determine whether the change  
 434 in resistance was inversion or eversion. In future human trials, we will assess changes in degrees of  
 435 ankle complex movement from specific ranges of sensor resistance. Measurement results of the Liquid  
 436 Wire sensor are shown in Fig. 10.

$$R_{TPU} = 10.9831 + 0.01142D \quad (3)$$

$$R_{SIL} = 6.2922 + 0.05194D \quad (4)$$

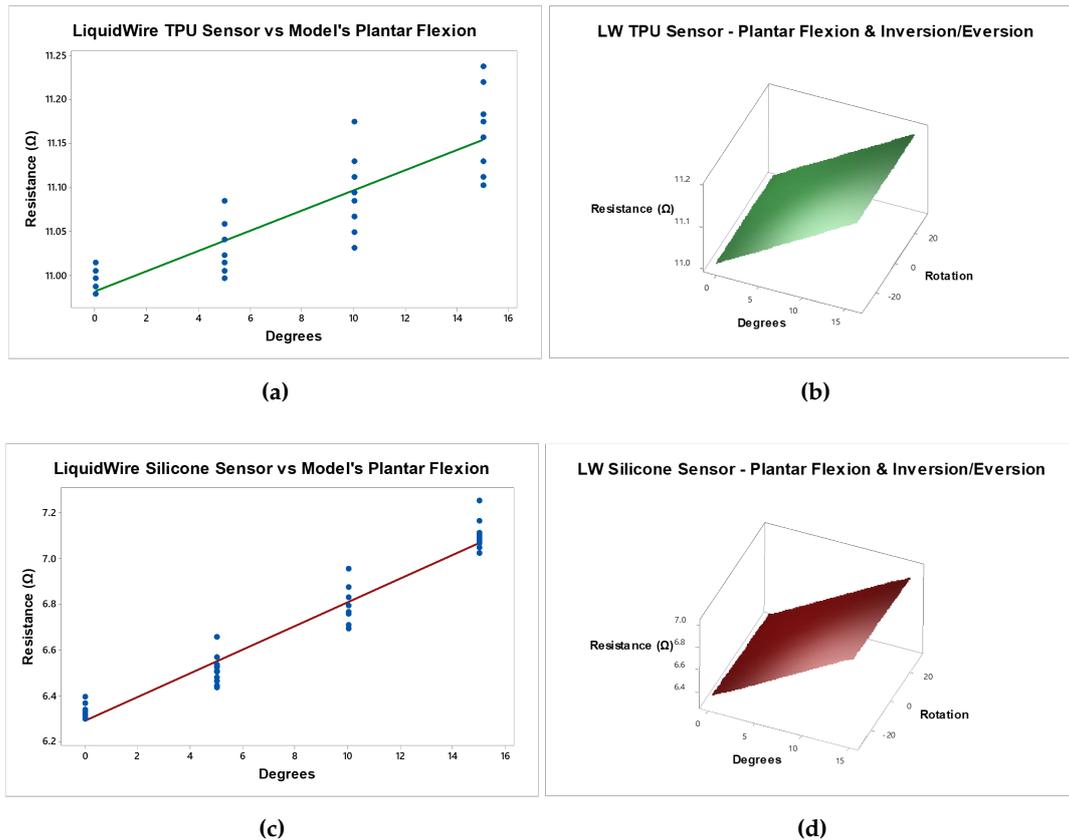


Figure 10. Liquid Wire TPU and Silicon Sensor measurements and model results.

#### 437 4. Conclusions

438 The purpose of this research was to find a way to mitigate some of the concerns regarding  
 439 wearable technology identified by the SMEs interviewed in response to the NSF I-Corp project. The  
 440 first noted concern was the lack of wearable solutions that capture data "from the ground up" and  
 441 provide meaningful data about the ankle complex. The researchers addressed this concern by focusing  
 442 on a sensor-based solution that could accurately capture movement of the ankle complex. The second  
 443 concern voiced by the SMEs was their lack of trust for existing wearable solutions. The identification  
 444 of this trust issue is accompanied by research in literature as there are known concerns with IMU  
 445 drift and the need for calibration of wearable equipment. To address this concern, the research team  
 446 investigated liquid metal sensors to determine if they would be an appropriate measurement option in  
 447 future wearable solutions. The researchers wanted to learn if liquid metal sensors could be utilized  
 448 to capture absolute joint angles as opposed the inferred joint measurements that are present in most  
 449 wearable solutions available during the time of this study. For this reason, Liquid Wire sensors were  
 450 selected.

