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Integrating Conductive Threads into Different Knitting Construction by Flat Knitting Machine to Create Stretch Sensitive Fabrics for Breathing Monitoring

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Title: Integrating Conductive Threads into Different Knitting Construction by Flat Knitting Machine to Create Stretch Sensitive Fabrics for Breathing

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II. ABSTRACT

During the last decade medical applications of textile sensors have been growing rapidly and textile sensors are the focal research point for many sensor projects. Textile sensors are still not available as a mainstream product to replace conventional electric sensors and electrodes. Textile sensors can be integrated in a textile garment to measure vital signs of a human being. In this regard stretch sensors are able to measure breathing rate of a person. In this project we use seamless knitting technique to make stretch sensors using conductive fibers. The resistance difference between stretching and relaxing of these sensors gives a pattern for human breathing. Four knitting structures with different conductive fibers are made and tested with *cyclic tester* to construct a graph between resistance and time to find the knitting structure which gives the best results. Tests are also done to check the results after washing. These sensors can be used in breathing monitoring of patients during daily life.

Keywords: medical applications, stretch sensor, seamless knitting, conductive yarns, *cyclic tester*

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1. Introduction

Since the introduction of smart textiles, there has been an effort to diversify the use of textile in all fields. The medical field is among one of them which has benefited with the introduction of sensors that can be used for monitoring vital signs of a patient. Initially the conventional sensors were simply attached to the fabric such as biomedical sensors. Now there has been a leap forward by the introduction of conductive yarns which can conduct electric signals. These conductive yarns when incorporated in textile fabric, by weaving or knitting, can be used for monitoring different physiological parameters of a human body, such as breathing rate. These sensors are flexible, elastic and washable when they are used in combination with textile substrates and do not cause any inconvenience in wearing. Especially the knitted sensors are comfortable to be used in daily life.

People have been trying to find a synergic combination between textile and sensors for some years to make practical textile sensors which can be used in daily life. WEALTHY project in Europe, VTAMN project in France and Life Shirt in USA are some examples of them which can be used to monitor temperature, ECG and respiration in a human body (Fabrise, et al., 2005). Fine example of textile sensors are the stretch sensors which can be used for functions such as force and movement sensors as well as breathe sensors (Li and Lena, 2009). These sensors can be easily made using weft knitting techniques in one step knitting. Respiration monitoring is important if we consider the importance of early detection of disorders and diseases such as pulmonary disease, heat failure and sleep disorder and one way to monitor respiration is using the textile based capacitive sensors (Carey R., et al., 2009). Typical medical sensor is attached to the body of a patient and it restricts the freedom of movement. To overcome this problem optical sensors are used which can monitor the patient during sleep without causing disturbance to the patient. This can be useful for dementia patients who are likely to become uncooperative in later ages (Hirroki, et al., 2003). Unfortunately there are no reliable methods for respiration monitoring at home (P.Grossman, 2004). Conventional sensing methods for respiration include inductance plethysmography, piezoresistive sensors and piezoelectric sensors (P.Grossman, 2004, G.Loriga , 2005). Knitted Stretch or pressure sensors made out of conductive yarns have the positive characteristic of not causing skin irritation in contrast to integrated electronic sensors and their change in resistance during stretching and relaxing can be used as sensory application. (sensory knits). Textile stretch sensors can also be used in combination with textile based passive electrodes and textile interconnects to minimize the chance of getting skin irritation by direct contact with metal but the results can be a little less precise (Tae-Ho Kang, et al., 2005). Furthermore, by using textile based electrodes, interconnections and sensors a higher degree of integration is achieved resulting in increased user mobility, privacy and comfort (R. Puers, et al., 2003). Obviously these sensors should be reusable and washable. In fact, the whole package for data handling and transmission integrated in a garment should be washable.

1.1 Background Description

In the past, the sensors were only used in the medical facilities such as hospitals and the monitoring of a patient could only be done in hospitals and medical institutions but, with the introduction of conductive fibers in smart textiles and formation of textile sensors whole scenario has changed and the monitoring of the patients can also be done even when they are in their homes. This process is achieved by using textile based stretch sensors which are able to conduct and transmit electric signals while we wear them and these signals can be used to record vital signs of a person. Conductivity in sensors is made possible by simply integrating conductive fibers into the fabric using weaving or knitting techniques. Initially, the textile sensors used were made by weaving and then joining the two piece of fabric separately. The elasticity limitation of weaving prevented appreciable results for application in sensors. Then the interest moved from weaving to knitting as the elasticity achieved by knitted fabric is good enough for sensor production. Also the processability of stiff and brittle fibers such as conductive fibers is easily done by using complete garment flat knitting in one single step. So, there is no need for a separate process to join the fabric afterwards.

In the past the sensors used were made either by using optical fibers or piezoresistive sensors. Conventional medical sensors were used in combination with wires and transmitter which would restrict the movement of the person wearing the sensor. Also, there have been reports of allergic contact dermatitis and skin irritation by using electrocardiograph sensor electrodes which is caused by both the adhesive part and the gel used in conventional electrocardiograph sensors (M. Avenel-Audran, et al., 2003). So, one way to increase person mobility and protect him from any skin allergies is to use textile sensors made entirely out of fabric. Moreover, by using textile based electrodes and interconnections, sensors can be reused i.e. they are washable. (R. Puers, et al., 2003)

Textronics a very important field made by synergic combination of textile, electronics and computer science in the year 2000. Textronics have many advantages such as being flexible, multifunctional and intelligent as it can interact and react with the environment, which also makes it a smart textile. Clothes have a direct connection with the human body so; they are directly responsible for the safety of the human body. This can be done by monitoring of the human physiological signals such as heart beat, ECG and breathing rate and that is where textronics play a vital role. Initially, optoelectronics, fabrics with optical fibers, were used as communicating textile. They were used in fields such as public safety departments, interior decorations and warning systems in automobiles. These optical fibers were also used for health monitoring systems in Life Shirt by an American sensatex company. Then it was realized, other special fibers such as conductive fibers can also be used to monitor physiological signals of a human body. This makes them suitable candidates to be used as sensors to monitor breathing rate in a human body (Janusz Zięba and Michał Frydrysiak, 2006).

1.2 Purpose

Breathing rate can be measured by different techniques magnetometers, strain gauge measurement and inductance plethysmography are among them but investigations have shown that when breathing is concerned there is no significant difference among strain gauge and inductance pletheysmography methods. So, keeping in mind the past efforts to record the breathing rate my purpose is to successfully produce knitted textile sensors with integrating conductive fibers into textile substrate to monitor breathing frequency/rate. There are a number of variables available for knitting structures and my aim is find the best possible structure to be used for sensory equipment. So, these fabrics can be easily used in daily life by patients at home, children in need of special care, firefighters and security personnel. It is equally important to find the best conductive yarn for textile sensors so that the fabric should be able to conduct the electric signals efficiently whether it is stretched or relaxed so, there is a noticeable difference when measuring and recording the breathing rate. The main goal is to produce sensors that can transfer and transmit the electric signals whether the person using it is sitting, sleeping, walking or running.

After making different samples using different fibers and different constructions, fibers must be tested for change in the resistance pattern when the fabric is stretched. For this purpose a device called *cyclic tester* is used, which successfully imitates breathing patterns by stretching the sample with different cycles at different intervals. The main goal is to find the best optimum structure by using different samples with different constructions so that the change is breathe in and breathe out is distinguishable.

1.3 Problem Statement

The sensor changes its construction and yarn diameter when it is stretched. This structural change can result in change of the resistance. These changes in structures are both complicated and difficult to predict. When the sensors are stretched, the changes in the resistance are linear to the elongation of the fabric. In other words, the more resistivity the less conductivity as they are inversely proportional to each other.

$$\sigma = 1/\rho$$

Where σ is "conductivity", the measure of materials ability to conduct electric current and ρ is "resistivity" the measure of resistance opposed by a material to flow of electrical current.

The suggested structures to deal with this problem are tucking and floating but all the selected structures will be tested using *cyclic tester*. The resulting sensor fabric would have uniform conductivity and elasticity.

1.4. Delimitation

In this project there are number of conductive as well as base yarns are available but, I have to restrict myself to the limited number so that the results can be comprehensively compared. In the same way, just four knitting structures are tested so that the results can be scrutinized. Also for the sake of simplicity this project is limited to examine the conductivity under stress of the sensor samples and data transmission, interpretation and storage of the signals is not considered. So, investigating the conductivity of sensors under breathing conditions, which are simulated by *cyclic tester*, is the main task. Also the conductive fibers used in this project are only the one with integrated silver or stainless steel; coated conductive fibers such as ployaniline are too complex and can be difficult to process. Carbon fibers are also not used because they cause skin irritation when directly in contact with the skin and their dust can lead to arcing and shorts in the electrical equipment (carbon fiber).

2. Theory

Initially, it was necessary to conduct a literature research to make sure what has been done in the field of textile sensors and especially stretch sensors. Smart textiles are the next generation of textiles which can actually sense, interact and react according to the environment. They have some value added properties such as conductivity and sensing. These textiles are becoming increasingly popular for their potential application in sport and health care areas. Other industries such as automobiles, textiles have an always increasing demand (Li, et al.). Textile sensors have the ability to replace the conventional rigid sensors (Cedric et al., 2008). People have been studying the piezoresistive properties of fibers for strain sensitive sensor applications (Hung-I Kuo, et al., 2007). Elastomeric coatings on fibers can also result in highly sensitive stretch and press sensors (Tognetti et al., 2004, Softswitch, Peratech). A combination of thermoplastic elastomer and carbon black particles can be used to make highly functioning strain sensors which can sense large strain of 80% (Corinne, et al., 2008). Knitted sensors for breathing have also been made using carbon and metal fibers (Bickerton, 2003, Van Langenhove, 2004). Inherently conductive polymers such as polyaniline and polypyrrole can also be employed as strain sensors in making soft smart garment with good sensing properties (Li, et al., 2005, Munro, et al 2008, Tsang, et al., 2005, Dunne, et al., 2006, Xiaoyin, et al., 2006). It can also be used to make some unique sensors such as intelligent knee sleeve which acts as a wearable biofeedback device and it senses knee movements and can be used for injury prevention and performance enhancements of athletes (Bridget J., et al., 2007). Aside from piezoresistive sensors, piezoelectric PVDF films can also act as a flexible strain sensor (Edmison, et al., 2002 and Lloyd, et al., 2001). Foam sensors with garments are also able to monitor breathing and shoulder movements, they are soft, pliable and washable and do not cause any inconvenience in wearing (Lucy E. Dunne, et al., 2006). There have been both yarn based and coated sensors for sensing stretch movement in a garment (Wiplfler, et al., 2008 and Mazzoldi, et al., 2002). Optical fibers can also be used as breathing sensors by sensing changes in abdominal and chest regions of human body without restricting the user (Hirroki, et al., 2003). Monitoring of ECG can also be done using textile based sensors alongwith respiration rate in children or adults inside or outside a medical institution using wireless data transmission system. There have been some big projects for this purpose such as WEALTHY, VTMAN, Life Shirt and some other small ones such as smart suit which have the ability to monitor multiple physiological signals. All of them have one purpose in common and that is the wellness of human being and early detection of diseases (Mu-Huo Cheng, et al., 2008, R. Puers, et al., 2003, Fabrise, et al., 2005). Some sensors are made especially for difficult situations such PROETEX used by firemen (Pacelli M, et al., 2007). Some of them are especially made for respiration monitoring which also includes this project (Carey R., et al., 2009, Chang-Ming Yang, et al., 2008, Pacelli M, et al., 2007). The textile based sensors are not widely used in practical applications because their results are not standardized and scrutinized. This means that there is no way to authenticate the results from any of them. All of these textile sensors are a part of an ongoing research and not finalized products.

For this project first crucial step was to decide how many conductive yarns should be used and how many variables of knitting structures should be tested. So, basically this project consisted of two halves “construction of sensors” using different structures and yarns secondly “testing of these sensors” using *cyclic tester*. Let’s take a look at each of these parts separately.

