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CHARACTERIZING SCREEN-PRINTED RESISTIVE TACTILE SENSORS

Faculty of Information Technology and Communication Sciences
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ABSTRACT

Akseli Nummi: Characterizing Screen-printed Resistive Tactile Sensors
Silkkipainettujen resistiivisten kosketusanturien karakterisointi
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This bachelor's thesis characterizes resistive tactile sensor prototypes made by master's thesis worker Ahmed Elsayes in Tampere University biomedical engineering laboratory. He has manufactured several sensors but only one is examined in this thesis. The sensor is characterized by drawing a curve illustrating the force–resistance relationship of each element in the sensor. It includes one larger sensing element and two smaller ones that are the same size. The elements are fixed between two layers of flexible plastic film. They are connected to an electrical circuit through thin screen-printed conductors that run inside the sensor. The intention behind the tactile sensors is to create an artificial sense of touch to use in conjunction with a prosthetic hand. They could also be utilized in other flexible electronics and soft robotics applications.

The sensor is used to measure the amount of force that is applied on it. The sensing elements are based on a phenomenon called piezoresistivity where a material's electrical resistance is proportional to this force. The stress caused by the force is either compressive stress or tensile stress. However, only compressive forces are present in tactile sensing applications. The piezoresistive elements are pieces of insulating fabric doped with conducting nanoparticles. As the fabric is compressed, the distance between the particles inside the material decreases, creating a conductive path through the fabric. Thus, the fabric's resistance diminishes. There are also other types of piezoresistive materials. Semiconductor materials, such as silicon, have been utilized in piezoresistive sensor for decades.

Using a Stable Micro Systems texture analyzer, different amounts of force were exerted on the sensor. A straightforward voltage divider circuit was used to transform the change in resistance to a voltage signal. The voltage across the series resistor was input to a PC using a National Instruments DAQ device. The voltage curve was then manipulated using MATLAB and Excel to plot the final force–resistance curves.

The characterized sensor indicated promising behavior. The force–resistance relationship of each piezoresistive element is logarithmic, as expected. The measurements were carried out without many errors as there was only one deviation in the data collected. The sensors seem largely suitable for the intended application. However, it was noted that when using extremely low forces, less than 0,5 N, the sensor's output was sometimes unpredictable. Also, it was not possible to measure forces higher than 5 N with the available laboratory equipment. The results that were gathered show good promise, nonetheless. Further research is of course needed to clarify these uncertainties.

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

A	cross-sectional area
l	length
R	resistance
ρ	resistivity
V	voltage
DAQ	data acquisition system
DC	direct current
NI	National Instruments
PC	personal computer
PET	polyethylene terephthalate
USB	universal serial bus

1. INTRODUCTION

As more and more biomedical devices are developed, there is an increasing need for tiny, flexible sensors that transform touch inputs into electrical signals. Touch interfaces in modern appliances are based on tactile sensors whose electrical characteristics are altered when a force is exerted on them. Tactile sensors are often modelled as resistors or capacitors with a variable resistance or capacitance, respectively. Some biomedical applications of these sensors, such as a hand prosthesis, require elasticity and thinness. Therefore, novel technologies and manufacturing methods for tactile sensors are heavily researched currently in the fields of electronics and biomedical engineering. Reliability has thus far been one of the main concerns in development. When complete, this technology could eventually be applied to a plethora of devices in medicine and robotics, for instance.

Ahmed Elsayes, a master's thesis worker and researcher at Tampere University Microsystems laboratory, has created flexible piezoresistive tactile sensors using a screen-printing technique. The objective of this bachelor's thesis is to characterize the sensors. In other words, the intention is to determine the sensors' force–resistance relationship in the laboratory. This thesis is a part of a larger piece of research regarding the sensors. Ahmed Elsayes is writing his master's thesis about developing the sensors and will make use of the results presented in this thesis.

Some general theory related to piezoresistive tactile sensors is briefly explored. Other sensor technologies are not discussed in this thesis. Piezoresistivity is a complex phenomenon and therefore will not be examined in extreme detail. For a similar reason, only a couple basic examples will be given of signal conditioning circuits.

Chapter 2 explains the theoretical background of piezoresistive tactile sensors. First, basic terms concerning sensors and measurement systems are defined. Second, the concept of piezoresistivity is studied. Third, resistive sensors are examined as a part of an entire measurement system. The most common signal conditioning circuits are discussed. Finally, applications of piezoresistive tactile sensors are briefly overviewed. The screen-printed piezoresistive tactile sensors made by Ahmed Elsayes are described in Chapter 3. The manufacturing process and material choices are key aspects. Chapter 4 focuses on the methods and results of the laboratory work itself. The research results as well as the main points of the whole thesis are weighed and summarized in Chapter 5.

2. PIEZORESISTIVE SENSORS IN GENERAL

2.1 Sensor Fundamentals

Measurement systems basically consist of four elements chained together, the first one being a sensor. Its purpose is to gather information from the world and send it to the next element in the measurement system. In more technical terms, it takes a variable as its input and gives an output based on that. [1, p. 4] An example of a possible relationship between an input and an output is illustrated in Figure 1 where the X-axis is the input and the Y-axis is the output. Because the curve is not a straight line and the axes are linear, the relationship is non-linear. [1, p. 10] The sensors researched in this thesis are expected to behave non-linearly.

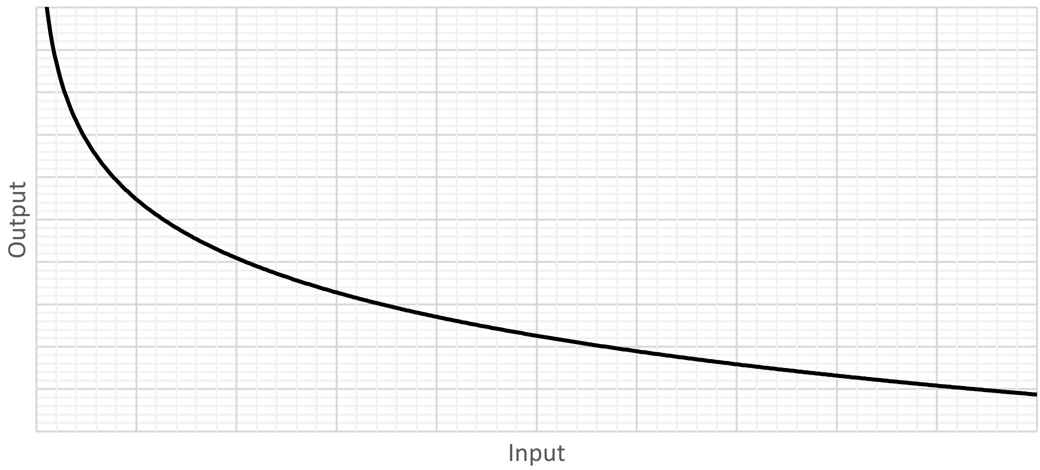

Figure 1. *A graph illustrating the working principle of a measurement system. A logarithmic curve such as this is expected to portray the tactile sensor's behavior.*

Sensitivity is one of the key properties regarding sensors. A highly sensitive sensor changes its output more easily than a sensor with low sensitivity. Even the tiniest change in the input can be detected in the output if the sensitivity of the sensor is high enough. This can be both a pro and a con. A very sensitive sensor yields more distinct output values. However, it could also register false inputs caused by temperature and pressure shifts, for example. Sensitivity is defined mathematically as

$$S = \frac{\Delta O}{\Delta I}, \tag{1}$$

where *S* is sensitivity, *O* is the output and *I* is the input. [1, p. 11]

Therefore, sensitivity is actually the slope of a curve drawn on an (*I*,*O*)-plane. In Figure 1, the sensitivity is thus clearly higher with smaller input values. As the input increases, sensitivity gradually decreases. A reliable sensor behaves similarly in different circumstances and over long periods of time. Hysteresis is a phenomenon that can cause difficulties. If a sensor has hysteresis, the shape of its (*I*,*O*)-curve depends on whether the input is increasing or decreasing at the moment. [1, p. 11–13]

Often it is advantageous for a sensor's output to be an electrical quantity, e.g. voltage, current or resistance. It is thus possible to modify the output and achieve the desired final output for the measurement system. The next element of the measurement system is signal conditioning. This generally means amplifying the electrical signal so that it can later be processed. In order to display or save the final output digitally, the analog signal needs to be converted to digital form. This is done in the signal processing element. The final element of the measurement system presents the data that was collected. [1, p. 4–5] The electrical circuit, DAQ and PC that are utilized in the laboratory work are an example of such a measurement system.

Sensors that have electrical outputs are divided in two categories. Passive sensors need energy from an external source to function; active sensors do not. If the output of a sensor is voltage or current, the sensor is active. If the output is resistance, capacitance or inductance, however, the sensor is passive. The reason for this is that resistors, capacitors and inductors do not produce current on their own. They must be supplied with current by a power source to bring about a readable output. Active sensors are sometimes called generators and passive sensors are called modulators. This distinction is where piezoresistive sensors differ from piezoelectric ones. Piezoresistive sensors' output is resistance, while the output of piezoelectric sensors is voltage. Therefore, piezoresistive sensors are passive and for that reason always require external power. [1, p. 149] This is one drawback that piezoresistive sensors have.

