FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Monitoring System for Compression Sleeves

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MESTRADO INTEGRADO EM ENGENHARIA ELETRÓTECNICA E DE COMPUTADORES

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Resumo

Linfedema é uma doença que tem como origem o tratamento do cancro maioritariamente e que não tem cura. Aquando a remoção do cancro através de cirurgia ou radiação, caso essa zona possuía nós linfáticos, a possibilidade de serem removidas é alta.

A drenagem da linfa é efetuada pelos nós linfáticos, caso não efetuem essa tarefa corretamente dá origem a um acumular de linfa, chamado linfedema.

Um dos tratamentos propostos para o linfedema é o uso de mangas compressivas, que ajudam na drenagem da linfa. Se a doença for monitorizada regularmente o risco de o inchaço aumente drasticamente é menor, pois pode ser logo tratado.

Com o surgimento de novas fibras condutivas tornou-se possível integrar na manga compressiva essas fibras. Para isso tricotou-se simultaneamente a manga com a fibra condutiva, que foram tricotadas de maneira a formar um retângulo em cada lado da manga. Sendo estes usados para medir a capacitância do braço relacionando-a distância entre retângulos tricotados.

Na realização deste trabalho foi descoberto que o uso do braço humano como meio dielétrico produz um meio com permitibilidade elétrica inconstante, contudo existe uma relação perímetro capacidade ainda que muito básica.

Outra abordagem elaborada foi obtenção do perímetro através da elongação da manga compressiva, o que faz com que os fios condutores se alonguem causando o aumento da resistência medida. Obtendo-se uma boa relação perímetro-resistência.

Abstract

Lymphedema is a disease caused by cancer treatment predominantly and does not have cure. When the removal of cancer by surgery or radiation , if the zone has lymphatics nodes, the possibility of being removed is high.

The limph draining is maind by lymphatic nodes, if this task can not be correctly made, the lymph build up, denominated lymphedema.

A proposed treatment to limphedema is use it on a compression sleeve, which helps lymph draining. If lymphedema was regularly monitored the risk of swelling increase is low.

The appearance of new conductive threads make possible integrate them in the compression sleeve. Knitting simultaneously the sleeve and the conductive thread forming a rectangle shape in each side of the sleeve. This rectangles are used to simulate a capacitor and measure the arm capacitance, relating with the distance between plates.

In realization of this work was discovered that using human arm as dielectric medium produce a inconstant electric permittivity, however it was found a realtin between capacitance and perimeter, even though much basic.

Another approach developed was obtaining the perimeter through the sleeve stretch, which makes the conductive thread change its cross-section area and length. This causes the increase of measure resistance. Obtaining a good relation perimeter-resistance.

Agradecimentos

O meu primeiro agradecimento vai para a minha família e namorada, pelo carinho, incentivo e total apoio em todos os momentos desta etapa.

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Joaquim Cardoso

"If something is important enough you should try,
even if the probable outcome is failure."

Elon Musk

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Abbreviations

Analog-to-Digital Converter (ADC)
Band Pass (BP)
Conductive Thread (CT)
Electrocardiogram (ECG)
High Pass (HP)
Intensive Combined Physical Therapy (ICPT)
Low Pass (LP)
Stereo Vision (SV)
Stainless Medium Conductive Thread (SMCT)
Wearable Device (WD)

Chapter 1

Introductory analysis of the problem

1.1 Context

Human body is a complex and complicated machine which performs several tasks. **Lymphatic system**, which is composed by a network of lymphatic vessels connected with lymphatic nodes, is responsible for some tasks such as fluid balance, lipid absorption and immune response. This immune response is due to composition of lymph, there, are white blood cells, that fight infections. Lymph also contains plasma, nutrients that came from blood and hormones, enzymes and waste of products that came from cells. And for that reason the lymph has a important mission in fluid balance, it is responsible to return the fluid that was in the interstitial space to the veins, otherwise, if the **lymphatic system** does not work correctly, it might form a swelling in the body, lymphedema[2] [3].

The **Lymphedema** has two main causes, Primary Lymphedema and Secondary Lymphedema. The first cause is connected to hereditary disease and malformations on lymphatics, like *Milroy disease* or *Lymphangiomas*. It occurs more often in women and in the lower extremities. Whereas the second cause the swelling that follows a infectionor cancer treatment. During the treatment, lymphatic nodes can be removed or radiated, that an stop the normal flow of lymph resulting in the build up of lymph, wich is the lymphedema. Lymphedema can also have different causes, such as: chronic venous insufficiency and even drug-induced edema. As has been reported in [4], lymphedema has been estimated to be present in over 1.33 per 1000 population, in the UK, occurring in all age groups[3], and in USA, there are two million breast cancer survivors, and twenty percentage of them developed the disease [5].

Lymphedema is commonly categorized by stages, there is not a staging predominant classification method, but there are some important methods, such as the *"Földi Method"* and the *"Staging by Limb size"*. The first is characterized by four stages, the higher is the stage less plausible is the reversibility of the edema. Whereas the latter, has three stages described by the limb size. It is accomplished by calculate the difference between affected and unaffected members diameter[3].

- **Mild:** less than 3 cm
- **Moderate:** from 3 cm to 5 cm

- **Severe:** more than 3 cm

The lymphedema symptoms get worse how late the disease is detected. The quality of life drops in equal proportion with the increase of symptoms, this is the reason to discover early the disease and monitor it[3].

1.2 Motivation

Nowadays there are several techniques used to measure the volume of lymph, but none of them fill all characteristics that as been reported in [6], the ideal measurement of volume method should be accurate, repeatable, independent of the person which will be measured as well as simple, cheap and fast.

The main technique used is *Water Displacement Method* because fills all the requirements, however the measurement time is to long, around ten minutes. Another disadvantage is the requirement of the patient for having a good motor function. Shivering affects the result of the measurement, due to the constant water displacement. When the goal is for speed, the chosen method should be *Frustum Sign Model*. This technique measures two circumference and space between them, the volume is then calculated, by truncating one cone with the previous measures. However the result obtained with *Frustum Sign Model* depends from person to person[6].

Lymphedema must be detected early to avoid the suffering of the patient. Because if it is not diagnosed on time, the swelling can cause severe dysfunction. This disease does not have cure, however it can be treated by physical exercises, massages and compressions. Monitoring the lymphedema volume is important as it gives an objective metric to whether the treatments are been successful or not[6].

1.3 Objectives

The purpose of this work is be able of monitoring the arm volume by a non invasive method. with the compression sleeve used in lymphedema treatment. To accomplish it will be used a conductive textile sewed to the sleeve, capable to measure the volume of lymphedema swelling.

System development is constrained by:

- manufacturing process,therefore the design should allow the manufacture sew independently of material.

To achieve the goal of this work is necessary:

- understand volume monitoring methods
- understand conductive threads characteristics
- understand knitting fabric characteristics

- relation between capacitance and perimeter
- relation between resistance and perimeter

Chapter 2

State of the Art

2.1 Lymphedema

In upper limbs the lymphedema is generally caused by the breast cancer treatment, which affects an estimated one hundred and forty to two million people worldwide. This treatments involve surgery or radiation in zones with cancer, if this area has lymph nodes, possibility of node removal is high. The lymph nodes function is to filter the lymph and to drain it away from the area where the node is, if the draining can not be accomplished the lymph will build up and it will create a swelling in that specific body part, designated lymphedema.

Lymphedema occurs more frequently in treatments of breasts, prostate, uterine, vulvar or cervical, areas where there are a higher lymph nodes concentration [2] [3] [7].

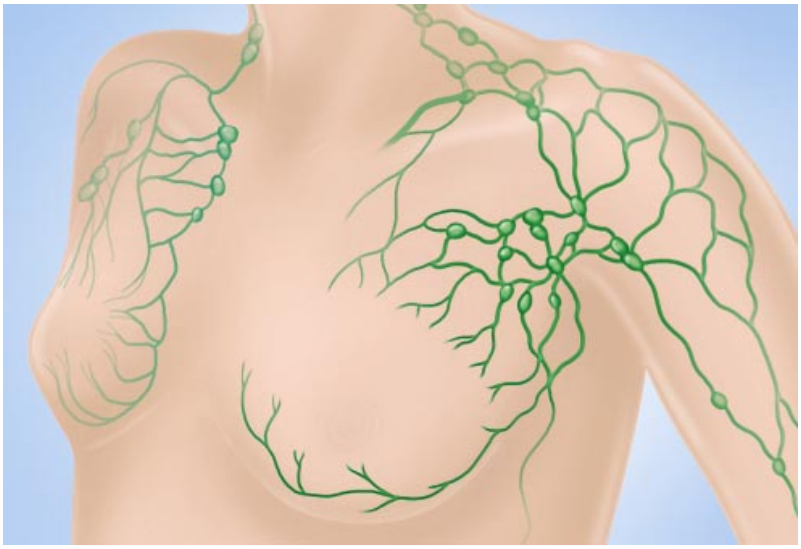


Figure 2.1: Lymph nodes under arm and in breast. Adapted from [8]

2.1.1 Lymphedema Monitoring Techniques

The lymph build up is peremptory to be detected in early stage, in order to the treatment can be more effective. For that reason it is need monitoring the lymphedema volume. Through the monitoring is possible understand the disease and predict the lymphedema behaviour, been possible act more rigorously.