2.1. Construction of Sensors

2.1.1. Flat knitting

The machine used for knitting of sensors is specially used to handle brittle, hard and conductive fibers and it is computerized to cope with the complex designs. It’s called Stoll CMS 330 TC and it is also shown in figure 1. This flatbed knitting machine offers many advantages. First and foremost is the processability of the stiff and brittle conductive fibers such as Bekinox which contains stainless steel. Flat knitting also gives the ability to complete the knitted garment in one step without any seam and the fibers also retain their circular shape rather than being flat as in weaving. The most important factors for this are obviously loop length and knitting speed. These special stiff fibers require the low tension setting of the machine so that there is no tension in the fiber or the fabric. In the case of stiff and brittle fibers there are three forces which are most important during loop formation, namely friction, tension and bending. When all these three forces act in combination to the fiber then it results in high degree of breakage and this machine provides the ability to control all of these factors.

Flat knitting provides resiliency and versatility in the structure. In comparison to the circular knitting machine which gives more rapid production, flat knitting can give several new design possibilities as they provide the ability to change the cams after every course and stitch. Flat or Seamless knitting was first introduced in 1995 at ITMA (Choi and Powell, 2005). This process provides variety of benefits such as knitting a full garment in one single step without any further process for cutting and sewing, which gives higher productivity and saves time and cost. Computerized flat knitting machine also gives the possibility of using computer-aided designs to produce complicated structures with different design patterns. It also eliminates those annoying stitched edges which makes a garment uncomfortable under the arms. By one single step process the defects can also be minimized which helps in achieving products with consistent quality. Finally, using a single step process for whole garment is also economic and environment friendly as there is less waste after the process is finished (Choi and Powell, 2005).

Besides some advantages there are also some drawbacks of the seamless knitting e.g. if, there are alternate needles selected for the garment the resulted fabric is more open and less elastic. Furthermore if there is a defect in the fabric such as a hole, the whole fabric becomes useless because of one step process. Apart from the demerits there are numerous advantages of flat knitting and flat knitting finds its use in apparel, upholstery, automotive and medical applications (Mowbray, 2002).

Figure 1: Flat knitting machine CMS 330 TC

2.1.2. Choice of Yarn

Selecting the conductive yarn for this project was very difficult as there were a lot of choices at hand but, some initial parameters were set to separate a few of them for this project. The base fiber or yarn could be polyamide or the blend of polyester with polyamide depending on the elasticity needed in the final product and the conductive yarn is the heart and soul of this project. The combination of both the base yarn and conductive yarn will make sure we have the best possible results and we are able to see the difference between breathe in and breathe out by using these sensors.

It is only fair to mention a few methods to produce conductive yarns here, the simplest way is to incorporate carbon or metals such as copper, nickel, silver, steel in the form of wires, micro or nano particles in spinning process (Conductive yarns, 2011). Generally carbon filled fibers are not used much because they cause skin irritations and metal fibers are more brittle and have high weight.

Second interesting way to produce a conductive yarn is by using an inherently conductive polymer such as polyaniline, polypyrrole etc. for making fiber. Polyaniline has attracted a lot of attention due to its good thermal and chemical stability. These conductive polymers can be specially used in applications where flexibility is required with conductivity (Conductive yarns, 2011).

Last but not least another method for producing conductive yarns is by coating the fiber with conductive material. Highly conductive yarns can be produced by metallic or galvanic coating of the fiber, but these yarns are used specifically depending on the end product usage. (Conductive yarns, 2011)

2.1.3. Choice of structure

Similar to selecting the yarns, the choice of structure is also very important as selecting the best suitable structure will give the best possible results. The preliminary studies have shown that, to get the best results the conductive fiber should form as minimum loops as possible during knitting. So, the proposed structures in this regard were tucking and floating but, to make sure nothing was left unnoticed a comparison was done between plain jersey, 1×1 rib, interlock, float and tucked structures. It was crucial that the structures are compared against each other to see which structure is feasible to get the expected results. A basic explanation of all these structures is given below.

2.1.3.1. Plain jersey

It is the simplest structure of the knit fabrics because both technical face and technical back have prominent wales and courses as shown in figure 2. It is the most widely used conventional method of filling knitting (Filling-knit fabrics, 2011).

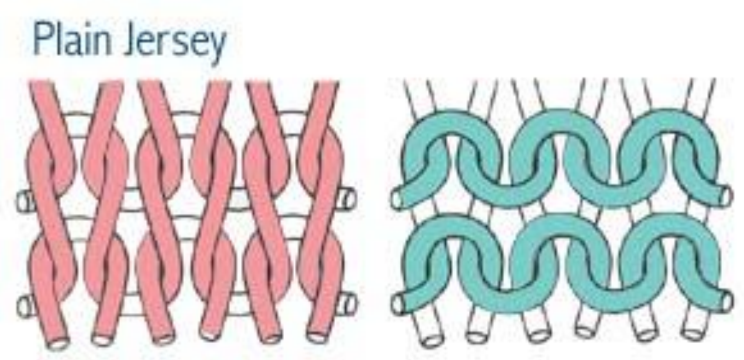

Figure 2: Colored yarns showing loops in plain jersey (filling-knit fabrics)

2.1.3.2. Rib

The rib structure is produced by two sets of needles with opposite needles off set for a half needle space. There are different combinations such as 1x1, 2x2, and 2x3. In the rib structure both the technical face and technical back have the same appearances. Compared with the simple plain jersey structure, rib structure has more elasticity (Double filling knits, 2011). Figure 3 shows the simple 1×1 rib structure.

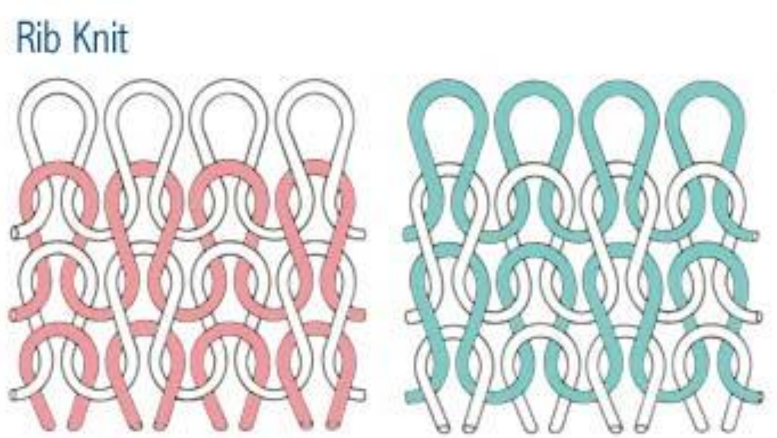

Figure 3: 1×1 rib structure with different coloured yarns (double filling knits)

2.1.3.3. Interlock

Interlock was originally derived from rib but requires a special arrangement of needles knitting back to back in an alternate sequence of two sets, So that the two courses of loops show on each side of the fabric. Interlock structure is more rigid and less elastic with smooth and fine surface (SAS articles). A demonstration of interlock structure is shown in figure 4.

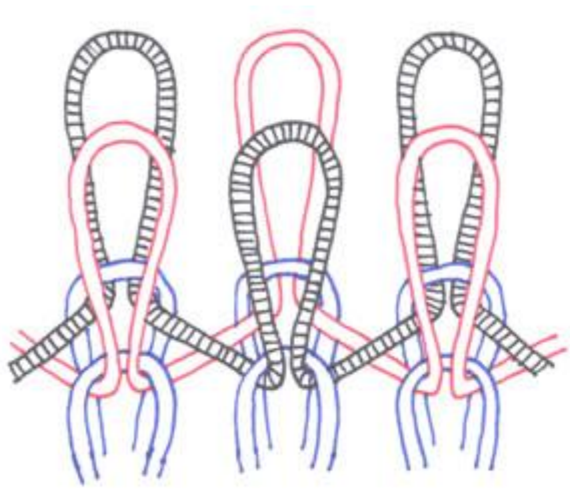

Figure 4: Different colored loops showing interlock stitch

2.1.3.4. Tucking

In the tuck stitch a loop is held with one or more tuck loops, for which the old stitch is not cleared from the needle. In this way a tuck stitch is on the technical back of the loop as shown in figure 5. These structures can be used to tuck one or more loops. It produces wider and thicker fabrics but its extension is not so large but, theoretically if conductive fiber is tucked then there would be minimum change in diameter of the fiber (Weft knitting, 2011).

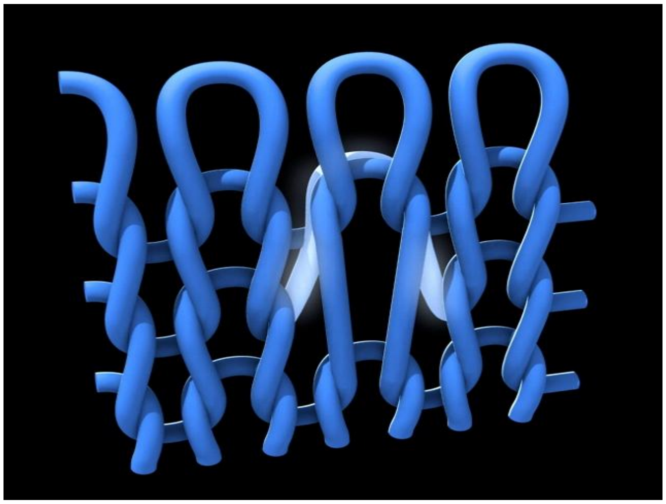

Figure 5: Blue coloured yarn showing tuck stitch (textile mania)

2.1.3.5. Floating

In this structure, there is no new stitch formed at the needle while new stitches are formed at the adjacent needles as shown in figure 6. This structure produces narrower, thinner less extensive fabrics. Similarly, the float stitch can be used for the conductive yarn to bypass on or more stitches (Weft knitting, 2011).

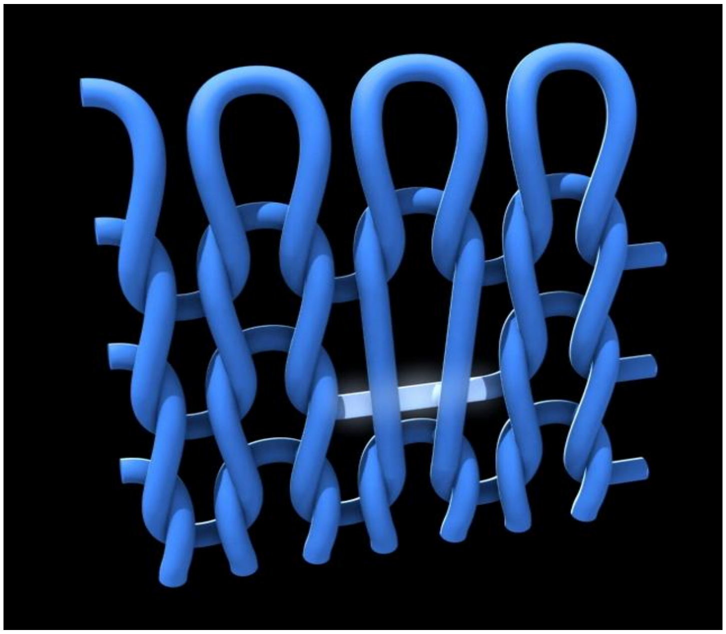

Figure 6: Blue coloured yarn showing float stitch (textile mania)

2.1.4. Sensor formation

After selecting the yarn and structure the next step was to knit a sensor sample to be tested. The conductive yarns alongwith base yarns are used to fabricate stretch sensors. These sensors are rectangular in pattern with a fraction of conductive yarn. Conductive threads are in the middle as the grey area shows in figure 7.

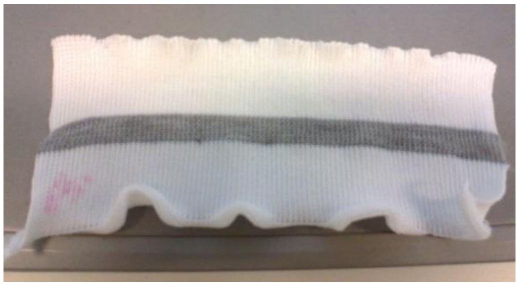

Figure 7: Stretch Sensor sample

2.2. Testing of Sensors

Now, comes the second half of this project which is "testing of these samples". To proceed to this part we must first get familiarize with testing devices, which are explained below.