2.2 Piezoresistive Sensors

Resistivity indicates how much a material inhibits the flow of current. Normally resistivity is constant for a specific material. [1, p. 156–158][2, p. 32–33] For some materials however, it has been found that their resistivity varies according to the force that is applied on them. As the material deforms, its internal structure changes in a manner that results in varying resistivity. These materials can be described as piezoresistive. Their inherent behavior makes it possible to use them in pressure and force sensors. [3, p. 238–243]

Resistive sensors have resistance as their output. Strain gauges are a common type of resistive sensor. They are made of metals that are a little flexible under stress. A force applied on the sensor results in a change in its resistance. In this regard, strain gauges function similarly to piezoresistive sensors. The resistance of a conductor is defined as

$$R = \rho \frac{l}{A}, \tag{2}$$

where ρ is resistivity, l stands for the length of the conductor, and A is the cross-sectional area of the conductor. [3, p. 238–243]

A change in resistance is a result of one or more of the three parameters changing. The relative change in resistance equals

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta l}{l} - \frac{\Delta A}{A}. \tag{3}$$

The difference between strain gauges and piezoresistive sensors can be explained with the aid of Equation 3. A variation in the resistance of a strain gauge is mostly due to a change in its dimensions, i.e. its length and its cross-sectional area. The resistivity of the metal does not change significantly, as a compressive or tensile force is applied. Therefore, for strain gauges

$$\frac{\Delta R}{R} \approx \frac{\Delta l}{l} - \frac{\Delta A}{A}. \tag{4}$$

For piezoresistive sensors, the situation is opposite. The change in resistance is mostly a result of a change in resistivity. The alteration of the sensor's dimensions is not substantial. Therefore, for piezoresistive sensors

$$\frac{\Delta R}{R} \approx \frac{\Delta \rho}{\rho}. \tag{5}$$

This difference in function between the two sensor types leads to piezoresistive sensors having greater sensitivity than strain gauges. Thus, piezoresistive sensors yield better results in force sensing applications where the force is particularly slight. This makes piezoresistive sensors fitting for use as tactile sensors, for instance. However, there is a related downside. Piezoresistive sensors are more prone to temperature fluctuations because of their more complex operation. [3, p. 238–243]

There are a few different choices when it comes to piezoresistive materials, two of the most prominent being doped silicon and nanocomposites. Utilizing doped silicon is the more conventional method of the two. Nowadays more and more sensor designs utilize nanocomposite materials, due to advances in nanomaterial and microstructure fabrication over the last years. [4]

Nanocomposites are soft polymer materials filled with tiny conductive or semiconductive particles. The polymer phase of the composite is often referred to as the binder, while the particle phase is called the filler. [5] The size of the filler particles is generally in the nanoscale, but sometimes larger particles whose dimensions are in the microscale are used. Some of the most common fillers are carbon nanotubes, graphite and carbon microfibers. [6]

The operating mechanism of nanocomposite-based resistive sensors is quite straightforward when some theory about physics is neglected. The binder polymer is a non-conductive material. To increase the composite's conductivity, conductive nanoparticles are doped into the polymer. The number of conductive particles directly affects the conductivity of the composite. At lower particle concentrations, they are further away from each other on average. As the concentration increases, more conductive paths are able to form inside the composite. [6] When no force is applied on the composite, a layer of insulating polymer separates the particles. Therefore, the resistance of the material is high. By contrast, when a force is applied, the particles move closer together, thus decreasing resistance. An ideal concentration for the particles has not been defined. Still, if the filler concentration is too high, the composite's mechanical properties will change. [5]

Doped semiconductor materials work well as piezoresistive sensors, silicon being the most common one. Doping means mixing a small number of atoms from other elements with the semiconductor. The goal is to alter the electrical characteristics of the material. The semiconductor is doped with an element from one of the surrounding groups in the periodic table. Thus, there are two doping options: doping with an element from the previous group or from the following group. One option produces an n-type semiconductor material, and the other produces a p-type semiconductor material. The essential semiconductor material, silicon, belongs in group 14. Thus, doping silicon with an element from group 13, boron for example, results in p-type silicon. Respectively, using an element from group 15, such as phosphorus, results in n-type silicon. In n-type semiconductors, electrons work as charge carriers, whereas in p-type semiconductors electron holes carry the charge. [7, p. 144]

2.3 Pros and Cons of Piezoresistive Sensors

The advantages and disadvantages of utilizing piezoresistive sensors are summarized in Table 1. Every property is presented in comparison to alternative technologies since everything is relative. The information is adapted from [8].

Table 1. The most noteworthy pros and cons related to piezoresistive sensing.

Pros	**Cons**
Low cost and simple manufacturing process	Nonlinear response
Commonplace materials	Susceptible to temperature fluctuations
Good resolution and high sensitivity	External power source needed
Many flexible material options	
Complex sensor circuits not needed	

As seen, piezoresistive sensors offer many advantages but a few drawbacks as well. However, the mentioned cons are often insignificant, or there might be a workaround to the problem. For example, the effect of temperature fluctuations can be eliminated by using a Wheatstone bridge circuit, and an external power source could be implemented with energy harvesting. In the end, when reviewing the pros and cons of piezoresistive sensors, they appear to be a highly appropriate choice for their purpose in this thesis.

2.4 Resistive Sensor Circuits

As discussed before, resistive sensors require power from an external voltage source to function. At the very least, some resistors are also needed. Connecting a single resistive sensor to a DC voltage source results in current changing, but voltage remains constant across the sensor, due to Kirchhoff's 2nd law. Usually it is desirable to use a voltage signal instead of a current signal as the output because a voltage signal is easier to condition and process. In order to have a voltage signal as the output of the sensor, a standard resistor is needed to form a voltage divider circuit. In Figure 2 is depicted the simplest possible circuit where a resistive sensor's input is transformed into a voltage signal.

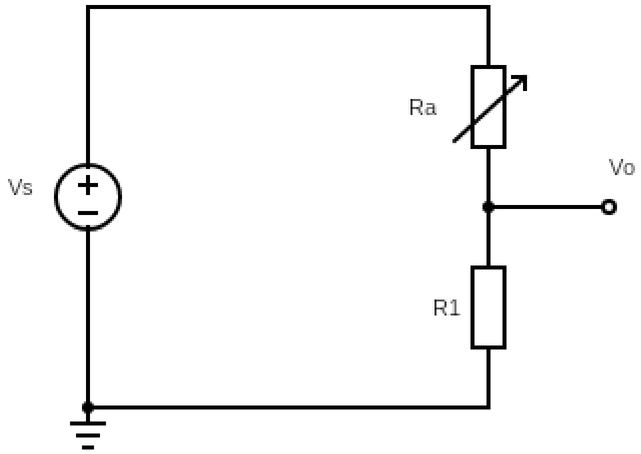

Figure 2. *A voltage divider circuit featuring a series resistor R_1 and a resistive sensor R_a whose resistance varies according to its input. The output is the voltage measured across R_1.*

The output of the circuit is the voltage across resistor R_1. The output voltage of a voltage divider with two resistors is

$$V_O = \frac{R_1}{R_1 + R_{snsr}} V_S \ . \tag{6}$$

Alternatively, the placement of the sensor and the series resistor could be switched. In that case, the output would be the voltage across the sensor. Therefore, an increase in the sensor's resistance would cause the output voltage to increase as well, instead of the opposite. In the end, it does not really matter which option is chosen, as long as it is taken into account in calculations. [2, p. 70–71]

An operational amplifier can be utilized to amplify the output of the voltage divider circuit, for example to around 5 V. After that, the signal is often digitized using an analog-to-digital converter. Then it is possible to save the data on e.g. a microcontroller or a PC. [1, p. 4–5]

A highly prevalent circuit for resistive sensors is the Wheatstone bridge. It is only a little more sophisticated than a voltage divider but offers some benefits like improved accuracy. [2, p. 81–82] A Wheatstone bridge consists of four resistive elements connected to a DC voltage source. Combinations of resistors and resistive sensors are possible. It is commonplace that all four elements are sensors because that way the effect of temperature fluctuations is reduced. [1, p. 206–211] Figure 3 portrays a Wheatstone bridge circuit where all four resistive elements are resistive sensors.

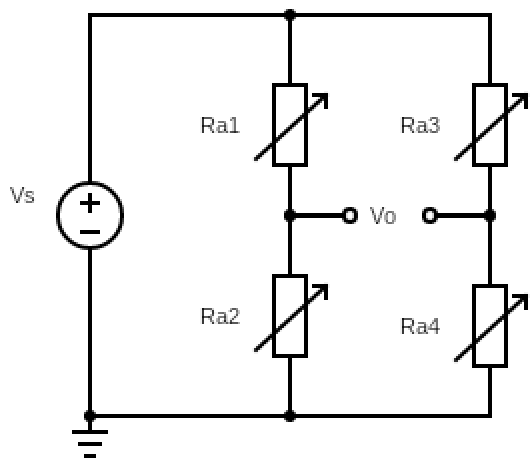

Figure 3. *A Wheatstone bridge circuit featuring four resistive sensors.*

The advantages of using a Wheatstone bridge were assessed to be unnecessary for the laboratory work presented in Chapter 4. A voltage divider provides acceptable accuracy for the purposes of the laboratory work. Also, the intention is to make the measurement system as simple as possible.

2.5 Applications

There is no general-purpose golden standard tactile sensor technology that is suited for all applications. This is due to the fact that the properties of materials being touched or gripped vary greatly. Some sensors work well with rigid objects and surfaces, while others work better with soft materials. This is why tactile sensors in general have not become common in industrial robotics. [9] If the piezoresistive tactile sensors were used to create an artificial sense of touch, picking up, holding and feeling all kinds of everyday items would be a vital function. Consequently, it may prove difficult to get the sensors working sufficiently with a wide range of materials.