451 In order to test the Liquid Wire sensors, basic tests were performed to validate the linearity of  
 452 the sensors using two methods: (a) Micro-Ohm Meter and (b) Wheatstone bridge. The results of both  
 453 methods concluded that the Liquid Wire sensors show a linear correlation between the increase in  
 454 stretch of the sensor and the increase in resistance. Linearity of the Liquid Wire sensor was tested across  
 455 different temperatures with the expectation being that these sensors would be close to or in direct  
 456 contact with human skin and therefore would become warmer than room temperature. Also, Liquid  
 457 Wire sensors comprised of different substrates were tested for linearity at different temperatures with  
 458 the similar expectation that they must be comfortable to the wearer if in close contact with the skin  
 459 and therefore different materials may offer different comfort. Linearity remained consistent regardless  
 460 of temperature or substrate. This is important to know as the the sensor could be closer to room

461 temperature at the beginning of an exercise and closer to body temperature as the exercise progresses so  
462 compensating for different resistance values will be important for correctly and consistently correlating  
463 ankle complex movement to sensor outputs. For future data collection, a computing unit was built to  
464 collect resistance values. This computing unit was validated against a Micro-Ohm Meter to insure  
465 accuracy and consistency of the readings. It was determined that the voltage divider circuit is more  
466 practical than the Wheatstone bridge at this time, since we don't currently have a consistent resting  
467 resistance to work with. Furthermore, using the voltage divider reduced the size of our circuit and  
468 allowed us to measure more sensors at the same time with the ADC module, which could end up  
469 working in our favor for future product hardening.

470 To further test Liquid Wire capability in the context of ankle complex movement, a model of the  
471 human foot and ankle was constructed to provide a platform on which to attach the sensor and test for  
472 very specific human movements such as plantar flexion. With the aid of the ankle complex model, both  
473 substrates were tested while performing the plantar flexion motion and both TPU- and silicone-based  
474 sensors were found to have a significant relationship between the positional change and the resistance  
475 values therefore confirming that the Liquid Wire solution is effective for accurately capturing these  
476 types of movements.

477 The results of the study ultimately confirm the researchers' hypothesis that liquid metal sensors,  
478 and Liquid Wire sensors specifically, can serve as a mitigating substitute for IMU-based solutions  
479 that attempt to capture specific joint angles and movements. The solution that the researchers have  
480 begun to design based on this Liquid Wire-based ankle complex wearable concept will be effective in  
481 overcoming the primary concerns identified by the SMEs that use wearable technology in athletic and  
482 training environments.

#### 483 4.1. Limitations

484 To the knowledge of the researchers performing this study, this research was the first of its kind;  
485 therefore, limitations were identified during the discovery process. First, the Wheatstone bridge  
486 circuit used to power the sensors and capture sensor resistance exhibited small levels of noise causing  
487 minimal variations in voltage output at the time of data capture readings. Creating a printed circuit  
488 board (PCB) for future research will help to solve this problem by reducing the sensitivity of the analog  
489 signal to noise. The Liquid Wire sensors themselves did not appear to contribute to the noise in the  
490 measurements and so a PCB solution should mitigate this problem.

491 Second, because a wooden model of the ankle complex was used and not a real human ankle, there  
492 were limitations in the ability to capture certain movements such as dorsiflexion. In order to capture  
493 dorsiflexion, the sensor needed to be fastened to the wooden model in such a way as to keep the Liquid  
494 Wire sensor in a stretched position so that a reduction in resistance could be measured as the "foot"  
495 was lifted back and toward the "shin". But if the sensor's position begins at rest and no stretching is  
496 applied to the sensor, then the resistance value will not change and therefore will not be representative  
497 of movement changes. Beginning trials with the Liquid Wire sensor in a stretched state posed an  
498 issue for the researchers because of the length of the sensor and the rigid nature of working with the  
499 wooden model that led to stretching the sensor beyond its 20% stretch limitations. This over-stretching  
500 often resulted in a damaged sensor or damaged sensor terminals. For this reason, dorsiflexion has to  
501 be demonstrated by a reverse of the methods used to test plantar flexion which prove the capability  
502 of the sensor in that it remains linear as the stretch state is removed but is not representative of real  
503 dorsiflexion movements. The researchers believe that the dimensions of the wooden model versus the  
504 dimensions of a real ankle complex attribute to this challenge. This measurement was also difficult to  
505 make because only one sensor was used, leading to the next limitation.

506 Third, ankle complex movements are complicated and three-dimensional in nature. Only using  
507 one sensor to take measurements limited the movements that could be studied. For example, inversion  
508 and eversion occur when the foot is turned either inward or outward respectively. A single Liquid  
509 Wire sensor is able to determine (through an increased resistance value) that movement at the ankle

510 has occurred when an inversion or an eversion movement is made. However, the sensor cannot  
511 differentiate between these two movements. Likewise, when a plantar flexion movement is combined  
512 with either an inversion or eversion movement, there is no way to differentiate between the amount of  
513 stretch caused by the plantar flexion version verses the other movement. Multiple sensors are needed  
514 to identify direction and magnitude of the ankle complex movement.