2.2.1. Cyclic Tester

After making the samples the next step was to test these samples in *cyclic tester*, which was built especially by one of our lab members in the context of this project. This device replicates the breathing pattern of a human being by to and fro motion between two arbitrary points. This device has the ability to simulate breathing pattern with different number of cycles and variable speed. This device can imitate breathing during sitting standing, running and sleeping in a human body by varying the speed and elongation of the device. Samples can be stretched with the maximum speed of 50mm/sec. This device has two clamps to hold the sample during stretching. A scale is attached with the device which consists of 400 points which is used to select points for a certain elongation%. The device is controlled by software which is used to vary stretching speed, stretching distance between two points and number of cycles to be performed during a test. *Cyclic tester* with a sample is shown in figure 8.

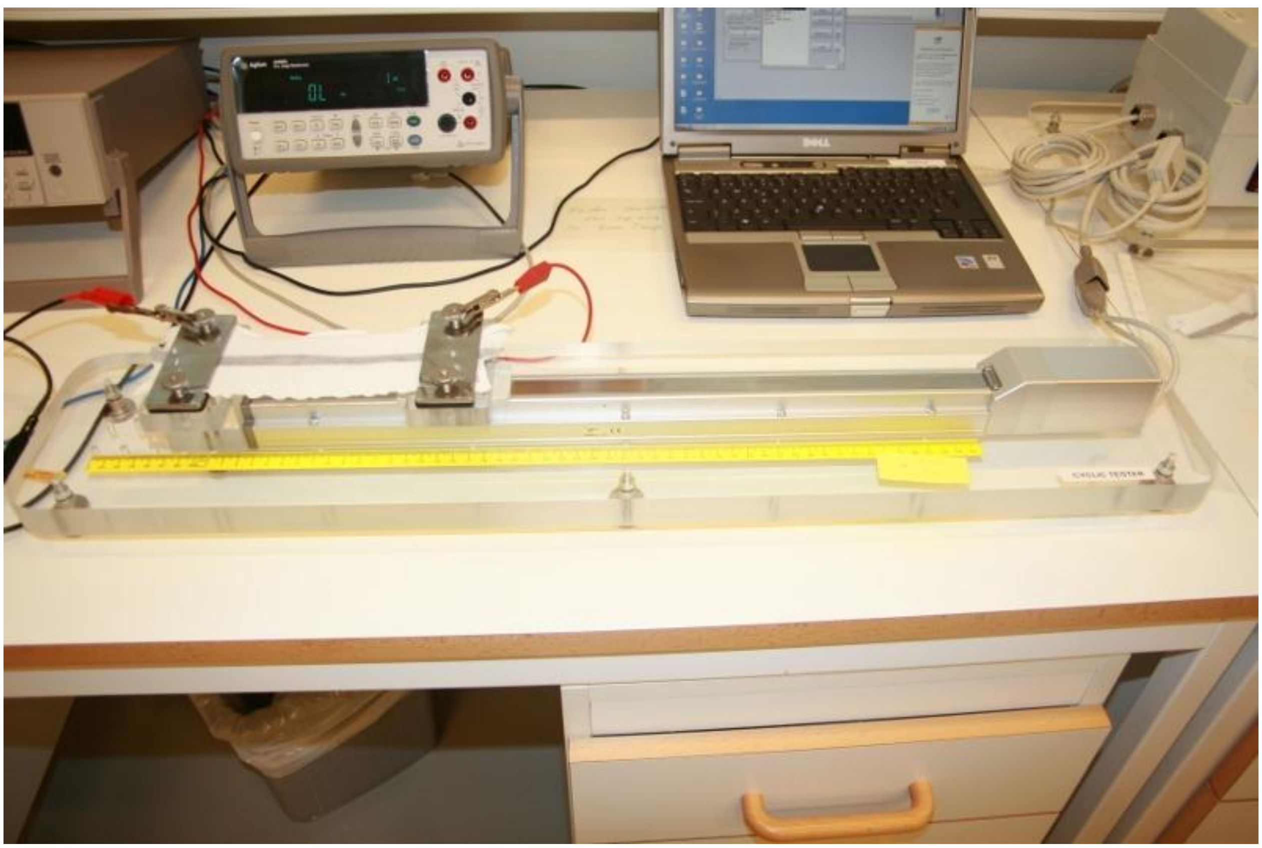

Figure 8: Cyclic tester

2.2.2. Agilent Multimeter

Cyclic tester is connected with a multi-meter to measure the resistance across a fabric while it is stretched, relaxed and under stress. This is done manually by reading the resistance from the display of the agilent multimeter shown in figure 9. Reading is observed during stretching and relaxation of the stretch sensor. Results from this test are used to conceive a graph which shows the highest and lowest points of a breathing pattern alongwith the interval between each cycle of human breath.

Figure 9: Agilent Multimeter

2.2.3. Keithley

One of the drawbacks of the agilent multimeter is that it only allows observing the values manually. On the other hand, there is another device called Keithley shown in figure 10, which can be used to measure the resistance values automatically, which rules out the chance of human error in reading the resistance values manually. To make this operable with *cyclic tester* there was some modification needed with the Lab-view software and my supervisor and one of her colleague were kind enough to sort that out for me. So, instead of using a manual measurement we opted for the automated option and it was a good decision as we got some elaborate results using Keithley. In these results it was possible to see minor details in the graphs which otherwise, we would have missed if we used the manual graphs.

Figure 10: Keithley

Keithley is connected to *cyclic tester* to record resistance for a sample. Keithley automatically records a graph between resistance and time. It gives the option to set the maximum current and voltage for recording the resistance. It is possible to count the number of breathing cycles from the graphs made by Keithley. Keithley and *cyclic tester* are both operated using separate software but, they can be operated at the same time. The whole setup including *cyclic tester*, multimeter and Keithely are shown in figure 11.

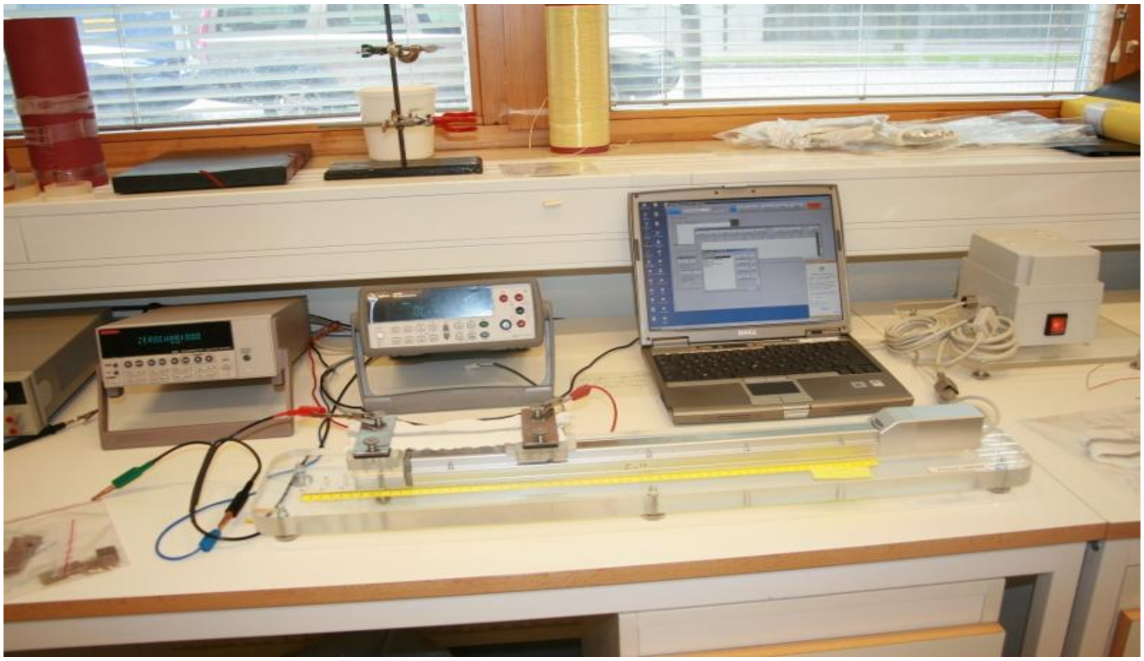

Figure 11: Cyclic tester, keithley and multimeter.

3. Practical Work

3.1. Material

For this project the fundamental resource was the yarns and especially the conductive yarns. In the beginning we considered the conductive yarns mentioned in table 1 to be used in this project but, as time passed we realized some of them were not in production anymore e.g. Trevia Neckleman and some would exceed the funding of this project. The preliminary choice made for conductive yarns is given in the table 1 with their resistance measurement and weight.

Table 1: Resistance of conductive yarns to be ordered

Conductive yarn	Dtex	Resistivity Ω/cm
Resistat	25	60
Beag EA1088	180	0.2
Trevia neckelman	N.A.	N.A.
Ugitech Sprintherm	1965	3.6
Amberstrand	N.A.	0.009
Bekinox	N.A.	N.A.
Silver Resistat	530	0.8

After comparing some properties it was concluded that using yarns in table 2 would be sufficient for this project. So, at last only under mentioned conductive yarns were used in this project.

Table 2: Resistance and thickness of conductive yarns used

Conductive yarn	Thickness	Resistance Ω/m
Copper	0.10mm	2.5
Copper, Stainless Steel	0.05mm	105
Bekaert Bekintex	Nm 50/1	270
Bekaert Bekintex	Nm 50/2	300
Statex Shieldex	235 34×2	35
Bekinox	Nm 9.1	70

Copper and stainless steel are purely metal yarns and were used as reference to check the impact of using textile conductive yarns instead of these metal yarns. Bekintex conductive yarn was used in two varieties one is single and other is double-ply yarn. It was also important that the selected yarns should be thick enough to be used in the knitting machine otherwise there will be breakages in the yarn during knitting.

Similar to conductive yarns there were some options for the base yarn,

1. Polyamide
2. Polyester
3. Combination of both polyester and polyamide

After knitting a few samples it was clear that polyester was good enough to be used for all the samples as polyamide was too much elastic and its sample would curl inwards which would make it difficult during testing in the *cyclic tester*. Polyester alone was elastic and resilient at the same time. So, we used PET 167/256/1.

3.2. Machine

Machines and devices used for the sake of this project are mentioned below.

1. Flat Knitting machine Stoll CMS 330 TC
2. *Cyclic Tester*
3. Agilent Multimeter
4. Keithley

Flat knitting machine was used for making the samples and previously we decided to make 5 knitting patterns.

1. Plain Jersey (used as reference)
2. 1×1 Rib
3. Interlock
4. Floating
5. Tucking

To overcome the problems in this project it was proposed that tucking and floating would be the best feasible knitting structures but, after testing the first tucking samples it became clear that this pattern was not suitable for stretch sensors as there were too many unwanted deviations in the results. In the end, we used the first four knitting structures for this project. Similarly another knitting pattern called fleecy was also tried in the initial phase of this project but, was soon discarded after observing its result.

For the purpose of testing the stretch sensors *cyclic tester* was used with either multimeter or keithley. The advantage of using Keithley is obviously the automated results as mentioned before but, there was also a limitation to using this device. This device could only be used for higher resistance values meaning only the samples with lower conductivity could be tested with this device but, it was soon figured out that this limitation was only related to Lab-view software and not a hardware problem. So, some samples were examined using multimeter and others using Keithley.

3.3. Method

Knitting machine was used to make sensor samples of dimension 20cm×5cm each for analysis. In the initial preparation for the project it was suggested stretch sensors would be investigated for all the daily life situations such as sitting standing, running, walking and sleeping which would mean testing of stretch sensors against different elongation and different stretching speeds to simulate different situations of daily life but, to keep it simple and short only elongation of 5% was used while varying the stretching speed. To imitate breathing at different rates, stretching speed of 20, 15 and 10mm/s was used. For each sample 20 cycles of breathing were recorded. For the manual recordings it was easy to count the number of cycles but, when Keithley was used it was necessary to work out how to get exact number of cycles required. As Keithley was plotting a graph between resistance and time, it was decided that by counting the number of minutes it would take to complete 20 cycles would give a pattern for the whole testing. It was calculated that for 20mm/sec breathing speed, it takes 2 minutes to complete 20 cycles.