To monitor the swelling, there are some techniques, present in the following table.

Table 2.1: Comparison of the most significant techniques for measure Lymphedema volume (Adapted from [6])

Method	**Accuracy**	**Repeatability**	**Measure Time**	**Cost**	**Operator dependency**
Water Displacement	99.7%	Finger 98% Forearm 99.1 %	Finger 3 min Other 15 min	Less than 1 EUR	None
Frustum Sign	92-98%	94-98%	1 min	Less than 1 EUR	High
Disc Model	92-99%	Finger 97% Forearm 98%	Finger 8 min Forearm 14 min	Less than 1 EUR	High
MRI[1]	Finger 92% Hand 98%	95%	Hand 15 min	250-300 EUR	Low
CT[2]	Finger 98% Hand 99.5%	98%	Hand 7 min	100 EUR	Low

By analysis the table 2.1, the most effective measure system is the water displacement. This technique uses a simple process, the amount of water overflow from a filled container represents the limb volume measured.

Water displacement is cheap, does not depend the operator , repeatable and high accuracy. However have some faults, like the lengthy process, body shivering influences the measure, patient must have some flexibility and can not have infections.

Another simple technique is the Frustum Sign, where in first place is measured two arm perimeter in different zones, $C1$ and $C2$ using a non-elastic string. The distance between measured places is represented as h, and d_s is the string diameter. Then the volume is obtained truncated cone between the measurements and can be expressed as,

$$V = \frac{\pi}{3} \times h \times \left[\left(\frac{C_1}{2\pi} - \frac{d_s}{2} \right)^2 + \left(\frac{C_1}{2\pi} - \frac{d_s}{2} \right) \times \left(\frac{C_2}{2\pi} - \frac{d_s}{2} \right) + \left(\frac{C_2}{2\pi} - \frac{d_s}{2} \right)^2 \right]$$

The advantage of the Frustum Sign for other techniques is the measure time. For a short time is possible obtain a good accuracy of arm volume.

The Disc Model approach allows a better repeatability by comparison with Frustum Sign, through more circumferential measurements, which are separated by 40 mm distance. The volume obtained by this method is calculate as,

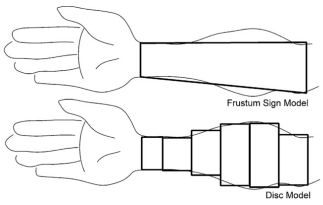
$$V = \sum_{i=1}^{n} \pi \times h \times \left(\frac{C}{2\pi} - \frac{d_s}{2} \right)^2$$

[1] Magnetic Resonance Imaging
[2] Computed Tomography

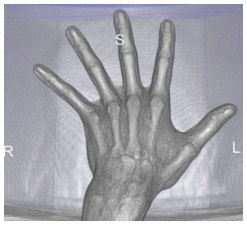
Magnetic Resonance Imaging or Computed Tomography are recommended when is request to measure only a specific region not the entire limb [6]. These are not often used because of the high costs.



(a) Water Displacement



(b) Frustum Sign and Disc Model



(c) Computed Tomography

Figure 2.2: Four mthods used in lmphedema monitoring (Adapted from [6])

2.1.2 Lymphedema Assessement

The Lymphedema is considered present in patient if the volume difference on swollen limb and unaffected limb is higher than 10 % or perimeter difference is more than 3 cm. Using the simplified measuring method reported in [9] is possible obtain arm perimeter in 3 positions and compare the affected and unaffected arm, according to assess the respective perimeter. The positions to obtain a measure are:

- 10 cm below the epicondyle
- 15cm above the epicondyle
- wrist

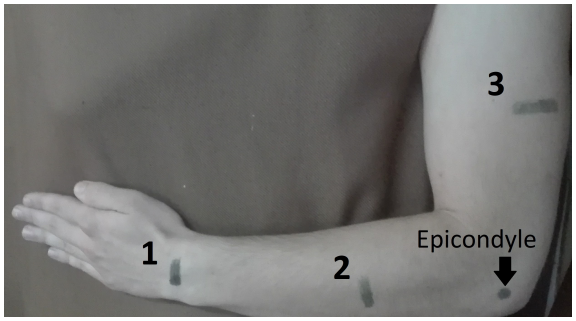


Figure 2.3: Three positions to measure perimeter

The figure 2.3 show with number 1 the zone to measure the perimeter, wrist. The 2 represent the zone 10 cm below the epicondyle and number 3 is 15 cm above the epicondyle. Theses 3 perimeter measures most be taken for a better lymphedema assessment, because lymphedema may appear in some arm areas and in others not.

2.1.3 Lymphedema Treatment

Treatment must start on a early stage of Lymphedema, to help decrease the swelling. **Complete Decongestive Therapy** (CDT) is the standard treatment, which includes specific massage form, exercises, skin care and compression sleeve [10].

As been reported in [11], the compression sleeve has a important function on treatment. Which begins with 1 or 2 weeks of intensive treatment, **Intensive Combined Physical Therapy** (ICPT), where, it is important to reduce the lymph swelling.

After 5 years of the ICPT, 60 patients were observed and divided in 2 groups. Group A was characterized by using the prescribed compression sleeves during the day, replace the compression sleeve at least once a year, continue with the prescribed physical exercises and attended examinations, once every 6 months. However the patients, in Group B, never complied with prescribed compression therapy, as compression sleeves, and continue with prescribed physical exercises.

Table 2.2: Assessment of lymphedema volume with and without compression treatment

	Swelling Volume Before ICPT	**Swelling Volume After ICPT**	**Swelling Volume After 5 years**
Group A	781.6	503.4	557.0
Group B	764.2	480.6	879.7

The conclusion reported in [11] explains that after 5 years of ICPT the group which continues compression therapy, group A, its lymphedema volume continues near the value obtained with the ICPT, as it is possible observe in table 2.2. On the other hand, the group B, which do not realize any prescribed physical exercises or use compression sleeves, its lymphedema volume after 5 years is bigger than before ICPT. So the compression therapy and physical exercises helps maintaining the lymphedema volume constant.

2.2 Volume measure

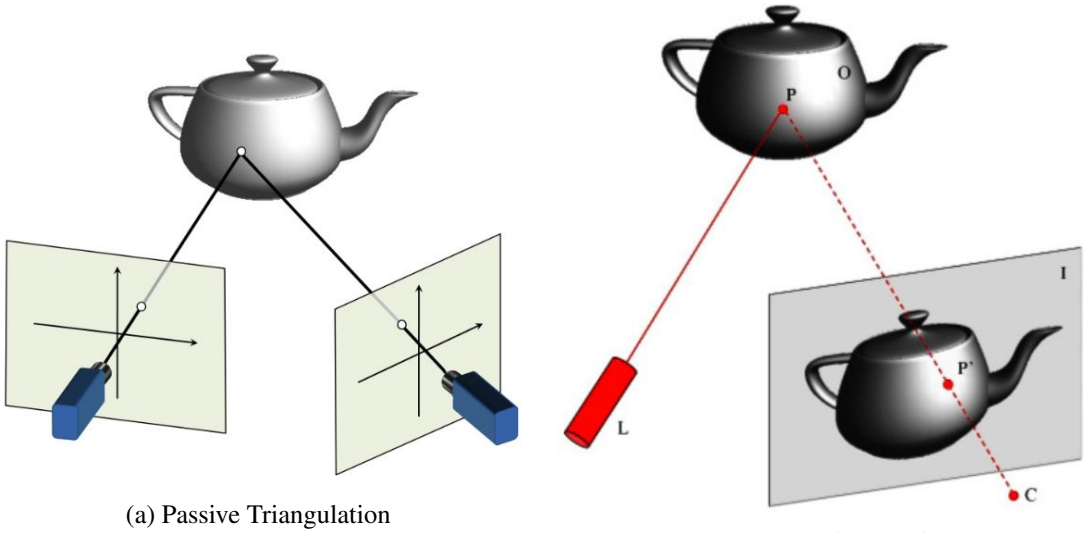
In lymphedema monitoring is accomplished through comparison arm volume of different days. Obtaining this way the disease evolution, for that reason is imperious obtain the arm volume.

The volume of a solid depends on its shape. If the solid has a regular geometric shapes, such as rectangular, cubic, cylindric or spherical, to get the volume is used known volume formulas for each solid. However if it has a irregular shape to establish its volume formula becomes more difficult. For a quickly approximation of the solid volume can be used the known regular shapes and determine its volume using them.