Simpler, cheaper and more reliable technologies, such as proximity sensors, are preferred in industrial environments. Therefore, there is little financial push to develop tactile sensors industry-wise. One exception is medicine where tactile sensors could be utilized in surgical robotics. They will probably become more broadly utilized in the future as tactile sensing technologies are developed further. [9] Tactile sensors like the ones examined in this thesis are still relatively new technology. It seems that there is more research to be made before becoming better-established in industry.

3. SCREEN-PRINTED TACTILE SENSOR

3.1 Materials and Manufacturing

Ahmed Elsayes has manufactured multiple piezoresistive sensor prototypes. He is a researcher and master's thesis worker at Tampere University Microsystems laboratory. One of his sensors is characterized in Chapter 4 of this thesis. The aim is to eventually use the sensors to create an artificial sense of touch for a prosthetic hand. Thus, the user is able to apply an appropriate amount of force to pick up an object without dropping or breaking it.

The sensor prototype to be characterized is depicted in Figure 4. The actual sensing element of the sensors is piezoresistive fabric doped with conductive particles. Each sensor has three sensing elements, two smaller ones and one larger one. The pieces of fabric are encapsulated between two sheets of polyethylene terephthalate (PET) film. PET is a commonly used thermoplastic in the packing industry. The thin plastic construction makes the entire sensor flexible, which enables the sensor to be used in various applications, as a part of a prosthesis for example. Another benefit of using PET films is that Elsayes was easily able to laminate the two layers together by ironing. [10]

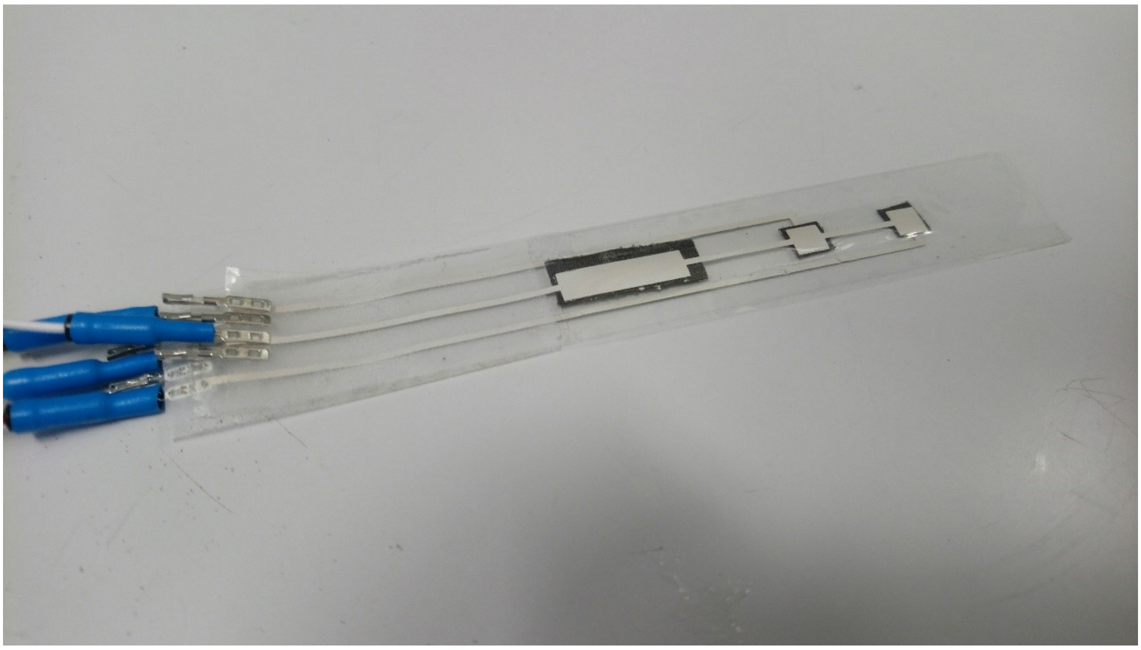

Figure 4. *One of the piezoresistive sensors. The dark gray sensor pads and silver wires can be seen through the layer of PET film. All three pads share a ground electrode connected to the white jumper wire seen on the left.*

Conductive wires are also enclosed between the PET films. The wires enable the sensing elements to be connected to a circuit in order to convert the resistance of the sensor into voltage. Using a technique called screen-printing, the metallic wires were printed directly onto one of the PET films. The ends of the wires stick out from between the PET films to enable soldering the sensor to a circuit. [10]

Some problems have appeared regarding the sensor prototypes. Firstly, the bond between the two PET films is not durable enough long-term. Because of this, the films tend to delaminate over time because of repeated bending. Fortunately, this problem can be fixed with a small piece of double-sided tape. Secondly, due to the experimental nature of the screen-printing process, there may appear issues regarding the durability of the silver wires. The length of their lifespan is unknown as durability tests have not been done.

3.2 Screen-printing

Screen-printing is a method that has attracted interest regarding flexible electronics. Utilizing screen-printing, it is possible to print thin, elastic, conductive traces on a substrate. Usually the inks consist of three phases: conductive particles or tubes, an additive that binds the particles or tubes together and a solvent, for example water. [11]

Because of its high conductivity and suitable mechanical properties, silver has been established as a great choice for flexible electronics applications. [11] Printed silver ink circuits were first researched in the 1950s. Since then, screen-printing has proven to be a suitable method of printing electrical conductors. Additionally, screen-printing is a robust method in the regard that even unexperienced people are often able to achieve a good outcome. [12, p. 86–88]

For these very reasons, Elsayes utilized screen-printed silver circuits in his sensor prototypes [10]. Figure 5 illustrates the principle of screen-printing.

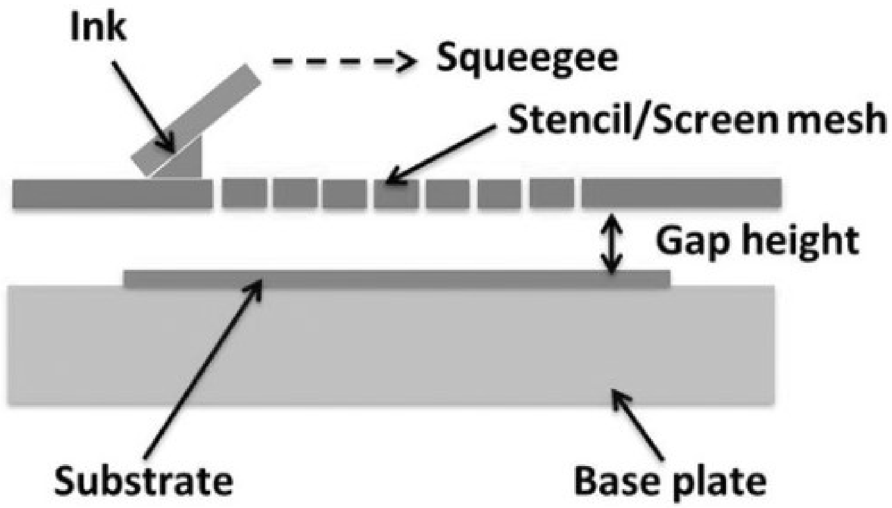

Figure 5. *An illustration of screen-printing equipment. The PET film, i.e. the substrate, is placed on the base plate. The silver ink is printed onto the PET film by pressing it through the stencil using a squeegee. Picture from [11].*

In screen-printing, the ink is pushed through a stencil using a squeegee. Openings are made in the stencil so that the desired printing pattern forms on the substrate which in this case is the PET film. Even though it is quite a simple process, it is possible to achieve a relatively high resolution for the printing pattern, up to a few dozen micrometers. Such a resolution is not enough for some advanced applications, of course. [11] However, the attained resolution is completely satisfactory for the prototypes in question since the printing pattern is extremely simple.

4. LABORATORY WORK

4.1 Research Goal

The aim of this thesis is to determine the force-resistance relationship of one of the sensor prototypes described in Chapter 3. To be exact, the intention is to draw the resistance of each sensor pad as a function of the force applied on it.

The hypothesis is that the curve will not be linear unless drawn on a semi-logarithmic scale. As the force increases, the resistance of each sensor pad decreases. In the end, the sensor's properties, such as sensitivity, linearity and reliability, can be determined from the results.

4.2 Methods

The measurements were made in cooperation with Ahmed Elsayes in Tampere University Hervanta Campus Microsystems laboratory in Sähkötalo. We used a Stable Micro Systems texture analyzer to apply a force on the sensor pads. The machine uses grams as its unit for force. The specifications of the machine do not allow forces greater than 500 g. Therefore, we only used a force as high as 450 g. A photograph of the texture analyzer is presented in Figure 6.

Having discovered that the sensors do not yield consistent readouts when using very low forces, we decided to begin with a force of 30 g. We measured the resistance using 10 force values between 30 g and 450 g. The results regarding the largest pad are an exception as only 7 data points were usable for the figures. Each test using one force value lasted for 10 seconds. After finishing with the first sensor pad, we moved on to the next one, and finally the last one.