515 Lastly, an important lesson learned on the part of the experimenters is the desire for consistent or  
516 common resting resistances (resistances when the liquid metal sensor is not stretched) for the Liquid  
517 Wire sensors. While all sensors were linear in their movement-to-stretch resistive output, not all  
518 sensors held comparable resistance values at rest. Because of the difference in resting resistances, a  
519 more flexible circuit was required, but this will add more complexity to the programming for the  
520 computing unit to determine resting resistances for the sensors. This was less of an issue as only one  
521 sensor was being tested at a time, but as this team moves forward with human trails and multiple  
522 sensors to capture the more difficult movements of dorsiflexion and inversion/eversion in addition to  
523 plantar flexion, a consistent resting resistance is preferred with a known, minimal variance.

#### 524 4.2. Future Work

525 Additional work has already begun with the Liquid Wire sensors including human trials where  
526 multiple sensors with the same resting resistances will be positioned on participants in order to perform  
527 static and dynamic movements of the foot and ankle. As the limitations of this study showed, multiple  
528 sensors will need to be positioned around the ankle complex in order to capture more complicated  
529 movements, but where these sensors should be placed and how they will be held in place on the  
530 participant is a critical discovery. Using machine learning, the researchers will be able to take the  
531 resistance values from multiple sensors anchored to a participant and determine the exact position  
532 of the foot and ankle. This positioning will then be validated using motion capture and force plate  
533 feedback allowing the researchers to identify the capability delta between the soft robotic sensor  
534 solution and the golden standard of human movement analysis. Further, once preferred Liquid Wire  
535 sensor placement is identified, a proper gait study on human participants using static and dynamic  
536 movement assessment techniques will be used to validate that data “from the ground up” is being  
537 properly captured and that precise ankle complex movements are correctly identified. Once the  
538 machine learning algorithms are adequately refined for walking movements, product hardening will  
539 occur for testing of training-based movements commonly used by athletes outside of the lab in their  
540 practice environments.

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545 strength and conditioning coaches and athletic trainers were asked to speak to the current state of the wearable  
546 market for athletics and their ability to make informed decisions about health and safety using the solutions  
547 available to their programs. These interviews represented men and women from multiple sports teams across  
548 collegiate- and professional-level organizations throughout the United States. The research was conducted in the  
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552 and Adam Knight; Data curation, Tony Luczak, David Saucier, Pan Wei and Tashfin Iftekhhar; Formal analysis,  
553 Tony Luczak, David Saucier, Reuben Burch, John Ball, Harish Chander, Adam Knight, Pan Wei and Tashfin  
554 Iftekhhar; Funding acquisition, Reuben Burch, John Ball and Harish Chander; Investigation, Tony Luczak, David  
555 Saucier, Pan Wei and Tashfin Iftekhhar; Methodology, Tony Luczak, David Saucier, Reuben Burch, John Ball, Harish  
556 Chander, Adam Knight and Tashfin Iftekhhar; Project administration, Tony Luczak, Reuben Burch, John Ball, Harish  
557 Chander and Adam Knight; Resources, Reuben Burch, John Ball, Harish Chander and Adam Knight; Software,  
558 David Saucier; Supervision, Reuben Burch, John Ball, Harish Chander and Adam Knight; Validation, David  
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## 565 Appendix A

566 The following equations provide a more detailed explanation of the mathematical calculations  
567 used to determine the resistance of the Liquid Wire sensor in the Wheatstone bridge circuit. Please  
568 refer to Fig. 2 for circuit components.

$$V_{12} = \frac{R_2}{R_1 + R_2} * V_{supply} \quad (A1)$$

$$V_{34} = \frac{R_{LiquidWire}}{R_3 + R_{LiquidWire}} * V_{supply} \quad (A2)$$

$$V_{12} + V_{measured} - V_{34} = 0 \quad (A3)$$

$$V_{measured} = V_{34} - V_{12} \quad (A4)$$

$$V_{measured} = \frac{R_{LiquidWire}}{R_3 + R_{LiquidWire}} * V_{supply} - \frac{R_2}{R_1 + R_2} * V_{supply} \quad (A5)$$

$$\frac{V_{measured}}{V_{supply}} = \frac{R_{LiquidWire}}{R_3 + R_{LiquidWire}} - \frac{R_2}{R_1 + R_2} \quad (A6)$$

$$\frac{V_{measured}}{V_{supply}} + \frac{R_2}{R_1 + R_2} = \frac{R_{LiquidWire}}{R_3 + R_{LiquidWire}} \quad (A7)$$

$$\alpha = \frac{V_{measured}}{V_{supply}} + \frac{R_2}{R_1 + R_2} \quad (A8)$$

$$\alpha = \frac{R_{LiquidWire}}{R_3 + R_{LiquidWire}} \quad (A9)$$

$$R_3 * \alpha + R_{LiquidWire} * \alpha = R_{LiquidWire} \quad (A10)$$

$$R_3 * \alpha = R_{LiquidWire} * (1 - \alpha) \quad (A11)$$

$$R_{LiquidWire} = \frac{R_3 * \alpha}{1 - \alpha} \quad (A12)$$

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