So, 20 mm/sec = 2 minutes

15 mm/sec = 3 minutes

10 mm/sec = 4 minutes

Afterwards the cycles can easily be counted from the graph. It was also necessary to operate *cyclic tester* in synchronization with Keithley. The number of cycles would not be exactly 20 as required sometimes, it would exceed by 2-3 cycles.

Testing process also constituted of two steps. The first step was to filter out the best possible conductive yarns from all the yarns used. This was done by comparing specific knitting patterns of all the conductive yarns with each other e.g. a result for the floating structure obtained from all the conductive yarns would be compared to see the difference in the conceived graphs. By performing this method repeatedly for all the present samples and comparing their results we were able to filter out the two less functional conductive yarns namely Shieldex and Bekinox and all of its respective structures, because there results had a less pronounced difference between breathe in and breathe out. So, we concluded that breathing sensor is not a suitable application for the highly conductive yarns, which makes this project even more cost effective by using low cost conductive yarns with high resistance values. This leaves us with only one conductive fiber Bekintex and its variant structures. This completes the first step of finding out the conductive yarn with acceptable resistance values.

The next step was to determine the optimal structure out of the four proposed knitted structures. Normally, two run for each sample were performed to rule out any unwanted deviations and sometimes the sample would be tested three times if the results are unsatisfactory and not comparable to each other. It was due to the fact that the knitted structure would perform differently each time it is stretched and it is difficult to predict the structural changes in knitted structure. After performing tests and analyzing the results it was successfully decided that the most stable structures for this project are interlock and floating but mostly interlock was favored in the results as it had the most elasticity and recoverability and at the same time it also provided the best possible resistance values in results to perceive the breathing pattern easily. This completes the second stage of this project.

4. Results

4.1. Initial Testing

Based on the fact that the *cyclic tester* is a new device and in order to properly learn its working I performed some initial testing with the samples that were already available. Those samples are shown below in the table 1 along-with the initial readings to measure resistance.

Table 3: Resistance measurement of different samples

Sample	Textile Substrate	Conductive Material	Resistance at stretch	Resistance on relaxation
S1	Polyamide	Stainless Steel	.25 kΩ	.49 kΩ
S2	Polyamide	Carbon	.127 kΩ	.103 kΩ
S3	Polyamide	Carbon	65.0 Ω	59.0 Ω
S4	Polyamide	Coated Ag	5.6 × 100 kΩ	11.5 × 100 kΩ
S5	Polyamide	Stainless Steel	8.3 × 10 kΩ	11.3 × 10 kΩ

These results show basically the difference in the final and initial reading for the resistance and among them S2 is the best as it shows wide difference in resistance when stretching and relaxed. The base fiber was polyamide. These samples were not made in context to this project actually they were used to learn the working of the *cyclic tester* and how we are going to use this machine. As it can be seen that the normal pattern is that there is high resistance when sample is relaxed and shows high conductivity when sample is stretched, which makes the conductive fiber more aligned. Sometime this pattern can also be reversed depending on the fact knitted performs differently every time it is stretched. These samples also include the carbon fiber samples which are not supposed to be used for this project.

The figure 12 below shows the initial resistance measurement of a carbon black filled in polyamide base fabric. The measurement is taken in 10 cycles with an elongation of 15%. These are just for the sake of learning the *cyclic tester* and to show how the results will be interpreted in graphical manner. Similar measurements done using different samples with different measuring cycles are discussed later.

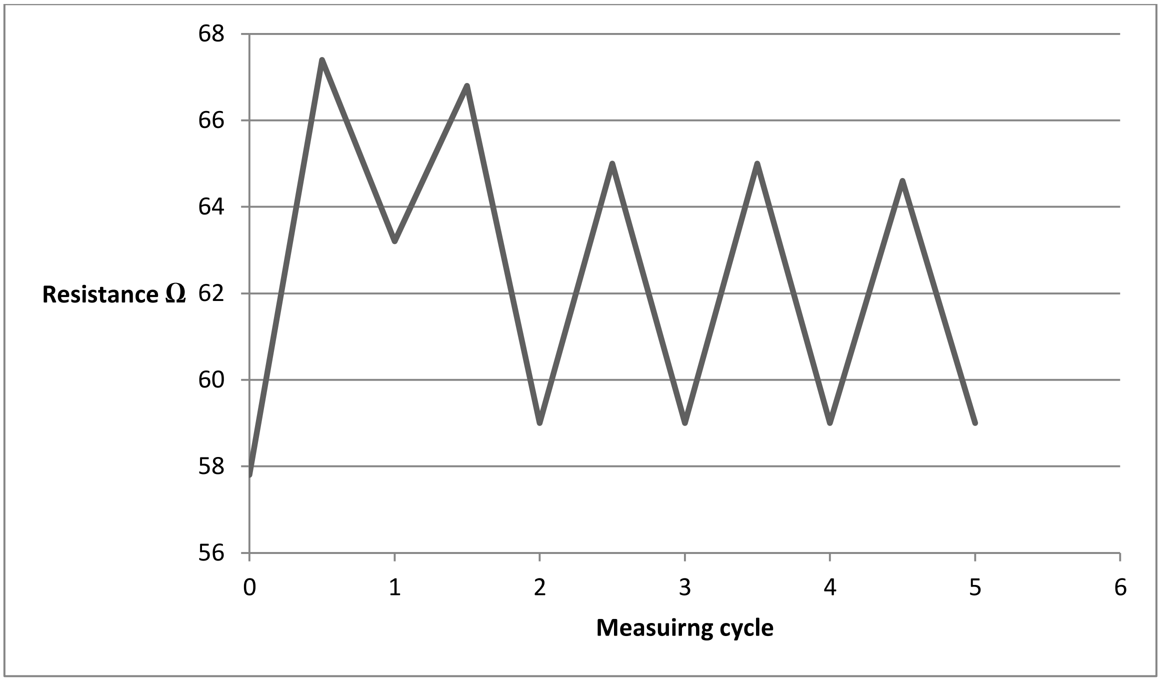

Figure 12: Resistance measurement taken in 5 cycles using carbon filled PA

This is a graph drawn between resistance and number of measuring cycles used for this measurement. The higher resistance values in the graph shows the relaxed state of the sample which represents breathe out. Similarly, the lower peak shows breathe in. The combination of breathe in and breathe out forms one cycle. The devices used for this purpose was *cyclic tester* and agilent multimeter. So, this graph is conceived manually using the resistance values from the multimeter.

Now, the real testing starts using the samples knitted for this project. Let's see the results from all the conductive fibers and all of its variable structures. X-axis shows 40 which means 20 inhalations and 20 exhalations, which makes 20 breathing cycles.

P.A. and Lycra with Copper and Stainless Steel

First of all we must know that the samples made from stainless and copper are just used for reference. Now let's look at the sample results turn by turn from every knitting structure. The base fiber for this sample is polyamide mixed with lycra. The first result is from a plain knitting sample and it is created using manual values from multimeter. As usual 20 cycles of breathing are performed to get the results.

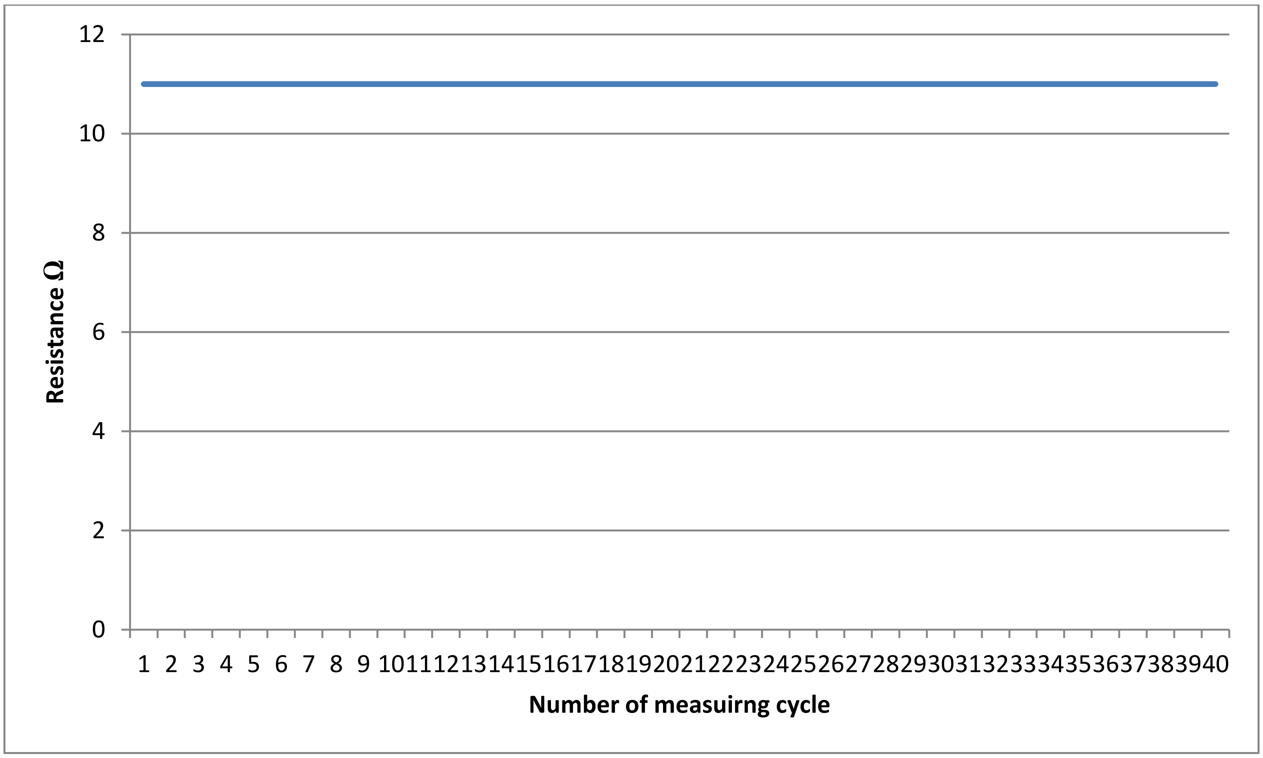

Figure 13: Resistance measurement for plain knitted stainless steel with P.A. lycra in 20 cycles with 20mm/sec stretching speed

From figure 13 it can be clearly seen that the resistance values remain unchanged whether the sample is stretched or not. It shows the low resistance value of only 11 ohms which is due to the high conductivity of the metal fibers used in this sample. Now let's look at the remaining samples from this conductive fiber.