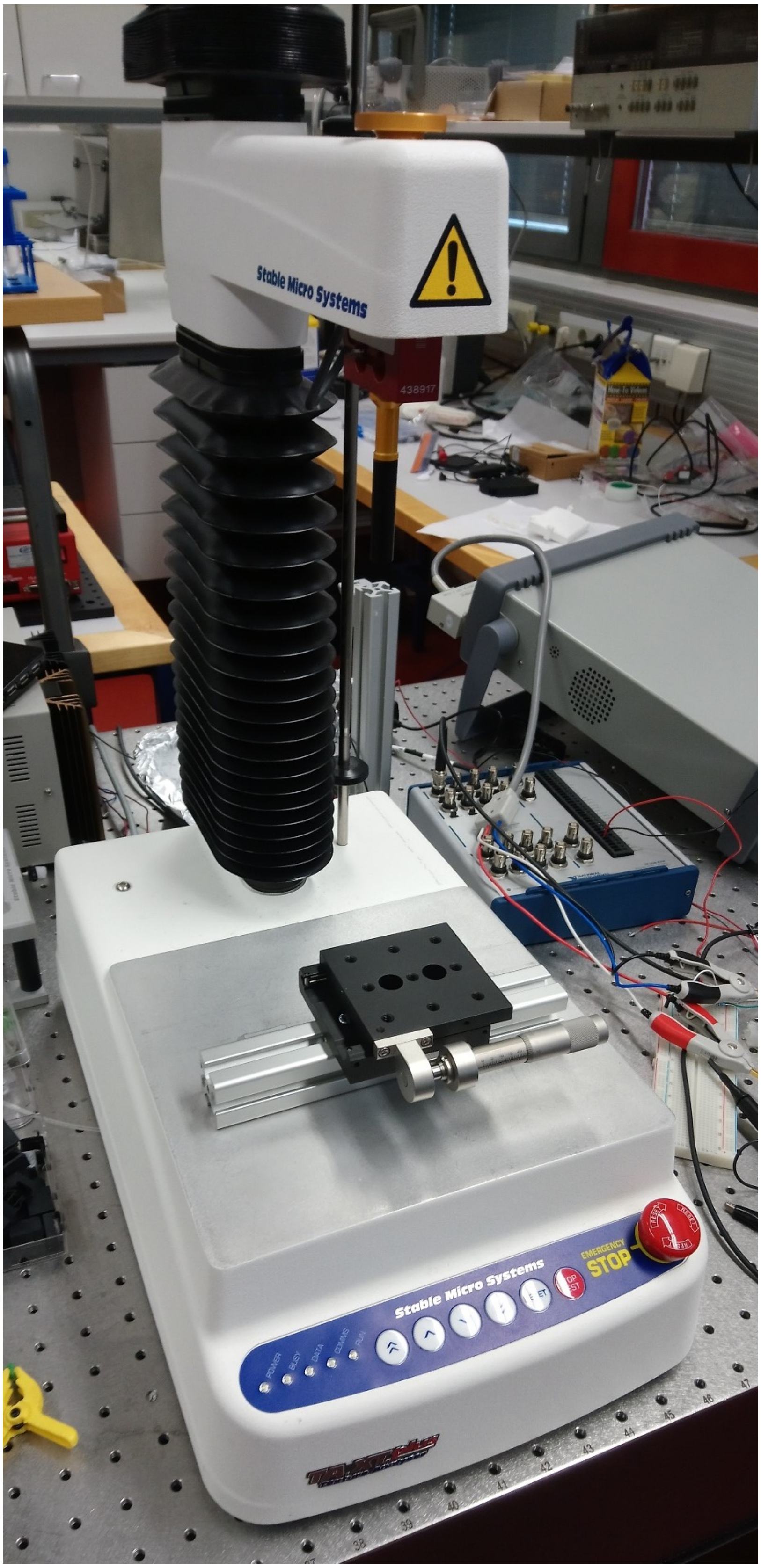

Figure 6. *This Stable Micro Systems texture analyzer was used to apply forces on the sensor pads. Texture analyzers are commonly employed in the food industry to test products' properties.*

Figure 7. *A National Instruments USB-6356 data acquisition device supplied the 5 V DC voltage to the circuit. It also was used to acquire the voltage data and export it to MATLAB.*

We used a National Instruments USB-6356 DAQ device to collect the data from the sensor circuit. To keep the circuit as simple as possible, we built a voltage divider on a breadboard, with a series resistor of 135 kΩ. It is best to use a resistor whose resistance is roughly in the same range with the sensor pads' resistances. We connected the voltage across the series resistor to one of the analog inputs of the DAQ device. By connecting it to a PC via USB, we were able to import the voltage data into MATLAB. Using a short script presented in Appendix A, we calculated the resistance of the sensor pad according to Equation 6. We plotted graphs with MATLAB where the resistance of the sensor pad could be matched with the corresponding force value. Finally, we typed the data points into Microsoft Excel and plotted the curves.

4.3 Results

The corresponding force and resistance values interpreted from the MATLAB graphs are presented in Table 3. The MATLAB figures are placed in Appendix B. As seen in the resistance curves in Figures 14–16, at the beginning and end of each test using one force value, the sensor pad's resistance peaks much higher than what the actual resistance is during the test. Deforming and reforming of the pads causes some unexpectedly high resistance values. These brief rises in resistance could be eliminated using a low-pass filter. A filter would also reduce other slight variations in resistance during the tests. Moreover, it is detectable from the figures that the sensor pads continued deforming throughout the test period of 10 seconds. This caused the resistance of the pads to decrease slowly until the end of the test.

Table 2 displays the resistance of each pad when the force applied is 0 N, i.e. R_0. The largest sensor pad was named Pad 1, and thus its resistance is R_1. Similarly, the smaller pads are named Pad 2 and Pad 3, and their resistances are R_2 and R_3.

Table 2. The value of R_0 for each pad.

	Pad 1	Pad 2	Pad 3
R_0 (kΩ)	6500	80	80

Pad 2 and Pad 3 are physically the same size, and so R_0 is approximately 80 kΩ for both. The value of R_0 for Pad 1 is much higher because of its larger size.

Table 3. The results achieved in the laboratory.

F (g)	*F* (N)	R_1 (kΩ)	R_2 (kΩ)	R_3 (kΩ)	R_1/R_0	R_2/R_0	R_3/R_0
30	0.294	2640	40	36	0.406	0.500	0.450
50	0.491	270	27	32	0.042	0.338	0.400
100	0.981	240	18	25	0.037	0.225	0.313
150	1.472	220	10	17	0.034	0.125	0.213
200	1.962	195	6	13	0.03	0.075	0.163
250	2.453	190	4	9	0.029	0.05	0.113
300	2.943	185	2	6	0.028	0.025	0.075
350	3.434	180	1	4	0.028	0.013	0.05
400	3.924	-	0	3	-	0.001	0.038
450	4.415	-	0	2	-	0.000	0.025

The force applied, *F*, is expressed in both Newtons and the original unit, grams. The data point in orange is disqualified because it does not fit in with the other points. Figure 8 portrays the data regarding Pad 1. The yellow curve is the resistance of Pad 1 as a function of force in grams. The green curve illustrates how much the resistance has decreased compared to the initial value, R_0.