However if a better volume measurement is required, i.e. when the volume value have to be precise or with a minimum error, there is the need to reconstruct the solid surfaces. For that need have been developed several techniques, which use non-contact systems based on light waves, such as 3D active sensors or 3D passive sensors [12]. Some applications of the 3D sensors are,

1. **Passive Triangulation**, this technique uses 3D passive sensors for the reconstruction of the solid shape, based on images captured from multiple cameras. These cameras, for a point in real world, obtain different localizations of their images. When intersecting these image it is possible obtain the three dimensions coordinates of the point, however, there is the need to know position and orientation of the cameras ray . Repeating the process for several points it is possible to obtain the object shape [1].

2. **Active Triangulation**, by replacing one of the camera by a laser become more easy to find the corresponding point on different cameras images. Also, it is necessary know the position and orientation of the laser ray and cameras ray. With these informations is possible intersect images and obtain a three dimension point. For obtaining the entire surface is necessary the laser moves at different points and each time an image has to be taken. This technique is include in 3D active sensors [1].



(a) Passive Triangulation

(b) Active Triangulation

Figure 2.4: 3D sensor applications (Adapted from [1])

After the obtained solid surfaces, the next step is calculate its volume, which is the integral of the 3D surface [13].

2.3 Wearables

The need of accessing personal biometric information is, nowadays, of high demand. As computer devices are equipments with a enormous capability of processing information, this feature can then be used for getting the desired personal biometric information. Devices like the laptop, cellphone and tablet, which are of small size have a substantial amount of computational power, and can be used for the required purpose [14].

Although these devices satisfy our computational needs, their size does not make them suitable for carrying them around on a daily basis. Along those lines, specialized computing peripheral

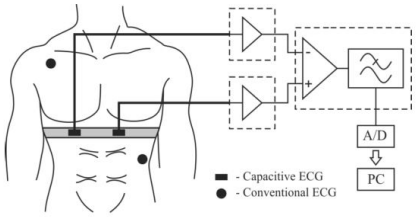
devices were created. These comprises devices like sensors that can monitor movement, heart rate, among other things. This kind of peripherals are suitable to be used either on top or under the clothes, giving them the designation of **wearable device** (WD)[14].

The WD has been improved its comfort for the user, which takes the fabrication process to use more comfort materials, as conductive textiles. These are more suitable to wear every day. Some WD users can be the patients with lymphedema. They needs to use compression sleeve in disease treatment and also they need to monitoring the arm volume, for these reasons and for a better comfort to patient will be used the compression sleeve with knitted conductive thread to measure the volume.

2.3.1 Medical Wearable Applications

Some WD have been developed to help in medical care. This it dues at ease of use, integration in quotidian devices or clothes. As appear new WD with main goal it is contribute for medical care, as **electrocardiogram** (ECG) waveforms or a device which measure human movements, in this section only will be approached the medical WD.

Figure 2.5: Two examples of medical wearable devices



(a) ECG monitor system (Adapted from [15])



(b) Joint Movements Monitoring (Adapted from [16])

1. **ECG monitoring system**, is a device which monitors the heart rate. There is a sensing part that is responsible of carrying body surface bio-electric current through insulated electrodes, which forms a coupling capacitor. The input current flows into the **high pass** (HP) filter, formed by the electrodes capacitance and two anti-parallel connected diodes in reverse

polarization. The HP is connected to non-inverter input of a amplifier, the inverter input is connected to a **low pass** (LP) filter. LP filter is responsible of integration and repair the ECG wave, because the HP derive the wave. The signal is amplified and it is inputted to a **Analog-to-Digital Converter** (ADC), after that the signal is processed by Matlab. The ECG waveform bandwidth is in range from 0 Hz to 40 Hz, and for that reason was used a HP filter has cut off frequency of 40 Hz. Another filter it is used, a LP filter has cut off frequency of 0.4 Hz, to remove motions artifacts (breathing, muscle activity)[15].

2. **Joint Measurements Movements Monitoring**, uses a fiber optic curvature sensor with a sensitive zone to obtain the curvature of movements, this is important for patients who need physical therapy or rehabilitation. The sensitive zone is an area when the fiber is sawed in teeth form. A fiber optic with a sensitive zone is placed on the knee side, when it moves, the fiber will be bended, and the leaking light occur from the sensitive sensor. As reported in [17], the fiber sensor voltage output decrease as curvature increases. Afterwards a micro-controller drives a LED, and measures the output signal using a A/D converter and transmit information to a PC via ZigBEE. Then data collect is available for remote monitoring [16].

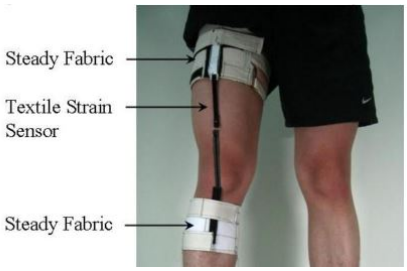
2.3.2 Conductive Textiles Applications

Currently available WD are all almost made by the traditional electronics fabrication process. Regarding that, their exterior structure is based on plastic boxes, which are attached to clothes. So, the current devices do not provide comfort for the user. Therefore, these devices are not truly wearable, as they are not integrated with the clothes [14]. The designation of wearable may change as a new kind of textiles appears, namely conductive textiles. This possible alteration of wearable meaning is due to the no longer need to use traditional process of fabrication because in a near future it may be possible to create circuit only recurring to conductive textiles. In Wearables Applications section is present ECG Waves Monitor and Joint Knee Movements Monitor, existing similar wearables made from conductive textiles.

Figure 2.6: Two examples of medical wearable devices using conductive thread



(a) ECG monitor system (Adapted from [18])



(b) Joint Movements Monitoring (Adapted from [19])

1. **ECG Monitoring** , the eletrodes are made from conductive fabric, Shieldex MedTex P-130, which is woven to a shirt. Then the signal is amplified and filtered by a Band Pass with passband of 0.2 Hz to 70 Hz. Then a signal is converted with an ADC and processed by a microcontroller [18].

2. **Device design for Monitoring the Flexition Angle of Elbow and Knee Movements**, use a elastic conductive webbing made from conductive yarns and elastic yarns to form a textile strain sensor. When the sensor is stretched the resistance decrease in linear proportion, with this relation elongation-resistance is becomes possible to monitor the flexition angle of elbow and knee[19].

2.3.2.1 Conductive Textiles Characteristics

The Conductive textiles can be divided in two categories: Conductive Fabrics and Conductive Threads. The conductive fabric is used to integrate a wearable, while the conductive threads is to be knitted to create a wearable. In table below is present some Conductive Textiles ans their characteristics:

Table 2.3: Conductive textiles characterization

Conductive Fabrics	**Plating**	**Surface Resistance**
Shieldex® Basel [20]	Silver	<0.6 Ohms/□
Shieldex®Bilbao [21]	Silver	<2 Ohms/□
Shieldex® Kiel +30 [22]	Copper	<0.02 Ohms/□
Conductive Threads	**Plating**	**Resistance**
Shieldex® Twisted Yarn 117/17 dtex 2-ply [23]	Silver	<3000 Ohm/m
Shieldex® 110/34 dtex 2 ply HC Premium Line [24]	Silver	65 Ohm/m ± 10 Ohm/m
Shieldex® 235/34 dtex HC Premium Line [25]	Silver, double layer	<30 Ohm/m

2.3.2.2 Knitting Conductive Threads

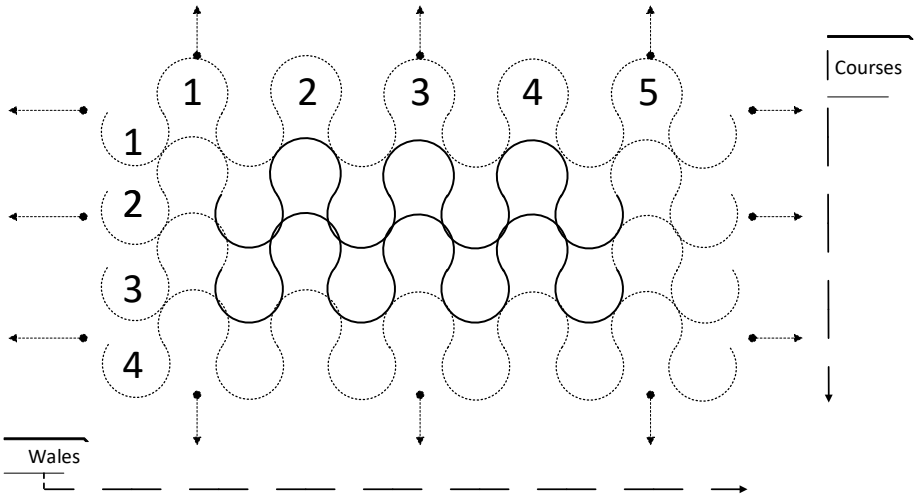


Figure 2.7: Model of knitted conductive thread

The clothing use mostly knitted textiles, which gives them elastic and extensible characteristics. Replacing conductive threads by normal textiles threads in knitted fabrics, which allows to create conductive zones with it, denominate sensors. The figure 2.7 show knitted fabric with 4 courses and 5 wales.