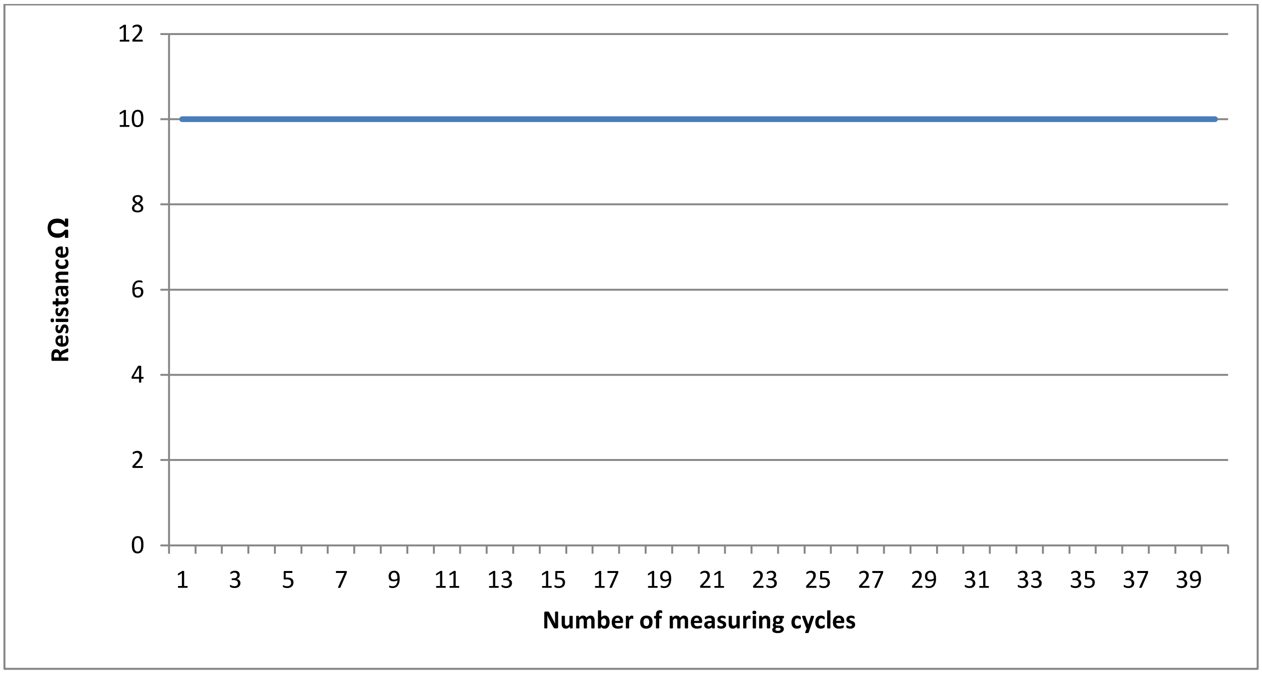

Figure 14: Resistance measurement for ribbed knitted stainless steel with P.A. lycra in 20 cycles with 20mm/sec stretching speed

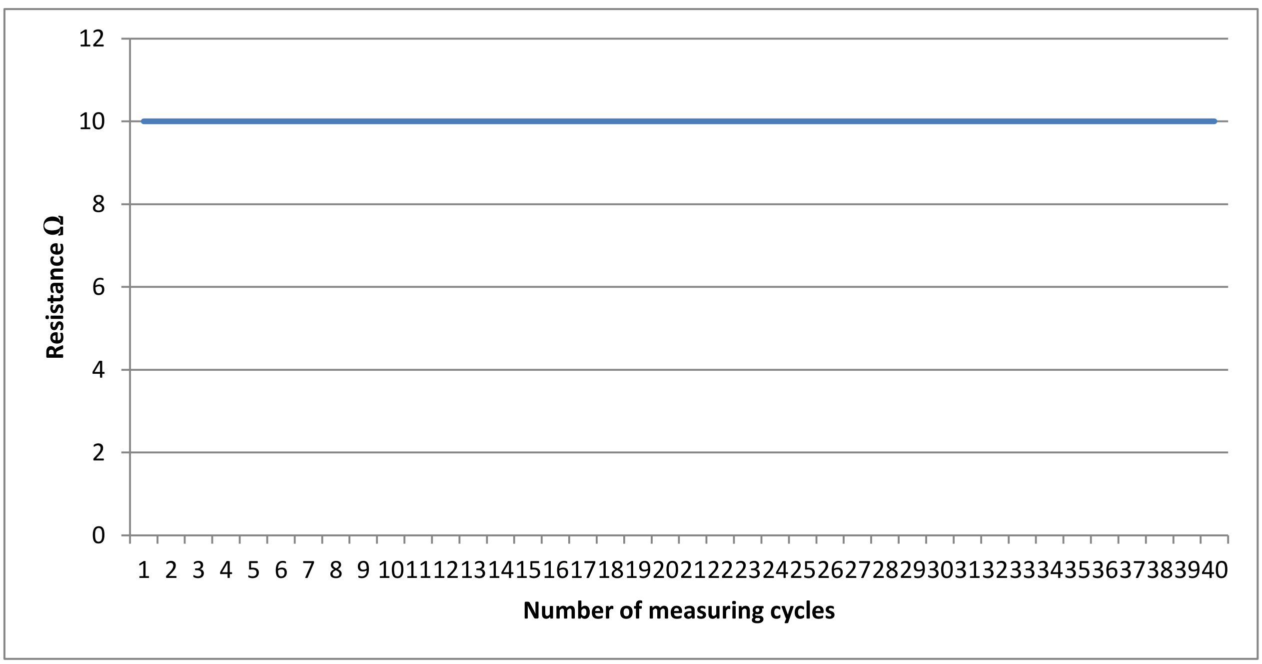

Figure 15: Resistance measurement for interlock knitted stainless steel with P.A. lycra in 20 cycles with 20mm/sec stretching speed

The figures 14 and 15 show the results for the ribbed and interlock knitting structures and they are replica of the results from figure 13.

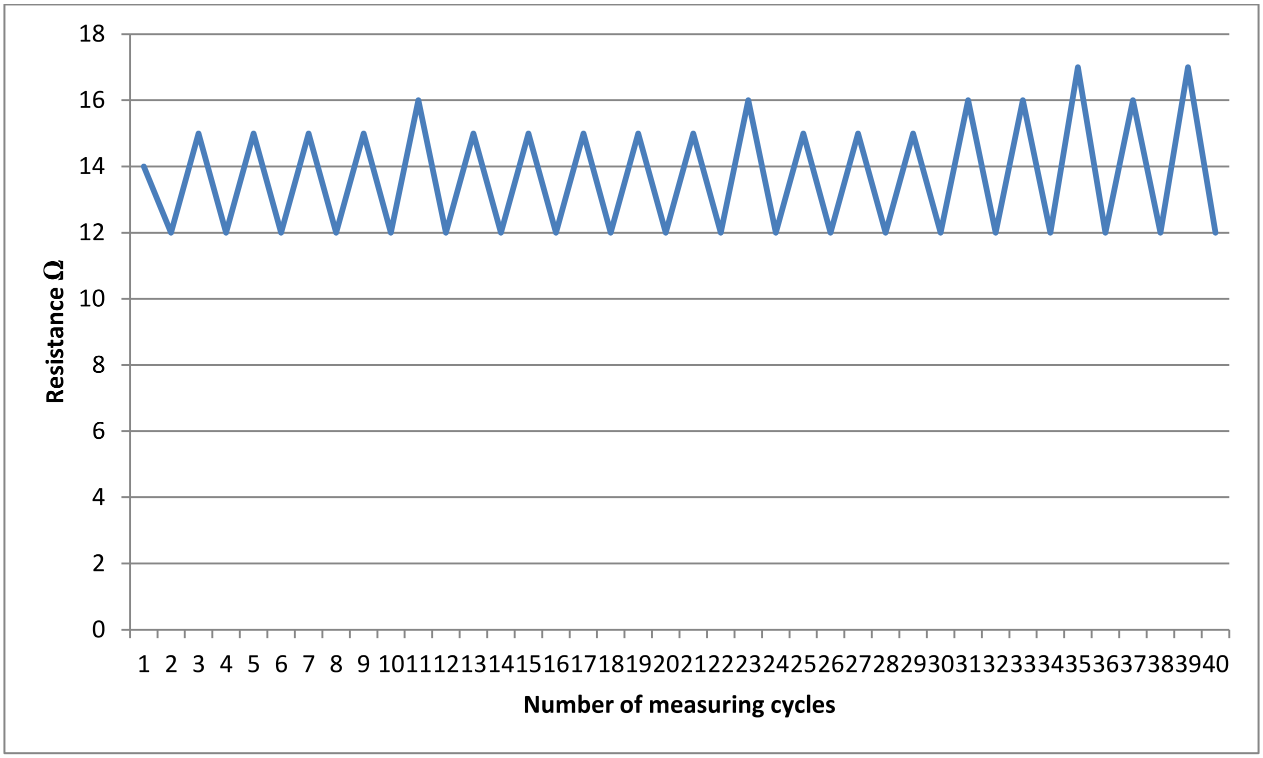

Figure 16: Resistance measurement for floating knitted stainless steel with P.A. lycra in 20 cycles with 20mm/sec stretching speed

In the figure 16 however, there is a change in the pattern and it shows a somewhat regular pattern for the breathing cycle and it can be used as a reference for the rest of the results.

P.E.T. with Stainless Steel

Now to get better results we used another metal fiber for the reference which is stainless steel with resistance of 105Ω/m. In this case we were only able to make two knitting patterns because the stainless steel fiber could only be used to make plain and floating patterns as it is not flexible enough to make ribbed or interlock structure.

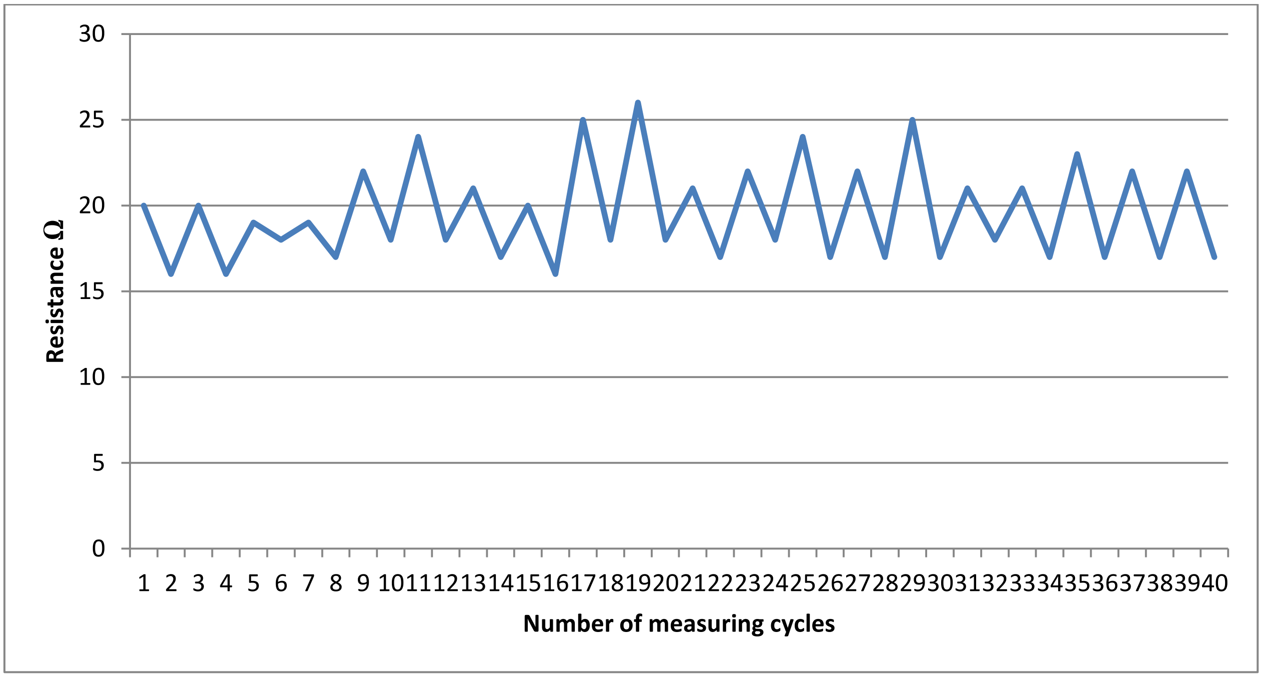

Figure 17: Resistance measurement for plain knitted stainless steel with P.E.T. in 20 cycles with 20mm/sec stretching speed

In figure 17 there is some unusual behavior shown by the sample but there is a pattern formed here more or less. As it can be seen there is a problem when the sample is relaxed and the peaks are changed almost every time.