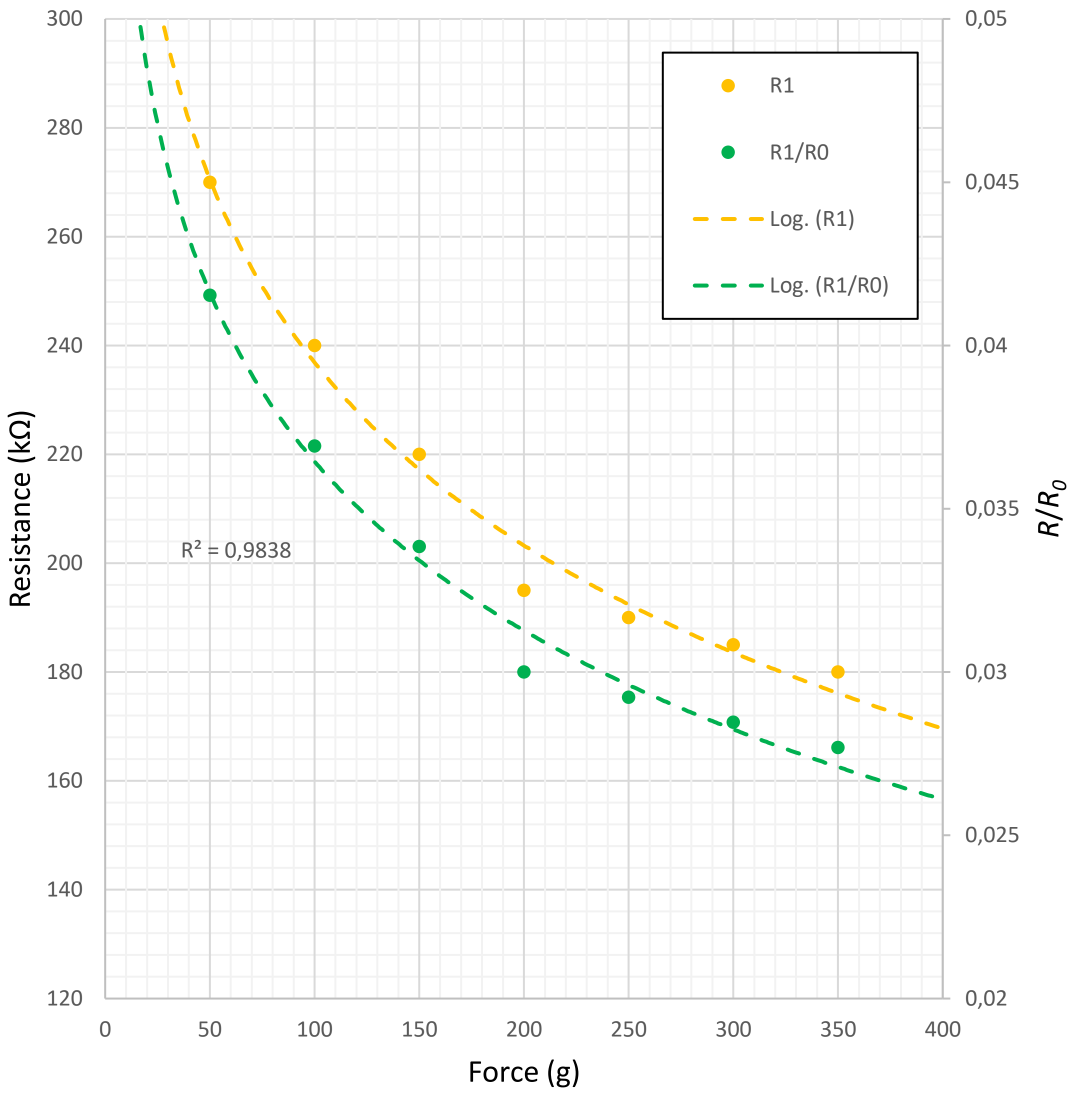

Figure 8. *The resistance as well as the relative resistance of Pad 1 as a function of force in grams. The value of the correlation coefficient is very high.*

In Figure 9 the unit of force has been changed to the more appropriate Newtons. Otherwise the graph is the same as Figure 8.

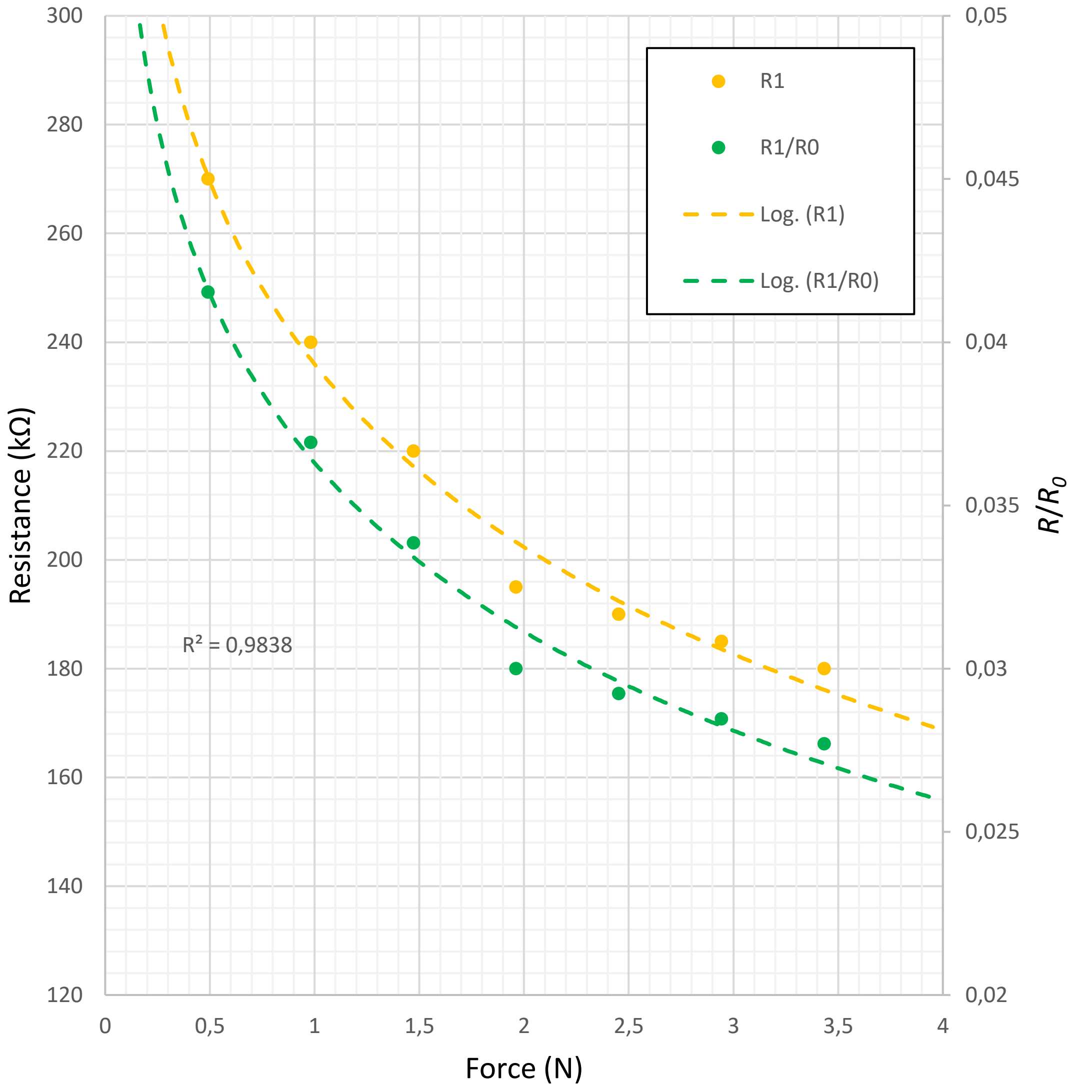

Figure 9. *The resistance as well as the relative resistance of Pad 1 as a function of force in Newtons.*

Applying even a small force of 0,5 N results in a large decrease in R_1. The value of R_1 reduced to around 4,2 % of R_0. The force–resistance relationship is clearly logarithmic. Figure 10 features the same information as Figure 9 but drawn on a semi-logarithmic scale.

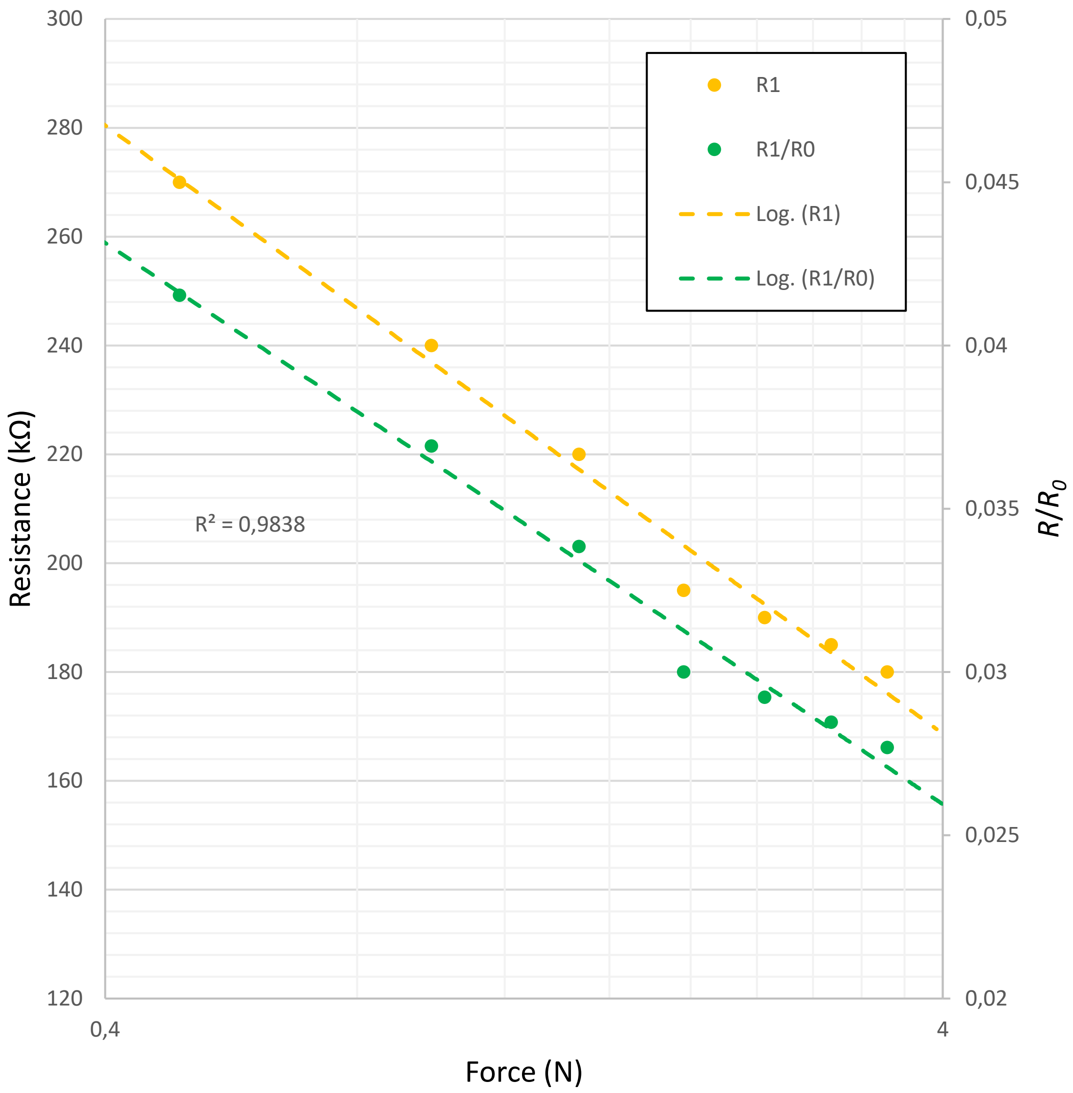

Figure 10. *The resistance as well as the relative resistance of Pad 1 as a function of force on a semi-logarithmic scale.*

According to Figures 8–10 Pad 1 shows promising behavior. All data points except one correlate well. The resistance changes predictably. Figure 10 proves that the force–resistance relationship is indeed logarithmic. However, with forces less than 0,5 N, it looks like the changes in Pad 1's resistance are unpredictable. The reason for this is probably the size of the probe that was used to create the force on the sensor pad. The probe is considerably smaller than the sensor pad itself. This means that the force was actually exerted on only the very center of Pad 1. If the entire sensor pad was squeezed, the results might be even more consistent. The problem with the size of the probe should have less significance in regard to Pad 2 and Pad 3 as they are smaller in size.