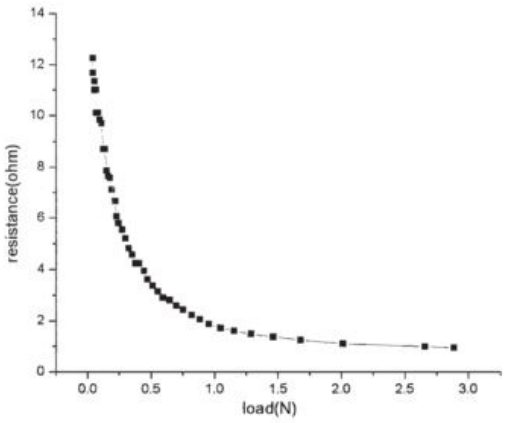


Figure 2.8: Relationship between load and resistance (Adatpted from [26])

These sensors are based on resistance variation. The change in resistance occurs with extension, deformation in the conductive thread. Stretching the knitted fabric, the contact points between threads increase doing the contact resistance decrease [26]. Obtaining a relation between load on knitted fabric and resistance.

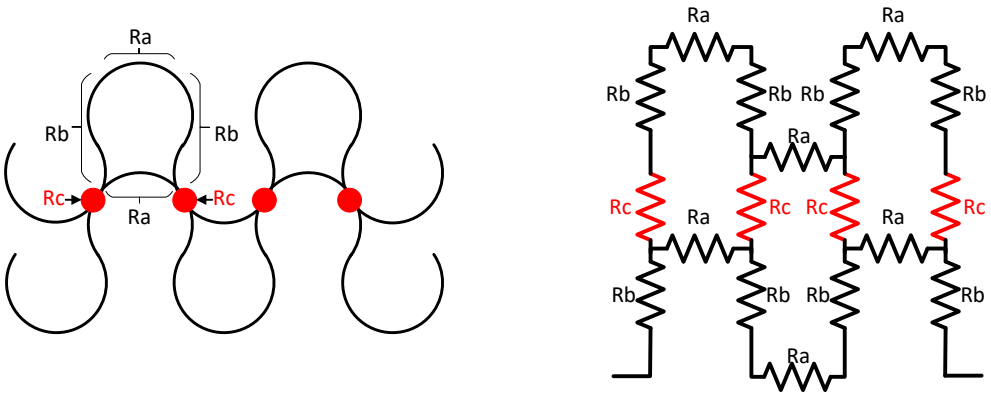


Figure 2.9: Resistive model with contact resistance

A theoretical model for conductive knitting fabric have been develop in [27], where is analysed the textile as a resistive model. Each unit cell is composed by a top needle loop, *Ra* resistance, two contact resistance between loop interlaced thread, *Rc*, two leg thread, *Rb* and a bottom needle loop, *Ra*, as show figure 2.9.

When knitted fabric is subjected to a tensile, the knitted fabric as the follow behaviour,

1. Occurs the straightening of loop thread, *Ra*
2. The straight thread then it is stretched
3. Compression on the contact points

$$R_c = \frac{\rho}{2} \times \sqrt{\frac{\pi \xi H}{P}}$$

Where ρ is the material resistivity, ξ is a correction factor, H is the contact hardness and P is the contact force.

$$R = \rho \frac{l}{A}$$

Where ρ is the material resistivity, l is the conductor length and A is the cross-section area.

These steps make the contact resistance drop by the increase of contact points and the loop yarn resistance increase because its cross-section area decrease and there is the length rise.

2.4 Organization of this Document

Following this introduction a literature review regarding the lymphedema disease, where it is analysed the monitoring techniques, then techniques to measure volume. After it is presented medical wearables applications and some of them using conductive textiles.

In Chapter 3 is introduced the solutions which will be exploited in next chapters, capacitive and resistive models. In Chapter 4 the solution presented is using capacitive model, where is done a analogy between a parallel plates capacitor and parallel conductive thread knitted on compression sleeve and the results is showed too.

The resistive model is in chapter 5 and its results. Then the conclusion and future work is in chapter 6.

Chapter 3

Problem Characterization

3.1 Problem

The objective in this dissertation is to be able of monitoring the arm volume with the a compression sleeve used in lymphedema treatment.

As the sleeve is permanently in contact with arm and it adapts to arm shape, using this sleeve characteristics to integrate a monitoring system on it.

3.2 Solution

The monitoring system will exploit a capacitive and resistive solution. The geometry of conductive thread knitted influences the solution to be measured.

In the capacitive solution will knitted two rectangles, placed on each side of the sleeve, simulating the capacitor plates. Monitoring the capacitance of the conductive thread will be possible to analyse capacitance fluctuation when there are volume change.

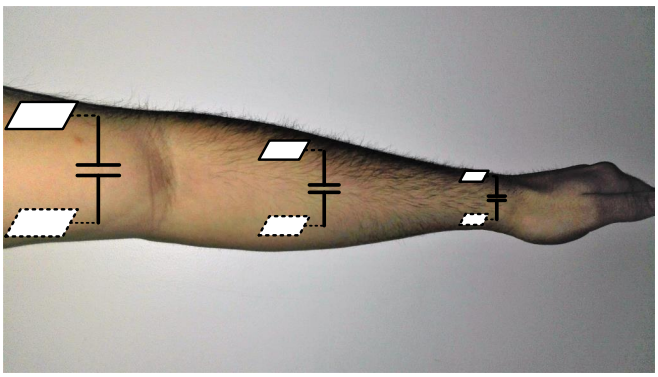


Figure 3.1: Capacity solution

In the resistive solution will be knitted a rectangle in one side of sleeve. The exerted load by the volume arm expresses in a resistive value. As the load increase the resistance should increase too.

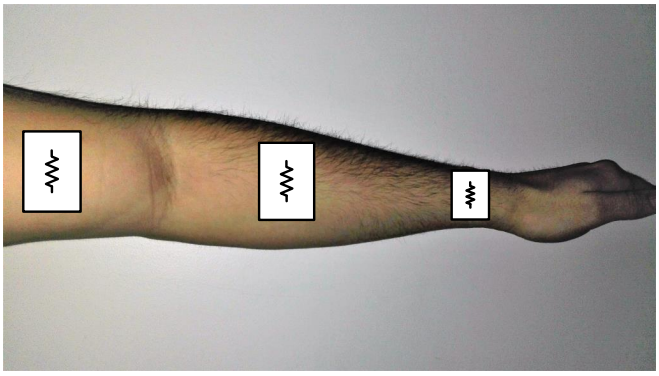


Figure 3.2: Resistive solution

Chapter 4

Capacitive Model

4.1 Overview

In this chapter will be presented a capacitive model capable to characterize the arm perimeter through the capacitance measured. As a parallel plate capacitor when distance between plates increase its capacitance decrease, the idea is to use the relation between plate distance and capacitance measured. After obtain two or more arm perimeters is possible obtain the arm volume by truncated cone between the measurements.

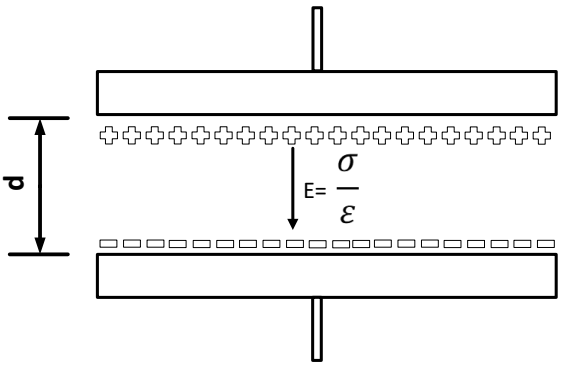


Figure 4.1: Model of parallel capacitor

Capacitance is the ability of a capacitor to store an electrical charge onto its two plates.

$$C = \frac{Q}{V}$$

Q is a charge stored in plates, and **V** voltage applied to the plates.

Voltage difference between the two plates can be expressed as the work done by the electrical field, **E**, on a test charge (**q**), which moves from the positive to negative plate.

$$V = \frac{workdone}{charge} = \frac{F \times d}{q} = E \times d$$

Electrical field, which is expressed as the fraction between charge density, σ , and permittivity, ε.

$$E = \frac{\sigma}{\varepsilon}$$

Charge density of a plate is expressed as, where plate area is expressed as **A**:

$$\sigma = \frac{Q}{A}$$

Relating the equations above is possible obtain the Parallel Plate Capacitance.

$$C = \frac{Q}{V} = \frac{\varepsilon \times A}{d}$$

Analysing the equation is deductible that capacitance is directly proportional to the permittivity and plate area, and inversely proportional to the distance between plates.

In the capacitor is used a dielectric, which has the function to be a electrical insulator. When is applied an electrical field to the dielectric, charges slightly shift from their equilibrium position causing dielectric polarization. Which create a internal electric field that reduce the overall electrical field, increasing the capacitance. So, the use of dielectric in capacitor increase the capacitance.