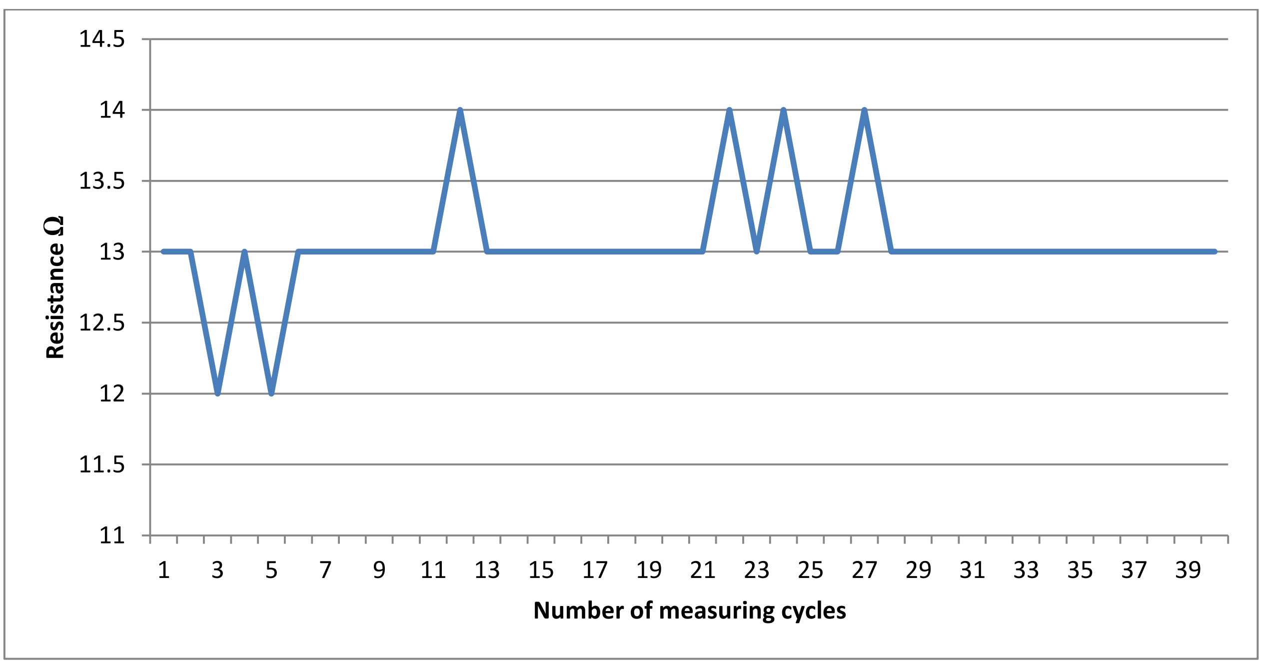

Figure 18: Resistance measurement for floating knitted stainless steel with P.E.T. in 20 cycles with 20mm/sec stretching speed

Now, in figure 18 the sample follows the pattern of first reference conductive fiber used and the resistance value remains unchanged for most of the breathing cycles. So, this also is no good to be used as a reference but, we know what kind of pattern we are looking for in the results as shown in the figures 16 and 17.

P.E.T. with Bekinox

This is the first conductive fiber used; Bekinox with polyester and it has stainless steel particles embedded in it. It has the resistance of 70Ω/m and its thickness is Nm 9.1. All of the above mentioned structures were made using Bekinox conductive fibers but only those results are shown which are worth mentioning.

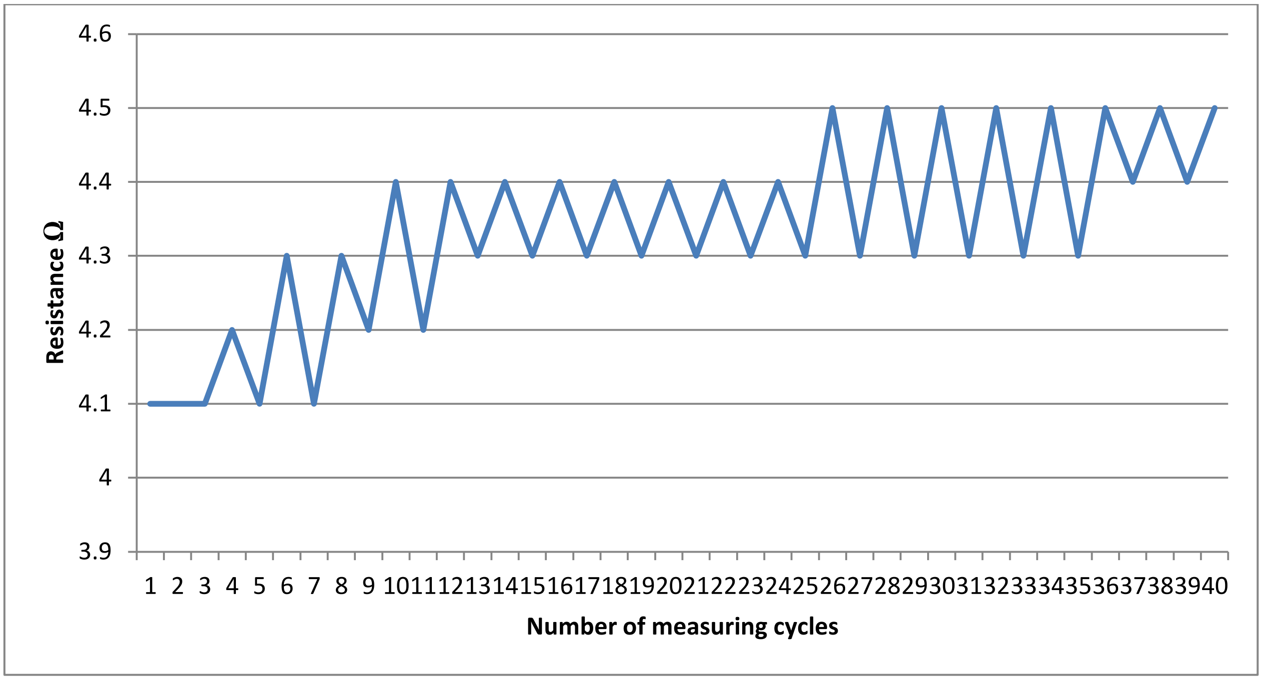

Figure 19: Resistance measurement for plain knitted Bekinox with P.E.T. in 20 cycles with 20mm/sec stretching speed

First is the plain structure which shows some pattern but the difference between two points are not too large as it can be seen from the Figure 19. The difference between breathe in and breathe out is only 4.1 to 4.5. This can be easily misinterpreted.

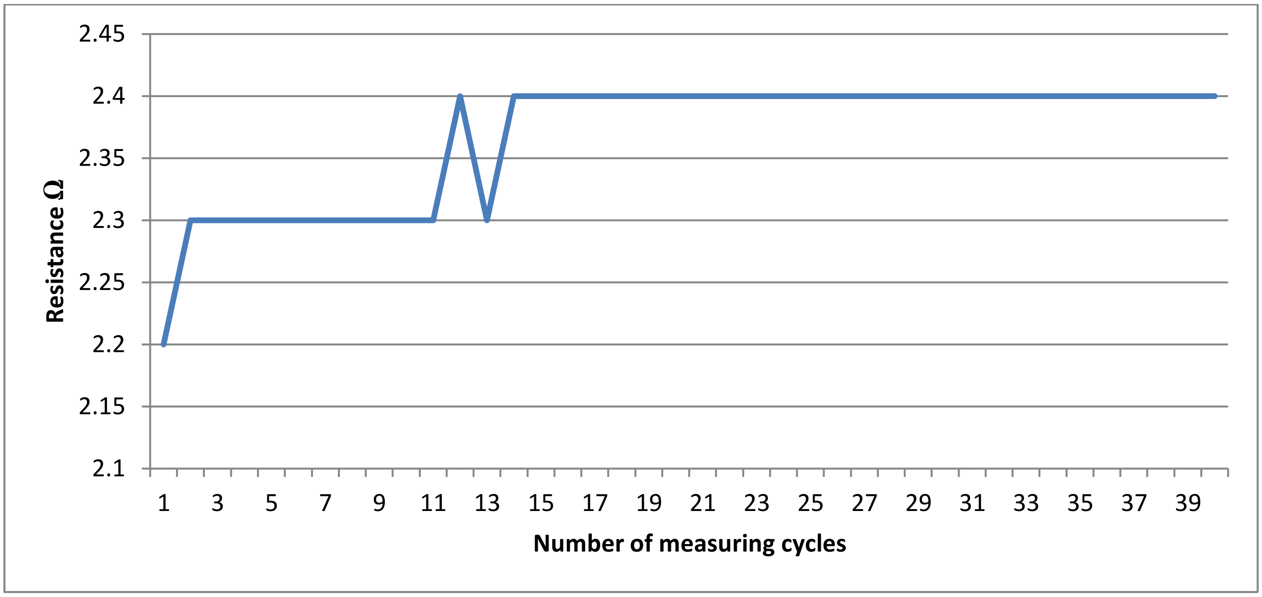

Figure 20: Resistance measurement for floating knitted Bekinox with P.E.T. in 20 cycles with 20mm/sec stretching speed

In the figure 20 it can be seen that the floating structure does not produce any appreciable results and does not follow the results of the reference structure.

P.E.T. with Shieldex Statex

The next conductive fiber used was Shieldex from Statex Company having resistance of 35Ω/m which is even less than Bekinox. So, it is much better conductor because it has silver coating on nylon. Let's take a look at the results.

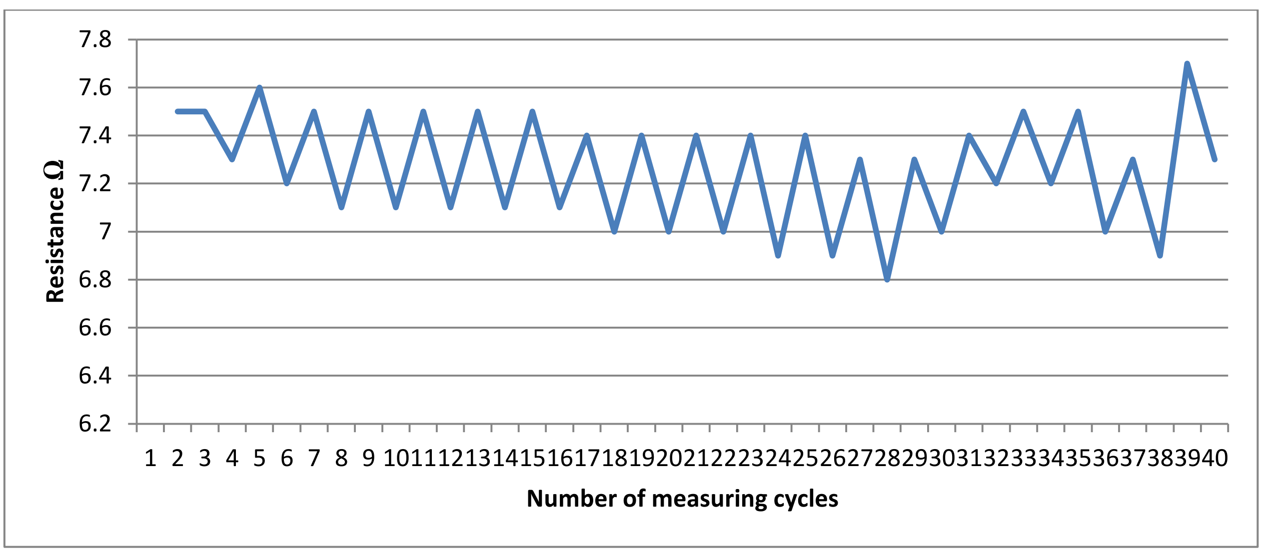

Figure 21: Resistance measurement for ribbed knitted Shieldex with P.E.T. in 20 cycles with 20mm/sec stretching speed