The results for Pad 2 and Pad 3 are combined in the same graphs because of their similarity. The raw data is portrayed in Figure 11.

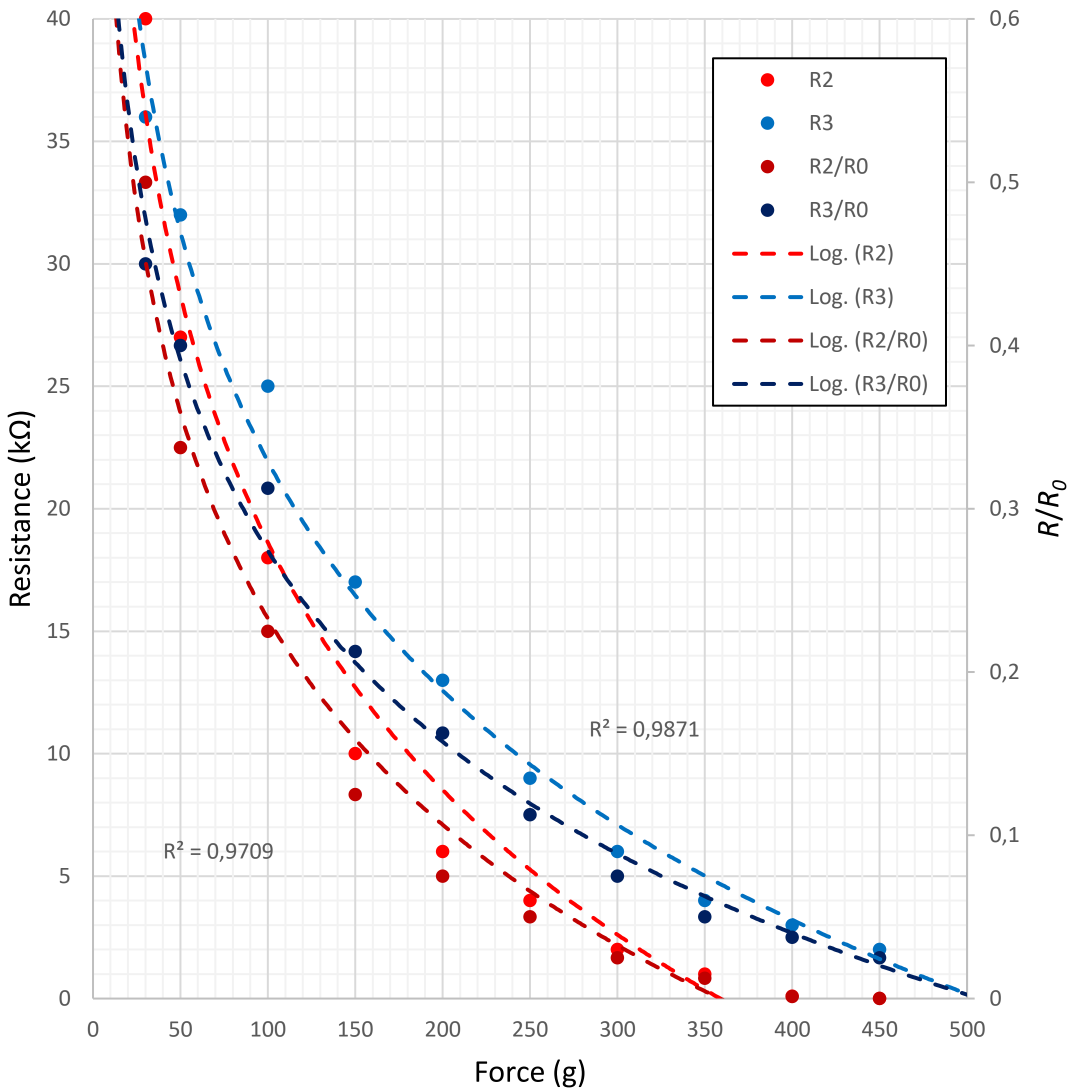

Figure 11. *The resistances and the relative resistances of Pad 2 and Pad 3 as a function of force in grams. Again, the value of the correlation coefficient for both pads is very high.*

Again, Figure 12 displays the same data as Figure 11. The only difference is the use of the proper unit of force, Newtons.

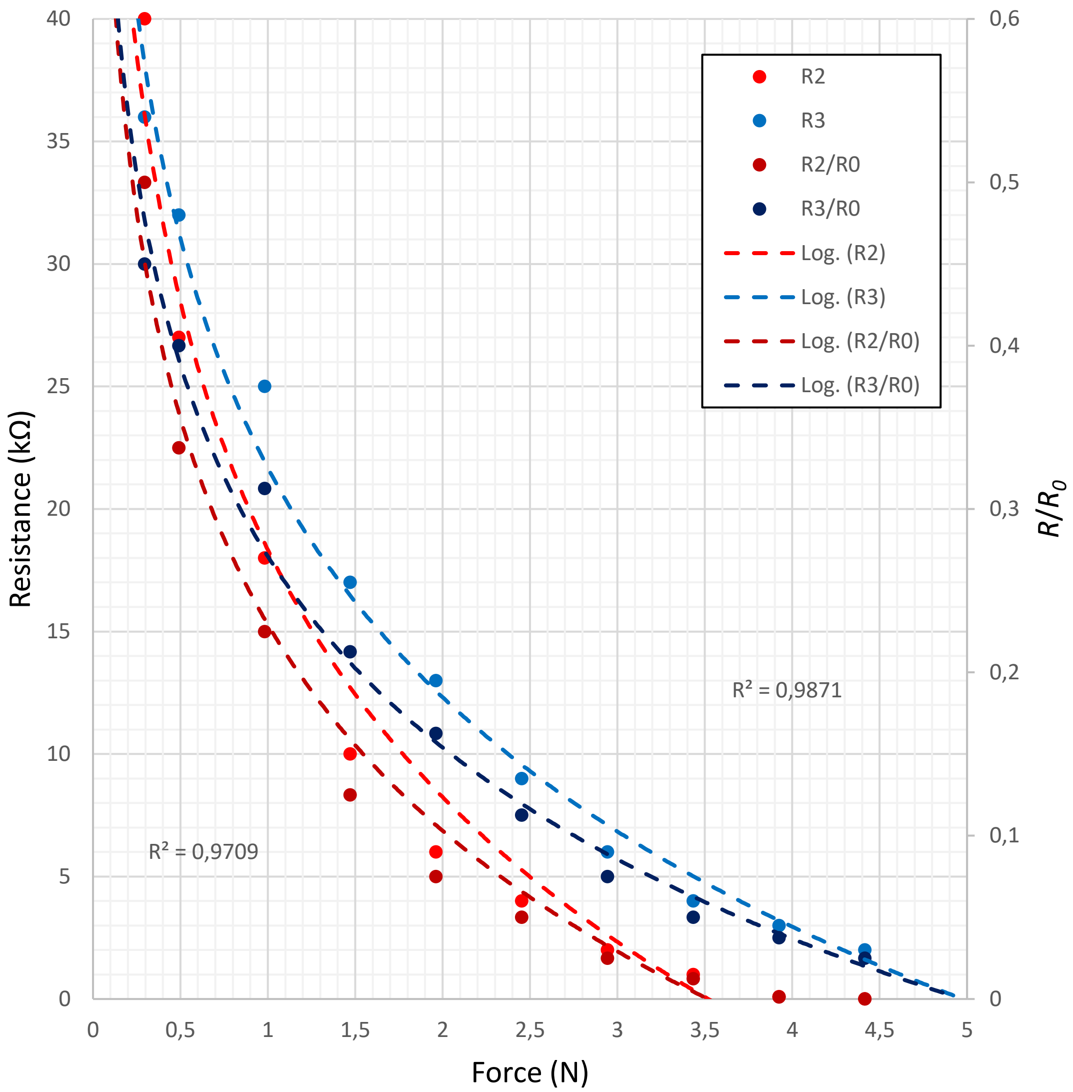

***Figure 12.** The resistances and the relative resistances of Pad 2 and Pad 3 as a function of force in Newtons.*

As seen in Figure 12, R_2 and R_3 do not decrease as drastically as R_1 does when a force is applied. They range from 0–50 % of R_0. The force–resistance relationship of both sensor pads is also logarithmic. Finally, Figure 13 presents the same data plotted on a semi-logarithmic scale.