4.2 Analogy between Parallel Plates Capacitor and Parallel Conductive Thread Knitted

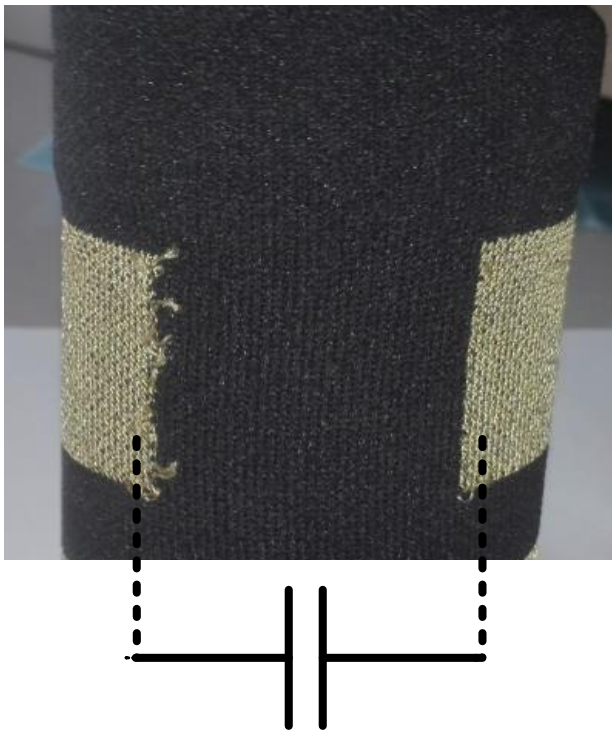


Figure 4.2: Knitted conductive thread on compresion sleeve

As it is possible see in figure 4.2, a conductive thread, with yellow color, is knitted to a compression sleeve. The contact points between wales become this geometry electrical continuous. The rectangle sewed to the sleeve can be compared to a capacitor plate.

In the sleeve is showed two rectangles sewed parallel, this geometry is similar to the parallel plates capacitor. When the sleeve is weared, it forms a cylinder shape but the plates continues in parallel to each one.

4.3 Theoretical Model

The monitoring system will be based on a conductive thread, which will have sensor function. The rectangles are made from the Shieldex Twisted Yarn 117/17 dtex 2-ply and they are knitted simultaneously as compression sleeve, which are used to lymphedema treatment.

The rectangles localization in sleeve makes it possible compare them to a capacitor with parallel plates.

Admitting area and medium permittivity is constant, when capacitance change, it is due to the distance variation between plates. Therefore, when the measured capacitance change owing to alteration in arm volume.

In such way that will be possible relate capacitance with arm volume.

$$C = \frac{\varepsilon \times A}{d}$$

In **first phase of experiment**, to validate this theory was sewed two rectangles with Shieldex Twisted Yarn 117/17 dtex 2-ply as show the figure 4.3, and it was measure the capacitance to different distance between sewed rectangles, so different perimeters. The reason to use of cylinders is to simulate the human arm shape. Also it was measure the capacitance of the conductive knitted rectangles in the sleeve.

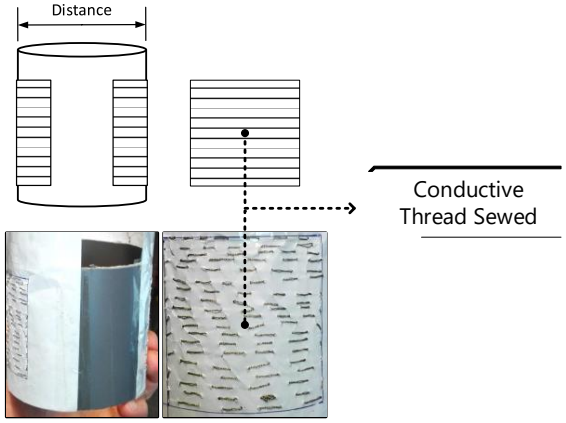


Figure 4.3: Methodology stages

In **second phase of experiment**, it is necessary understand the influence of human arm on the capacitance measured.

The dielectric, ε , is different from the first phase to second phase. As it is possible see in table 4.1, for the relative permittivity, ε_r, the lowest value is the air, and highest is for muscle. It is possible conclude $\varepsilon_{air} < \varepsilon_{human\,arm}$.

Table 4.1: Relative permittivity of human composition for 1 kHz frequency

	Relative Permittivity (ε_r)
Air	1
Bone	5632
Blood	5258
Fat	24104
Lymph	56558
Muscle	434930
Skin	1135.6

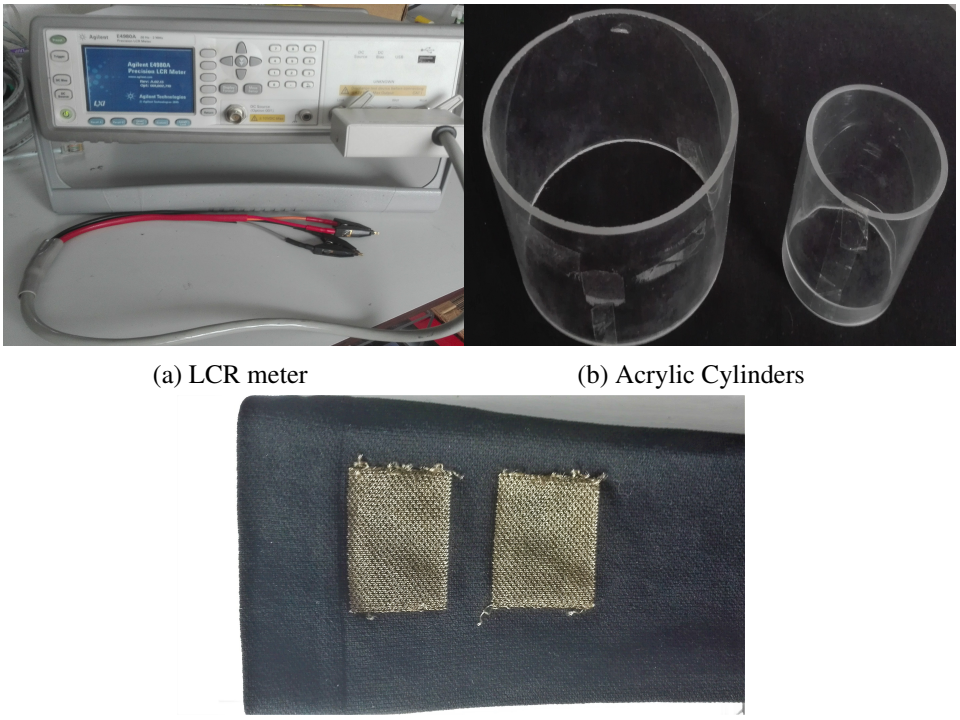
So, it is expectable the capacitance measure for similar perimeters will increase.

4.4 Methodology

The methodology has a lot of importance because there are many unknown variables in the characterization of sleeve perimeter through the capacitance measured. Therefore, the measures has to be capable of being related to one another, the research approach must has research approach has two important phases. These phases in research are,

- Measure the impedance of conductive knitted plate on sleeve
- Analysing the data measured

4.4.1 Material



(a) LCR meter (b) Acrylic Cylinders

(c) Sleeve model example

Figure 4.4: Material used in capacitive approach

The first phase is used a LCR meter, acrylic cylinders, a human arm for test, a rule and knitted sleeves.

- The **LCR meter**, Keysight E4980A/AL, is used to obtain the impedance of an eletronic component for a frequency band.
- The **acrylic cylinders** is used to simulated the change in the arm volume, for that reason there are 3 cylinders with different perimeters, 22 cm, 28 cm and 38 cm.
- The **human arm** allows to know what is the arm dielectric.

- The **ruler** is used to measure the sleeve perimeter, where are the conductive thread sewed.
- The **knitted sleeve** has many ways to produce and for that reason was knitted 4 types. Each one with a different type of use of conductive thread in knitting of the sleeve.
  - Sleeve with 1 conductive thread, which leaves after loom
  - Sleeve with 2 conductive thread, which leaves after loom
  - Sleeve with 1 conductive thread, and with vaporized and moulded
  - Sleeve with 2 conductive thread, and with vaporized and moulded

In second phase is used the Matlab program.

- The **Matlab** is a program with high numerical computing capability, allows operations with matrix, plotting of functions, algorithms implementation. Which is useful to relate the distance with capacitance.