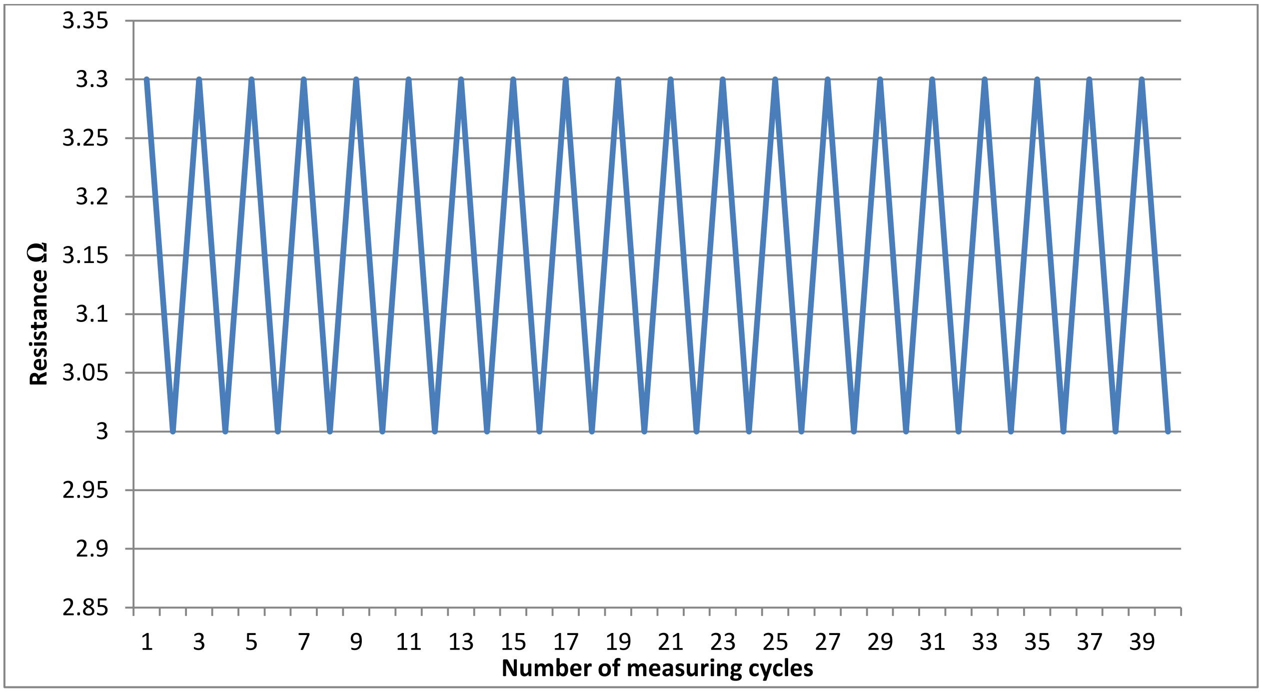

Figure 22: Resistance measurement for interlock knitted Shieldex with P.E.T. in 20 cycles with 20mm/sec stretching speed

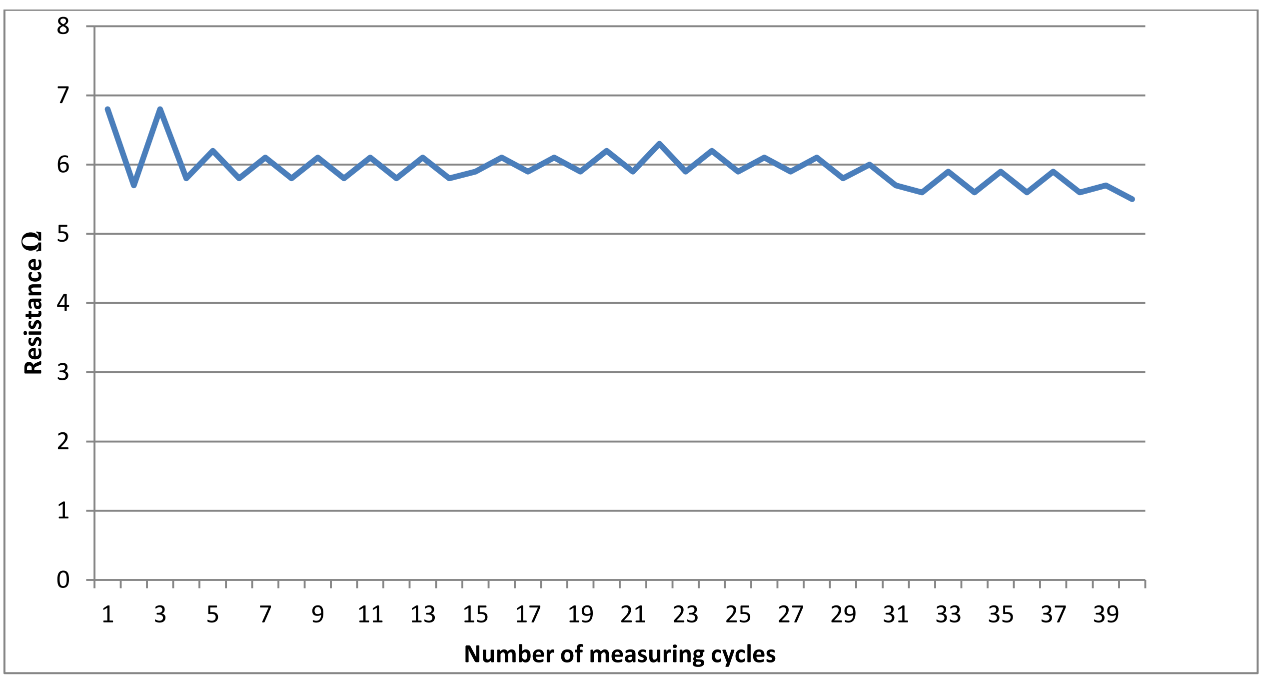

Figure 23: Resistance measurement for floating knitted Shieldex with P.E.T. in 20 cycles with 20mm/sec stretching speed

Ribbed structure made from shieldex gives much better results than Bekinox and the breathing pattern is easily recognizable as shown in figure 21. The result in figure 22 is even better but still the separation of breathe in and breathe out is only 3 to 3.3 which is very small and these graphs are made manually. If the results are done using an automatic device such as Keithley, then a little malfunction would make these results useless. So, the difference has to be wider to make sure the results are clear for everyone to read. In figure 23 the results are not good as the difference is not wide enough and the pattern is not visible.

P.E.T. with Bekaert Bekintex

This is the last conductive fiber with two variations, single and double yarn. This is made out of 20% stainless steel and 80% polyester. It has much higher resistance of 400Ω/m than the other two conductive yarns used previously.

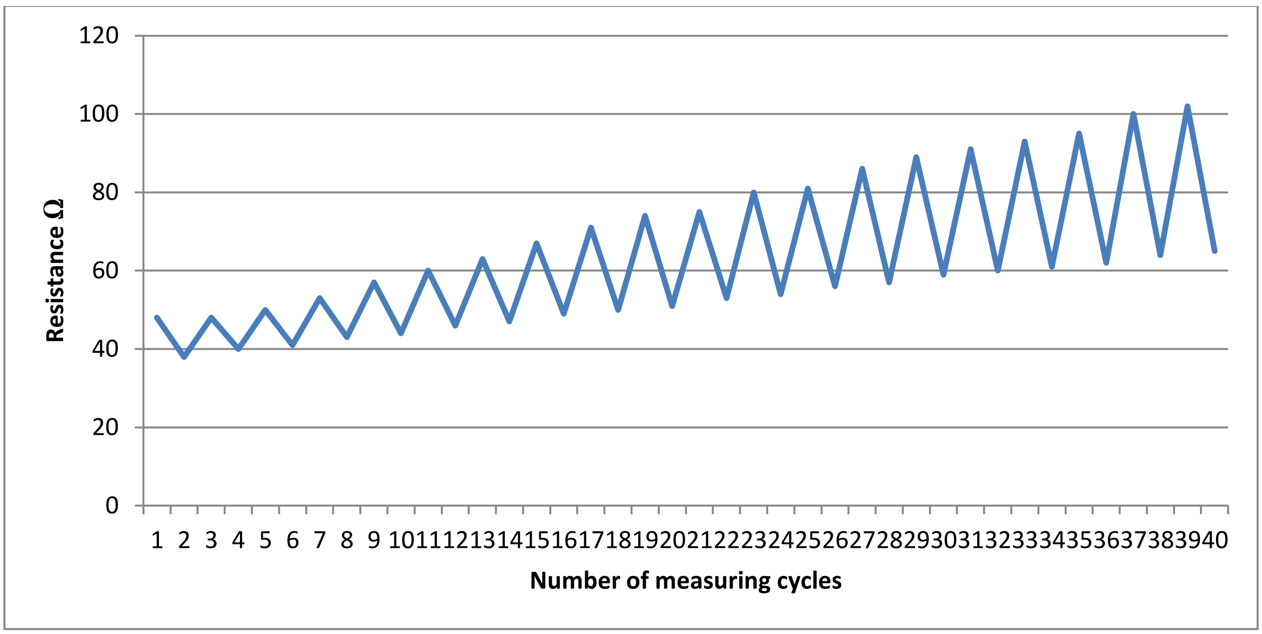

Figure 24: Resistance measurement for interlock knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed

As this fiber has high resistance values, which makes it suitable to be used with Keithley and we can get some computerized results without any man-made errors. Before we take a look at the results from Keithley figure 24 shows the results from manual observation of interlock structure of this particular conductive yarn.

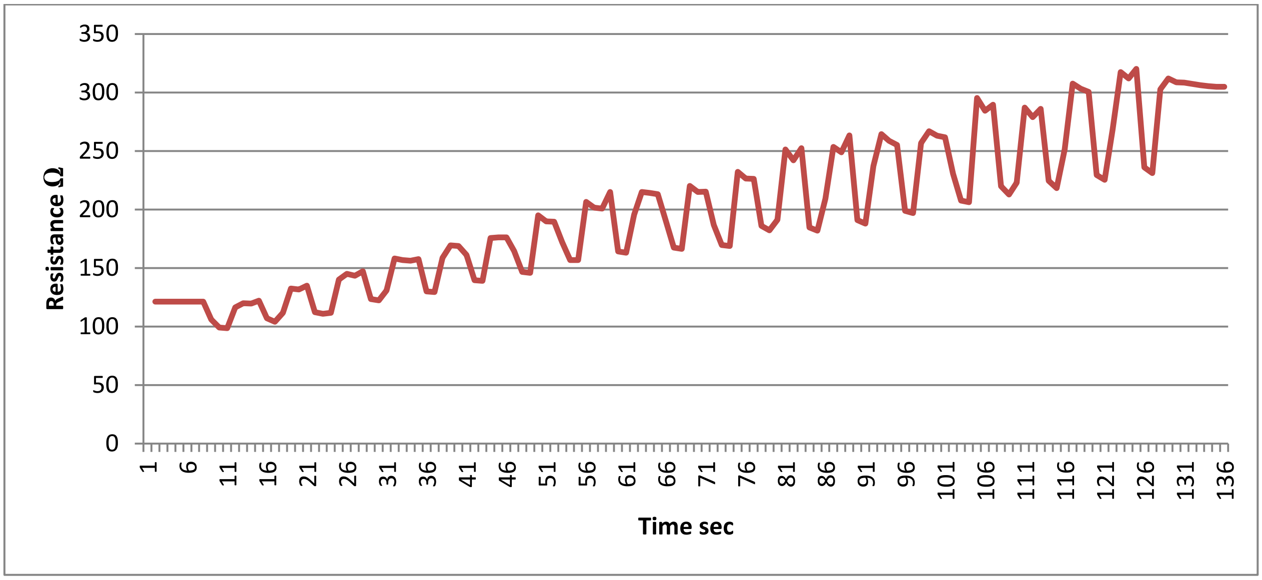

Figure 25: Resistance measurement for plain knitted Bekaert with P.E.T. in 20 cycles with 20mm/sec stretching speed

Figure 25 shows the result of plain jersey structure with Bekintex single conductive yarn. It can be clearly seen that the resistance value is much higher and starts from 120 ohms and the pattern is clearly visible. This graph is between resistance and time so; the number of cycles had to be calculated in a different way. As discussed earlier in the method section we calculated the number of cycles using time and counting the cycles from the graph. The number of cycles was approximately equal in all the results but it should not be less than 20 because we wanted to make sure that the results are stable for at least 20 cycles.