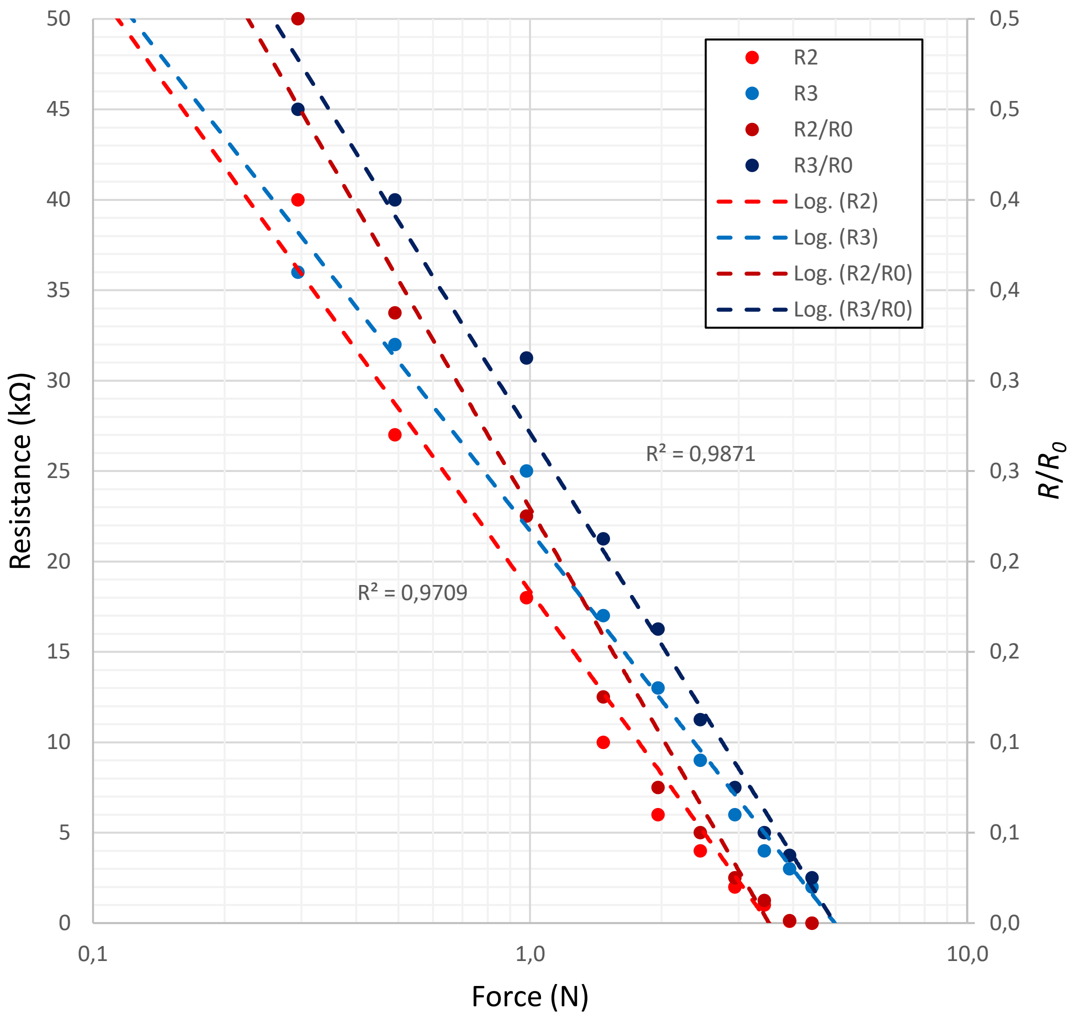

Figure 13. *The resistances and the relative resistances of Pad 2 and Pad 3 as a function of force on a semi-logarithmic scale.*

Figures 11–13 show great promise for Pad 2 and Pad 3. All data points correlate well with each other. Contrary to Pad 1, good results were achieved with a force as low as 0,3 N. The problem regarding the size of the probe is not present here, although if the probe covered the entire sensor pad, the results would probably be even more consistent. Because Pad 2 and Pad 3 are the same size, their curves should in theory be identical. The reason for the difference is in the crude manufacturing process of the sensor prototypes. The pads are not the exact same size as they have been crudely cut out of a large piece of the piezoresistive material probably using scissors. There is also no knowing if the microstructure of the material is perfectly uniform. The screen-printed wires inside the sensor that are connected to Pad 2 and Pad 3 are not the same length. Therefore, the measured R_3 is constantly a little higher, even though the significance of this should be minimal. It can, however, be seen in Figures 11–13 that R_3 is higher than R_2 regardless of the force applied.

5. CONCLUSIONS

Piezoresistive sensors offer many benefits, such as low cost, high accuracy and sensitivity and the possibility of using flexible materials. They do not require a complex measurement system; a simple voltage divider is enough. These factors make them a great choice for the intended application, creating an artificial sense of touch for a hand prosthesis, which enables the user to pick up items and complete other everyday tasks. Their simplicity also makes it rather effortless to conduct laboratory experiments about them.

To summarize the laboratory work, the results seem promising. Since the relationship of force and resistance was verified as logarithmic, the piezoresistive sensor prototype worked as predicted. The data collected is very consistent as the obtained correlation factors are all nearly 1. The reliability of the sensor pads is therefore adequate. However, forces smaller than 0,5 N may cause unexpected resistance values.

More laboratory work is absolutely needed to completely understand the behavior of the sensors. Oscillating forces and using different sized probes were not yet tested. Forces greater than 5 N were also not tested. In addition, the long-term durability of the sensors needs further testing as it was discovered that the sensors are somewhat lacking in that regard. Of course, the sensors are prototypes, and the manufacturing process could be refined if necessary.

Piezoresistive tactile sensing is a relatively novel technology, and thus it has yet to replace more conventional alternatives in industry. Nevertheless, with new applications in the fields of soft robotics and medicine, the future of piezoresistive sensors is prevalent, with various possibilities in sight.

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APPENDIX A: MATLAB SCRIPT

```
% Ahmed Elsayes
% Script for acquiring data from a piezo-resistive sensor by using NI USB-6356
%% reset the program
clear all; clc; close all;

%% this script is to acquire data from piezo-resistive sensor
R2 = 914;        %this is the values of voltage divider resistance
Vs = 5;     %value of source voltage
d = daq.getDevices;         % to get the information about the connected device
s = daq.createSession('ni')   % to start session

ch = s.addAnalogInputChannel('Dev2','ai0', 'Voltage')  % to determine the required channel
ch.Range = [-5,5];        % to set the required range of voltage to get specific resolution: [+V - (-V)]/2^16

data = s.inputSingleScan;   % to scan the data provided through the assigned channel(only momentary check renders one value)

s.Channels   % to give me the properties of the chosen channel
% ch.TerminalConfig = 'SingleEnded'

s.Rate = 100;  % To determine the sampling rate of my signal
s.DurationInSeconds = 5400;    % to determine the time for capturing the signal

[Volt_NI,time] = s.startForeground; % getting two arrays of time and data acquired from sensor during this swept time

R1 = R2 * ((Vs./Volt_NI)-1); % the values acquired in K-ohm range

subplot(2,1,1);
plot(time,Volt_NI);
xlabel('Time (secs)');
ylabel('Voltage')

subplot(2,1,2);
plot(time,R1);
xlabel('Time (secs)');
ylabel('Resistance K-ohm')
```