4.4.2 Stages

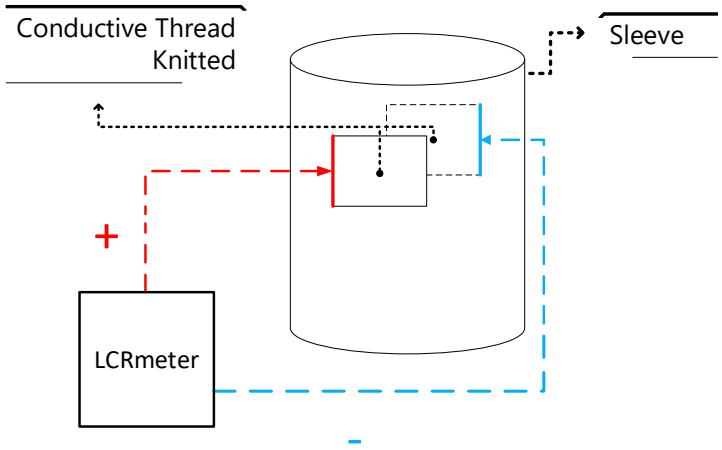


Figure 4.5: Connect LCR probes to sleeve

Data analyse is preceded by 5 important stages, which are:

1. **Place sleeve in desired local**
   - First phase of experiment, papers with conductive thread sewed placed each side of acrylic cylinders or the acrylic cylinder was placed inside the sleeve. Each cylinder has a different perimeter.
   - Second phase of experiment, the zone sleeve where has knitted the conductive thread was placed in different arm places.

2. **Connect LCR probes with Conductive Thread**, it is necessary the probes have a good contact with the thread, as show in the picture.

3. **Set up the LCR parameters**, in this stage was necessary choose the frequency, the input voltage and type of data. The frequency chose was 1 kHz, 3 V input voltage and data in impedance form (Ω).

4. **Start the measurement**, after all procedures complete can start the measurement.

5. **Collect Data from LCR meter**,

6. **Data Analysis**, obtain capacitance through the impedance measured and relate it with perimeter.

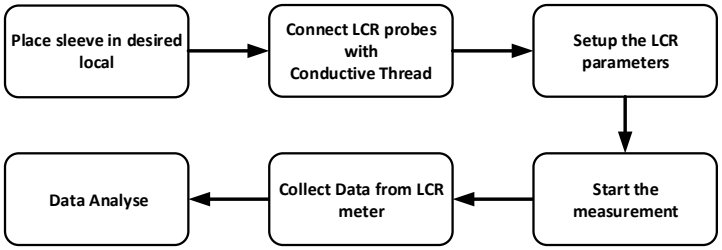


Figure 4.6: Methodology stages

4.5 Results

In this section is presented the relation between the perimeter and capacitance for the capacitive model stages.

In **First phase**, the results for the impedance measured of conductive tread sewed to paper for different distances, as showed in figure 4.3, appears in figure 4.7.

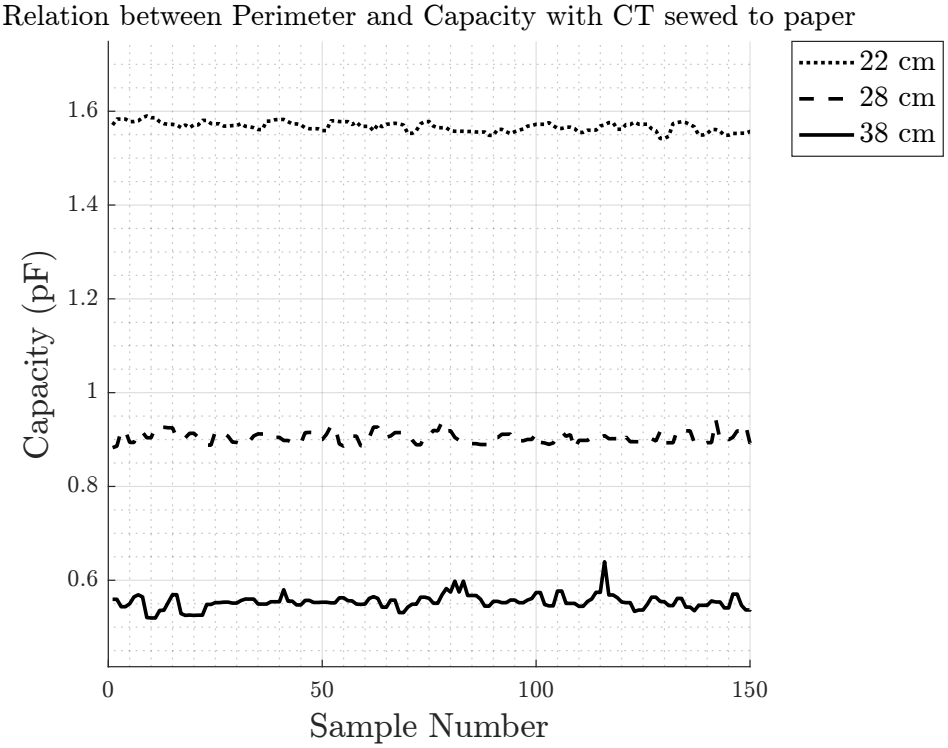


Figure 4.7: Relation between capacitance and distance of CT sewed to paper

The graphic shows the perimeter influence and capacitance, increasing the perimeter, increase the distance between sewed plates, so the capacitance decrease. The cylinders with perimeter of 22cm, 28cm and 38 cm have respectively 7cm, 9cm and 12cm of cylinder diameter. This mean the distance between sewed paper is equal to the diameter. The medium between plates used is air, and its relative permittivity is, $\varepsilon_r \approx 1$, so the permittivity used to calculation was $\varepsilon_0 \approx 8.85 \times 10^{-12} F/m$. And area of zone with conductive thread equals to $42 cm^2$.

Theoretical the values measure for each distance should be as shown in the table below.

Table 4.2: Theoretical values and measured values of sewed paper with conductive thread

Distance	**Theoretical Values**	**Measured Values**
7 cm	0.53 pF	1.56 pF
9 cm	0.41 pF	0.91 pF
12 cm	0.31 pF	0.55 pF

The theoretical model is described as a parallel plate, however the plates placed in each side of cylinder do not are completely parallel. This is a reason for a higher values measured.

After the validation of relation capacitance-distance, the next step was measure the capacitance on the knitted sleeve. However it was need measure the capacitance of each different type of to knit conductive thread to a sleeve.

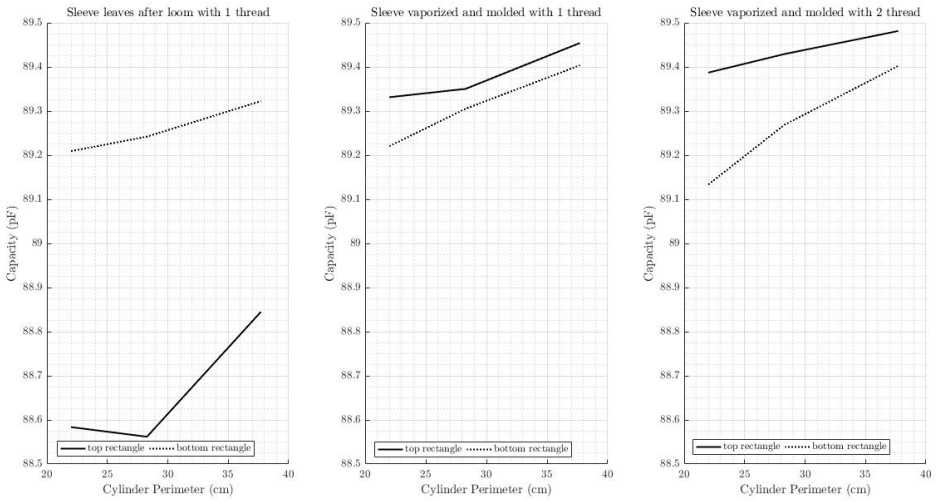


Figure 4.8: Relation between capacitance and distance of CT knitted to sleeve

In figure 4.8 is presented three different types to make CT integrate sleeve, these three types have the most linear relation capacitance distance. The influence of perimeter still present in knitted sleeves and it is noticed the increase of capacitance measured. Which is due to better sewing, with less spaces between conductive thread, forming a stronger electric field in comparison with the paper sewed with conductive thread. The capacitance increase as the plates are moved apart, this happens because the sleeve is stretched and the plates area increase.

In **Second phase**, the principal change was the dielectric, which it starts to be used the human arm as dieletric. After the selection of sleeves with behaviour better linearity, theses sleeves was wore and for each arm zone was take a measure. The most small perimeters was measured in forearm and biggest perimeters was measured in upper arm.

Assuming the upper limb is constituted predominantly by blood, bone and muscle the theoretic relative permittivity used was 26317, using 10% of blood, 30% of bone and 60% of muscle .

Table 4.3: Theoretical values for knitted sleeve with conductive thread on human arm

Distance	**Theoretical Values**
7 cm	271.68 pF
9 cm	211.31 pF
12 cm	158.48 pF

The figure 4.9 shows a relation between different forearm and upper arm, by figure analyse it is showed that $\varepsilon_{r,forearm} < \varepsilon_{r,upperarm}$ because for the same perimeter, 26 cm, the values measured are much unequal.

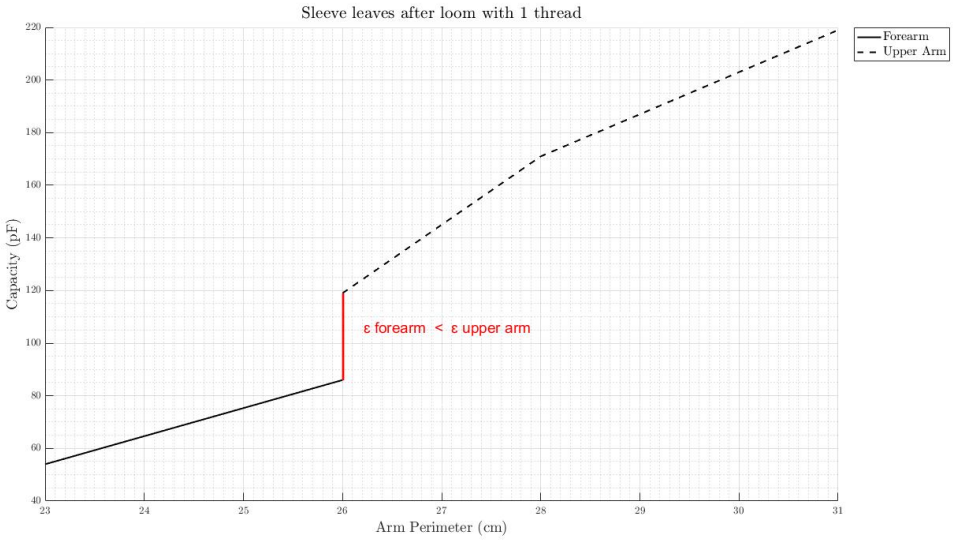


Figure 4.9: Relation between capacitance of forearm and upper arm

To validate the theory that dielectric modify with the zone the sleeve is worn, it was measured the capacitance in five zones of arm and its results are presented in figure 4.10.

- **Wrist**, 21 cm perimeter
- **Forearm**, 25 cm perimeter
- **Forearm**, 29 cm perimeter
- **Elbow**, 28 cm perimeter
- **Upper Arm**, 31 cm perimeter

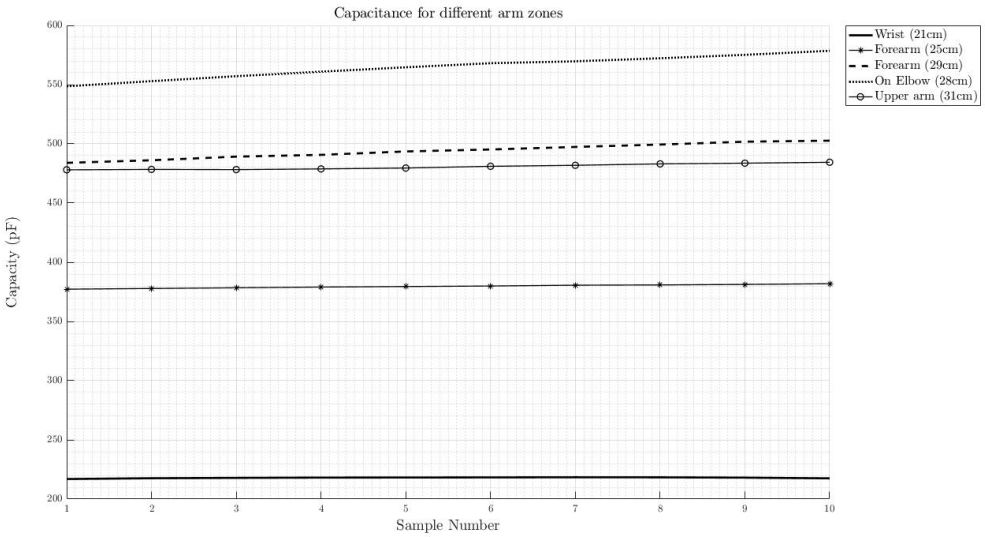


Figure 4.10: Capacitance for different arm zones

The results indicates that the ε_r is different for each zone of arm and this relative permittivity variation influences the capacitance measured. The first approach indicts a difficulty in relate the arm perimeter with capacitance.

For that reason it was worn the sleeve in same zone for 6 days, in a trial to obtain a characterization of relative permittivity this zone.

Table 4.4: Capacitance variation in different days

	28 cm Perimeter	**32 cm Perimeter**
Day 1	521 pF	303 pF
Day 2	497.2 pF	338.6 pF
Day 3	1406 pF	749.3 pF
Day 4	1717 pF	1076 pF
Day 5	1259 pF	1128 pF
Day 6	1193 pF	884.8 pF

By the table 4.4, it is possible obtain the mean value for each perimeter and its standard variation. For 28 cm, the mean value is $1098.9pF$ with $491.3pF$ standard deviation. For 32 cm perimeter it is obtained a $746.6pF$ mean value and $356.7pF$ as standard deviation.

Chapter 5

Resistive Model

5.1 Overview

In this chapter will be introduced a model, which relates the resistance measured with arm perimeter. The replacement of conductive threads over normal threads in knitted fabric allows to create conductive zones. This zones have electrical resistance associated.

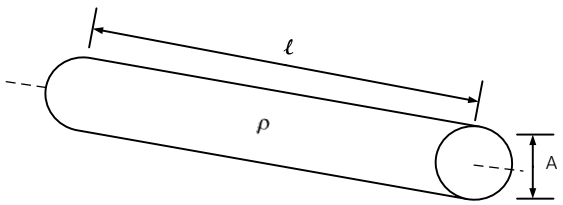


Figure 5.1: Resistor model

A electrical conductor has a resistance proportional to its resistivity, ρ, and length, l, and inversely proportional to its cross-section area, A.

$$R = \rho \frac{l}{A}$$

For this model the resistor used will be the Shieldex Twisted Yarn 117/17 dtex 2-ply, its resistance value is shown in table 2.3, which will be knitted to the sleeve. The stretching load at the sleeve does the equivalent resistance change.

5.2 Theoretical Model

The conductive thread knitted to the compression sleeve forms a knitting stitch network, as show the figure 5.2.

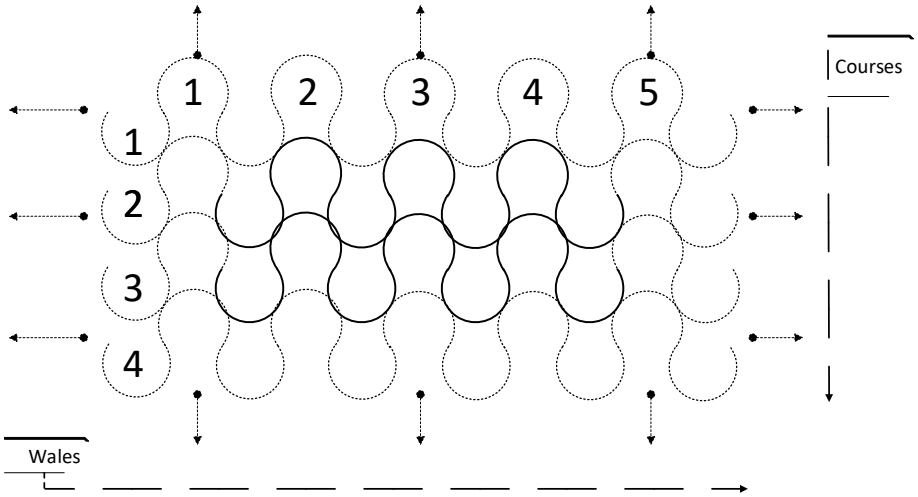


Figure 5.2: Model of knitted conductive thread

Theses stitches are all connected with their neighbour stitches. This connection can be expressed as a contact resistance, R_c. Through this contact between different threads, it is possible obtain a equivalent resistance.

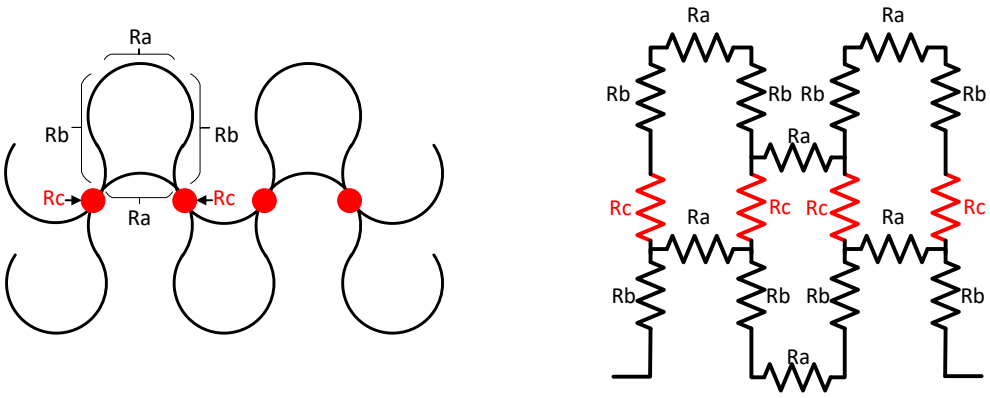


Figure 5.3: Using resistors to simulate the conductive thread

In figure 5.3 it is presented a model with 2 wales and 2 courses and its equivalent circuit. Through this model is possible to construct a circuit for a desire number of wales and courses.