APPENDIX B: MATLAB FIGURES

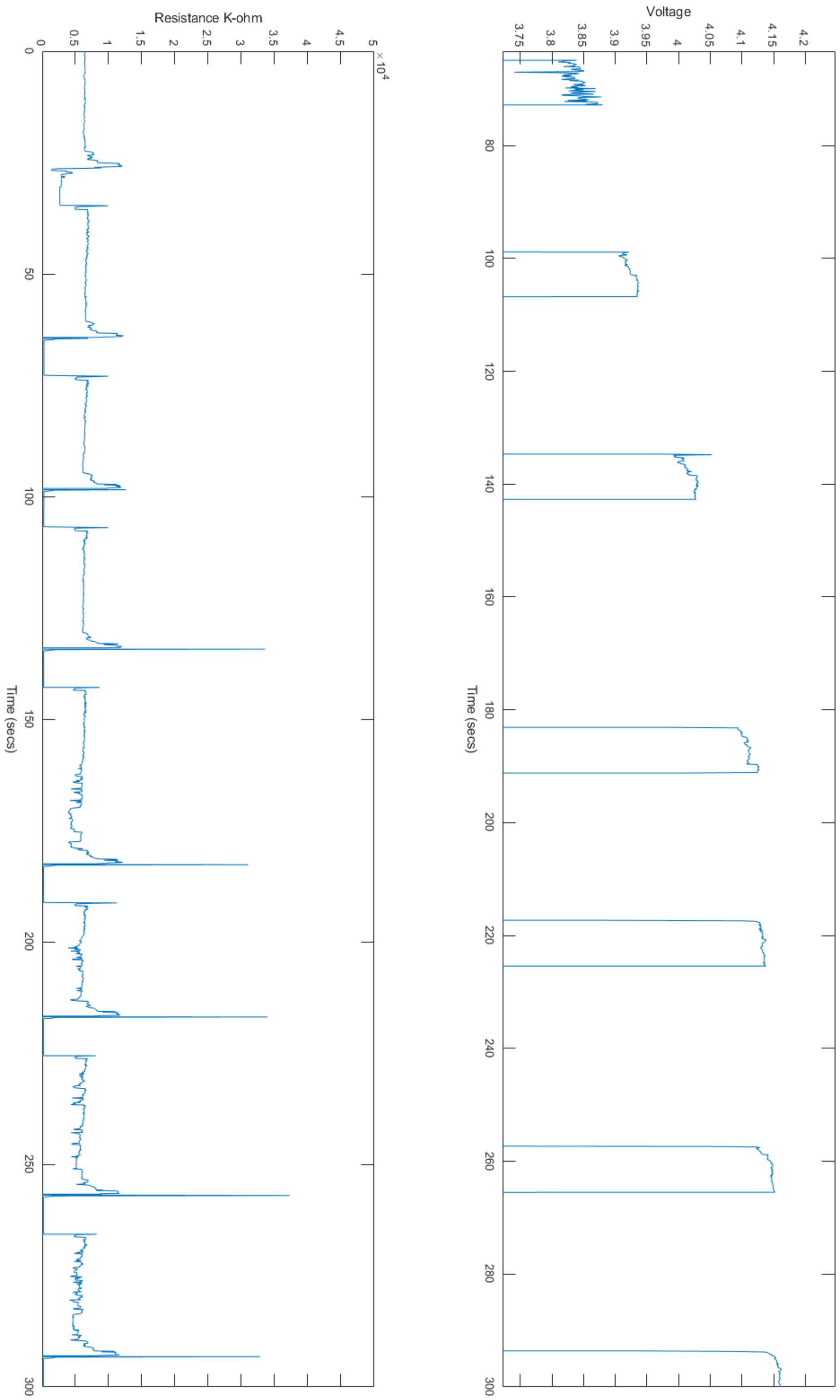

Figure 14. *Voltage and resistance as a function of time regarding Pad 1.*

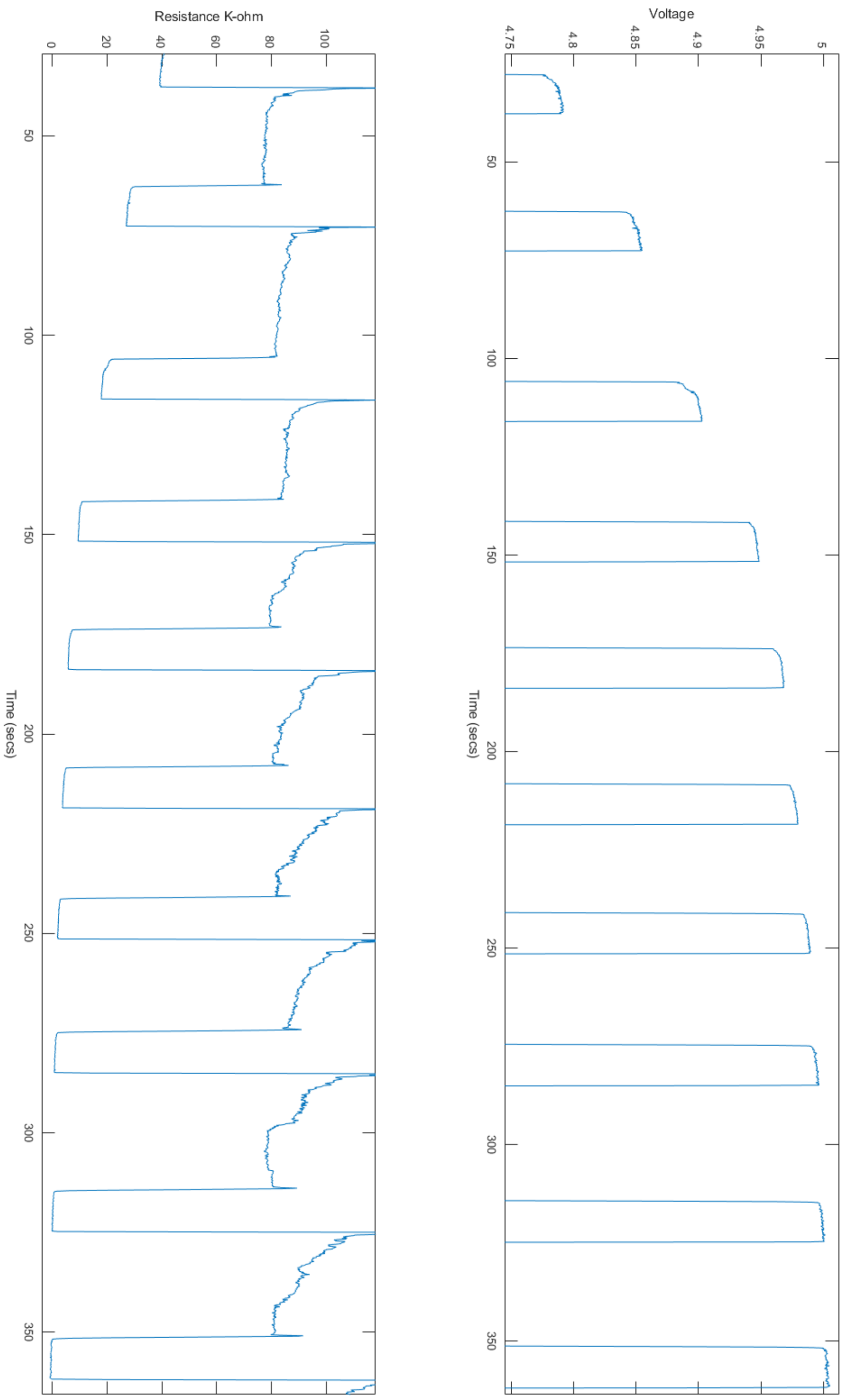

Figure 15. *Voltage and resistance as a function of time regarding Pad 2.*

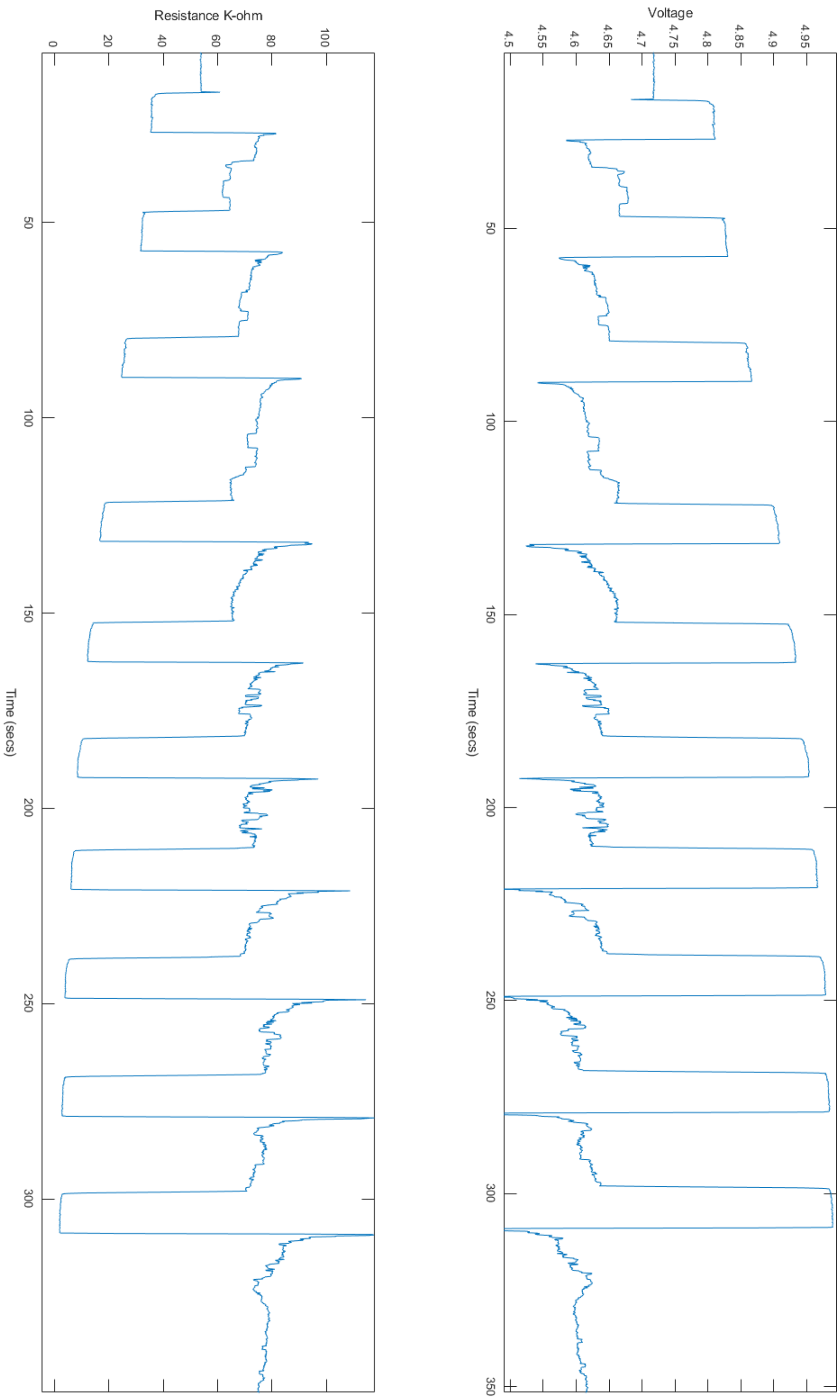

Figure 16. *Voltage and resistance as a function of time regarding Pad 3.*