The relation between perimeter and measured resistance is get by the influence of the length and cross-section area in the resistive value.

In this analyse when the arm perimeter increase the sleeve will be susceptible to a stretching load, which it will make the thread length increase and its cross section area decrease. These alteration in thread characteristics make the equivalent resistance of knitted network increase.

5.3 Methodology

The methodology has divided in three important phases. These phases in research are,

- Simulate the equivalent resistance
- Measure the resistance of conductive knitted plate on sleeve
- Analysing the data measured

The first phase starts with the counting of the number of wales and courses. After the counting, it will be simulate in virtuoso platform the circuit, obtaining the equivalent resistance for the knitted network.

In second phase is necessary that all measurement must be taken in equal conditions, to minimize the unknown variables.

After all measures taken is necessary analyse the values obtained using the Matlab program.

5.3.1 Material

- **Virtuoso plataform**, which allows designing integrated circuits and circuit simulation.
- The **digital multimeter**, Keysight 34410A ,allows to measure the resistance, voltage and current.
- The **human arm** allows to place in different arm zones, with that change stretch on sleeve for different perimeters.
- The **ruler** is used to measure the sleeve perimeter, where are the conductive thread sewed.
- The **knitted sleeve** has many ways to produce and for that reason was knitted 2 types. Each one with a different type of use of conductive thread in knitting of the sleeve.
  - Sleeve with 1 conductive thread, which leaves after loom
  - Sleeve with 1 conductive thread, and with vaporized and moulded
- The **Matlab** is a program with high numerical computing capability, allows relate the perimeter with resistance.



(a) Digital Multimeter 34410A [28]



(b) Sleeve model example

Figure 5.4: Material used in resistive approach

5.3.2 Stages

1. **Desgin and Simulate Circuit**

   The counting of wales and courses numbers is important to know the amount of resistors each circuit has. As the figure 5.3 show it is possible simulate the conductive behaviour of thread using resistors.

   After the exact number of wales and courses is possible design the equivalent circuit of the knitted stitches network and to simulate the equivalent resistance behaviour when the parameters changes,R_a, R_b, R_c, simulating the sleeve stretch. The value of the resistors R_a, R_b, R_c was obtained by measuring the resistor section in the sleeve with the multimeter.

2. **Measure the resistance of conductive knitted plate on sleeve**

   - First it is validate the simulated resistance for each sleeve without any stretch load.
   - Then the zone sleeve where has knitted the conductive thread was placed in different arm places.
   - It is measured the arm perimeter local where is the conductive thread, with the ruler.
   - The digital multimeter is placed over first and second course, and the resistance value is collected.

3. **Analyse the data collect**

   In this stage, it is related the resistance measure with arm perimeter.

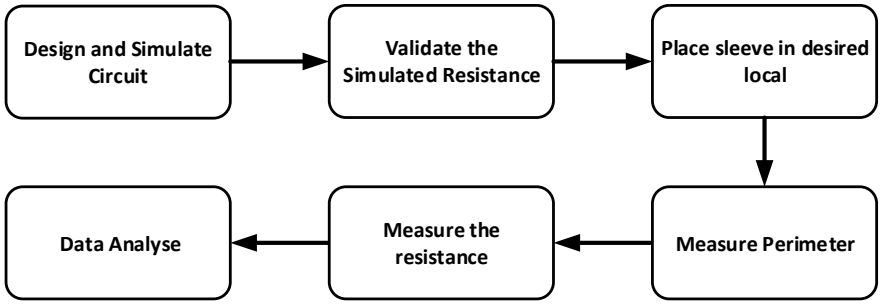


Figure 5.5: Methodology stages for resistive model

5.4 Results

In **first phase** was measured the resistance of R_a, R_b. The contact resistance,R_c, was measured as 25 Ω .

Theoretical the resistance value must be under 3 Ω /mm and the length of R_a and R_b is approximately $1mm$.

Table 5.1: Measure resistance for R_a and R_b

	Measured Resistance
R_a	2.3
R_b	2

The number of courses and wales for each different sleeve is shown in table 5.2

After to obtain the values for all resistors of the network. The next step was design the circuit and simulate with the value obtained.

The represented circuit in figure 5.6 shows a 36 courses per 35 wales.

Table 5.2: Number of wales and courses

	Courses	Wales
Leaves after loom	36	35
Vaporized and moulded	56	72

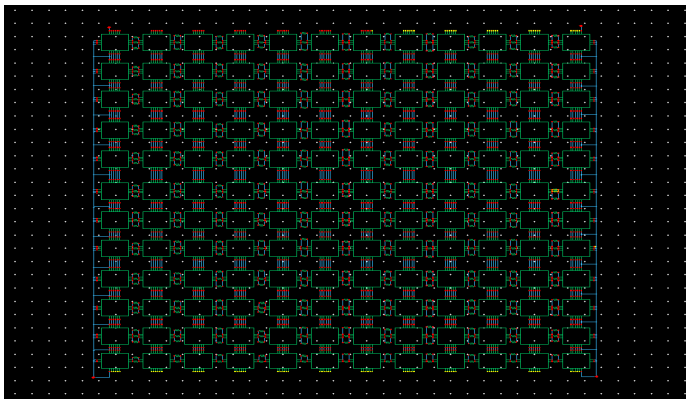


Figure 5.6: A design of a 36 courses per 35 wales

The resistance values was obtained by a s-parameters simulation are presented in table 5.3, together with measured values for each sleeve.

Table 5.3: Simulated and measured resistance

	Simulated Resistance	Measured Resistance
Leaves after loom	8.36	8.24
Vaporized and moulded	6.58	160

The measured values indicate that the sleeve, which is subjected to a vaporization and moulding loss conduct properties. Which cause the increase of the resistance. As the vaporization in conductive thread is characterized, in next step only will be used the sleeve with 1 thread, which leaves after loom. This sleeve has a resistive value very similar to the simulated.

The next was used the selected sleeve in arm to change the stretch load in conductive thread. The results is show in figure 5.7 .

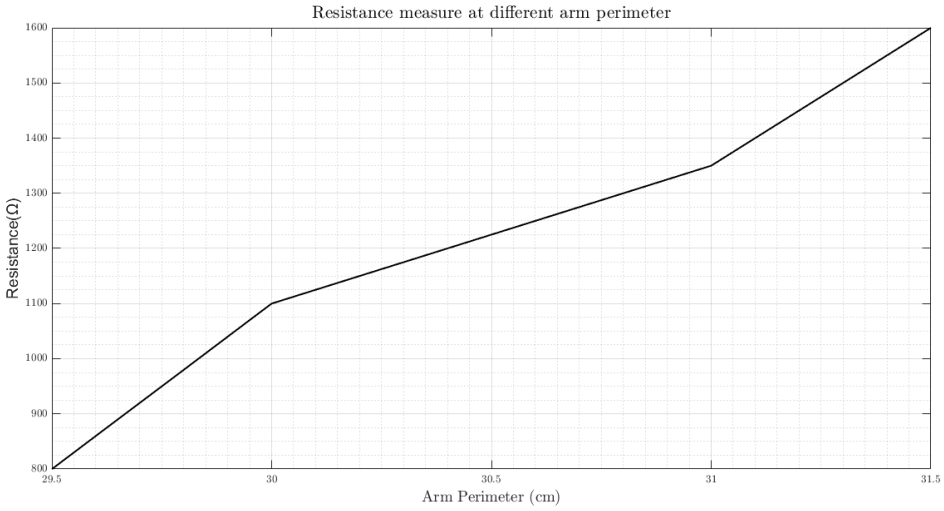


Figure 5.7: Measured resistance for different arm perimeter

Chapter 6

Conclusion and Future Work

6.1 Conclusion

The development of a preliminar model able to measure capacitance with knitted conductive thread was found.

With this model a relation between arm perimeter and measured capacitance was found, with some imprecision but it indices the existence of such relation. A first step to monitoring the perimeter changes through the capacitance was given.

Each measure, in this work, takes a long time to take because of the used tools, as such, in future work will be possible a more detailed analysis using the exploited possibilities in this thesis.

Another approach was tried using the sleeve stretching caused by perimeter increase. It was concluded that the conductive thread after being subjected to vaporization loses its conductor characteristics.

The used sleeve just have been knitted and will be used after the loom. Through this technique was possible obtain a relation between perimeter and measured resistance, with consistent results.

6.2 Future Work

In capacitive model the future work must be made a mathematical model of the arm constitution. Because the main obstacle to not realizing this model was the relative permittivity. Throughout this work was understood that using human arm as a dielectric reveals to have a inconstant permittivity. For equal perimeters in different arm zones, forearm and upper arm, the measured capacitance very unequal. By analysing the same zone in different days the capacitance reveals with a high deviation, which it makes the monitoring lymphedema impossible to accomplish through this method.

After a arm model realized the relation perimeter capacitance will be more easy to obtain.

In resistive model was possible obtain a relation perimeter-resistance. The future work must be design a electronic system, which use the resistance measured processing it to inform the patient of the lymphedema evolution.

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