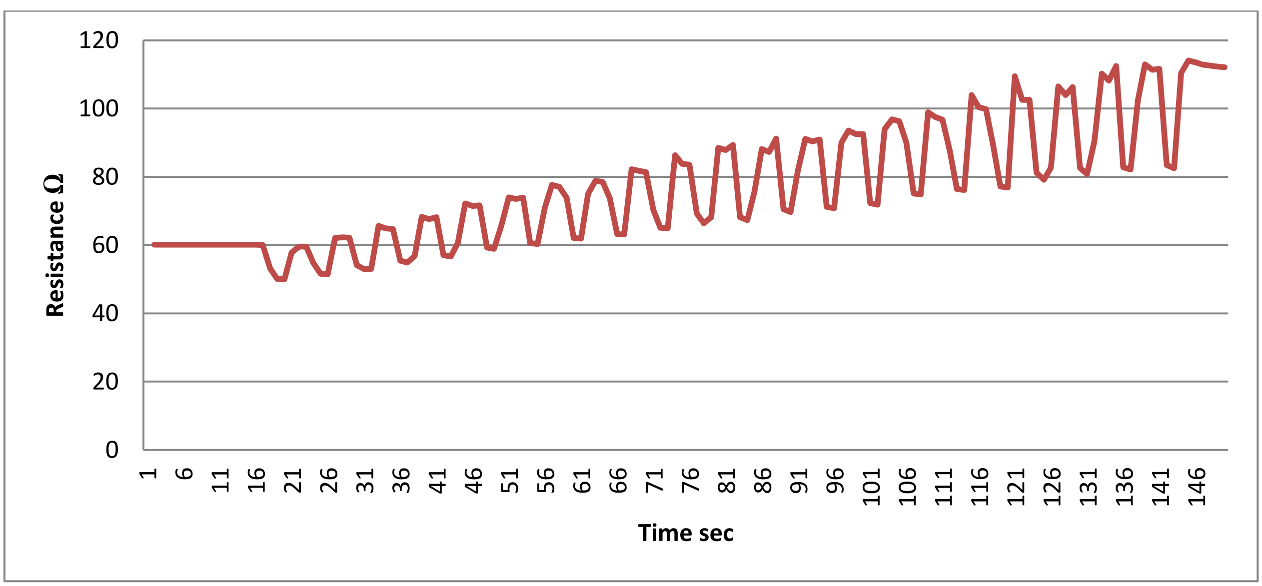

Figure 26: Resistance measurement for ribbed knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed

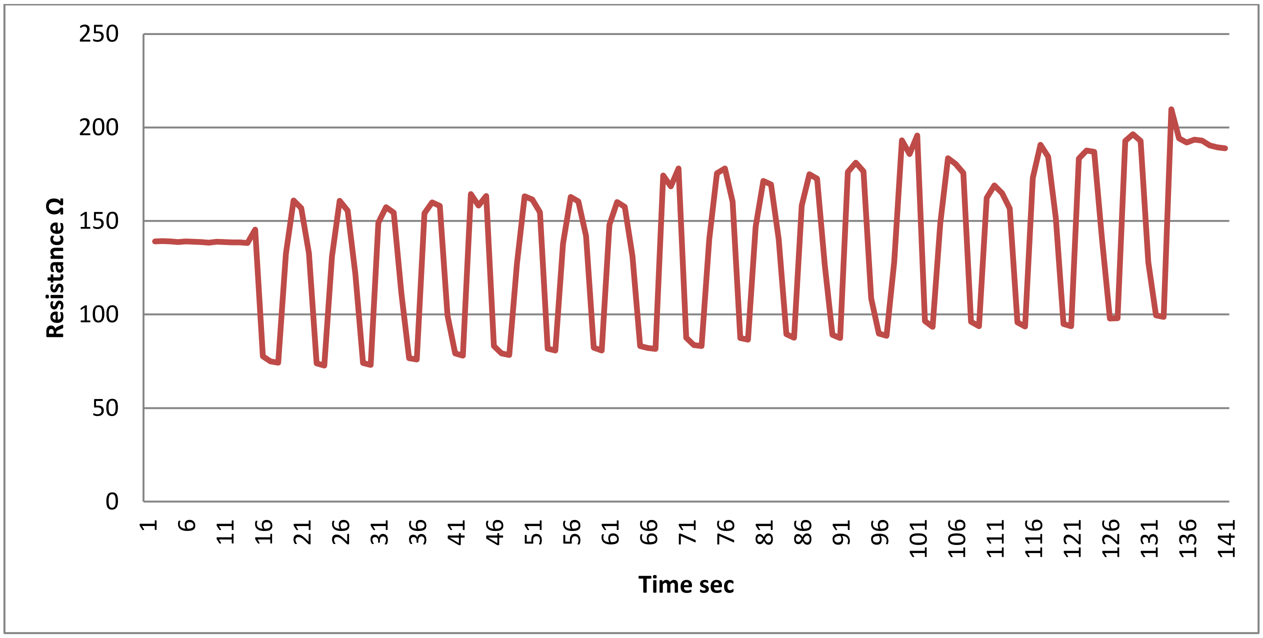

Figure 27: Resistance measurement for interlock knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed

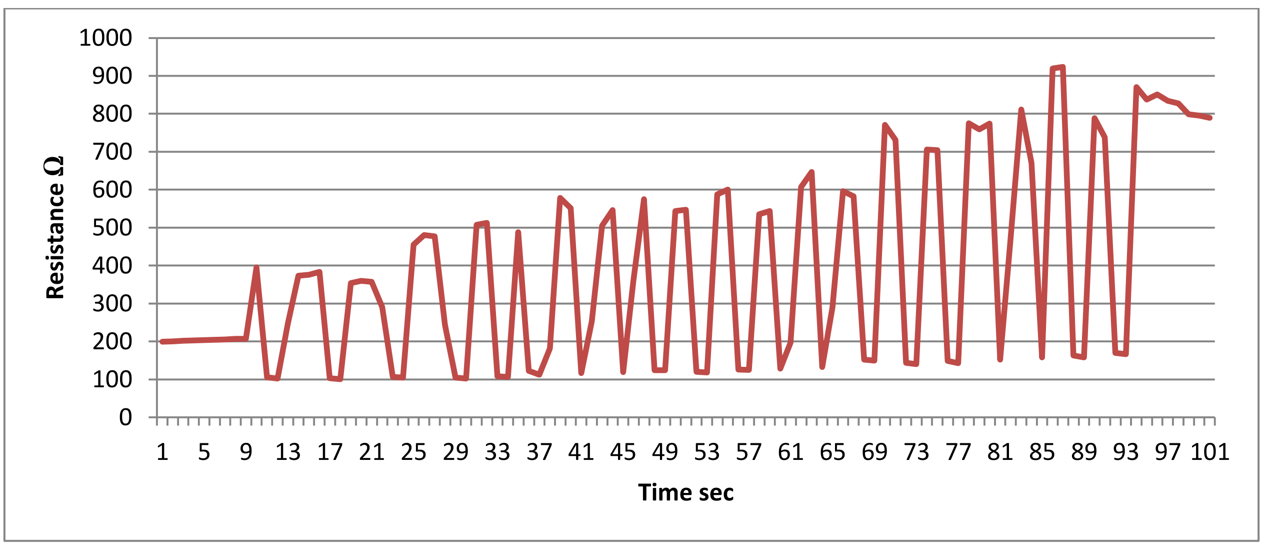

Figure 28: Resistance measurement for floating knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed

These results are much better than the manual results because it also shows the fluctuations at the top and bottom of the peaks. This makes these results more meaningful. Figure 27 shows why the interlock structure is better than the other structures as the resistance values are stable and cycles are well distinguished. Figure 28 shows the result for the floating pattern and they are comparable to interlock structure results.

Now, we take a look at the results from the double conductive Bekintex yarn.

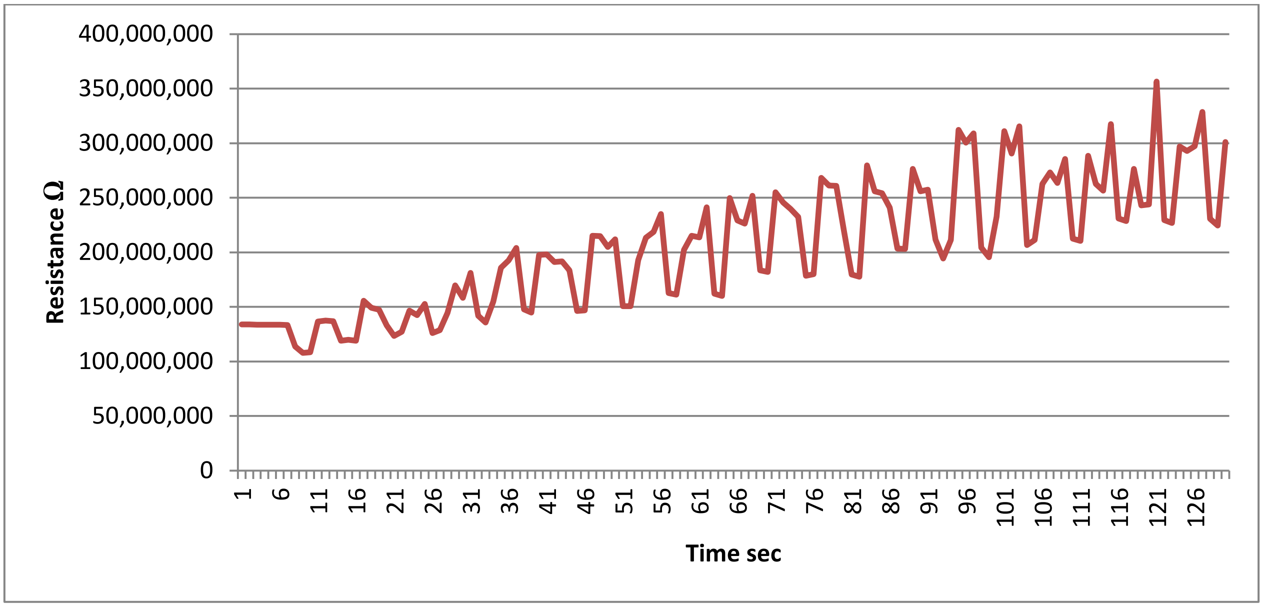

Figure 29: Resistance measurement for plain knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed

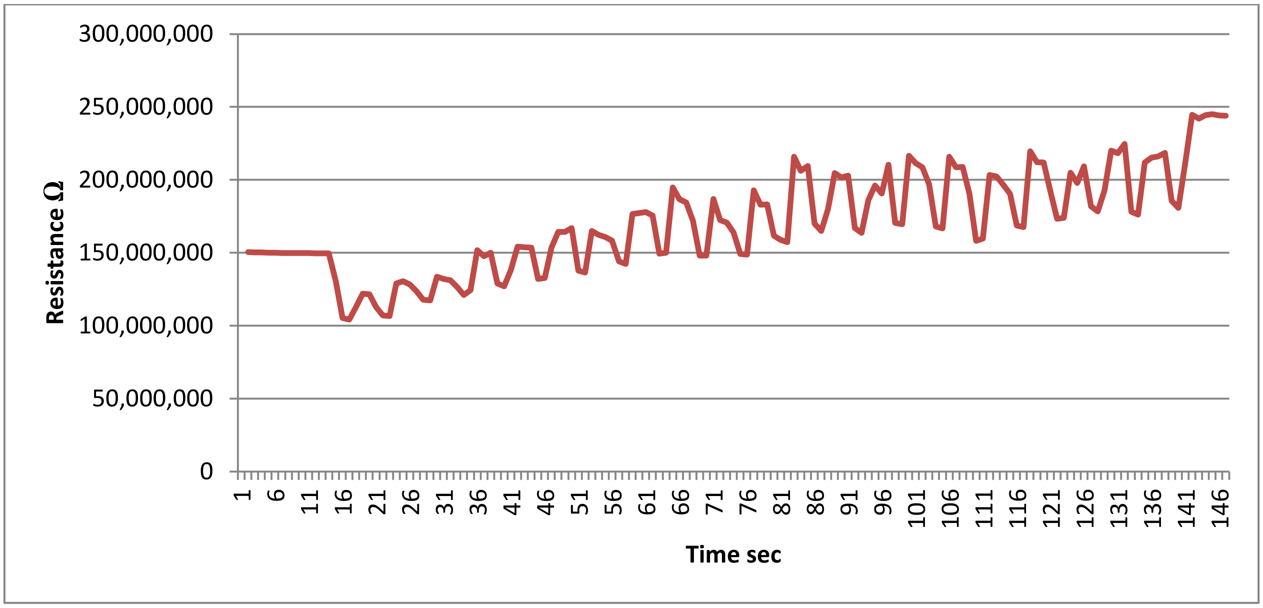

Figure 30: Resistance measurement for ribbed knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed

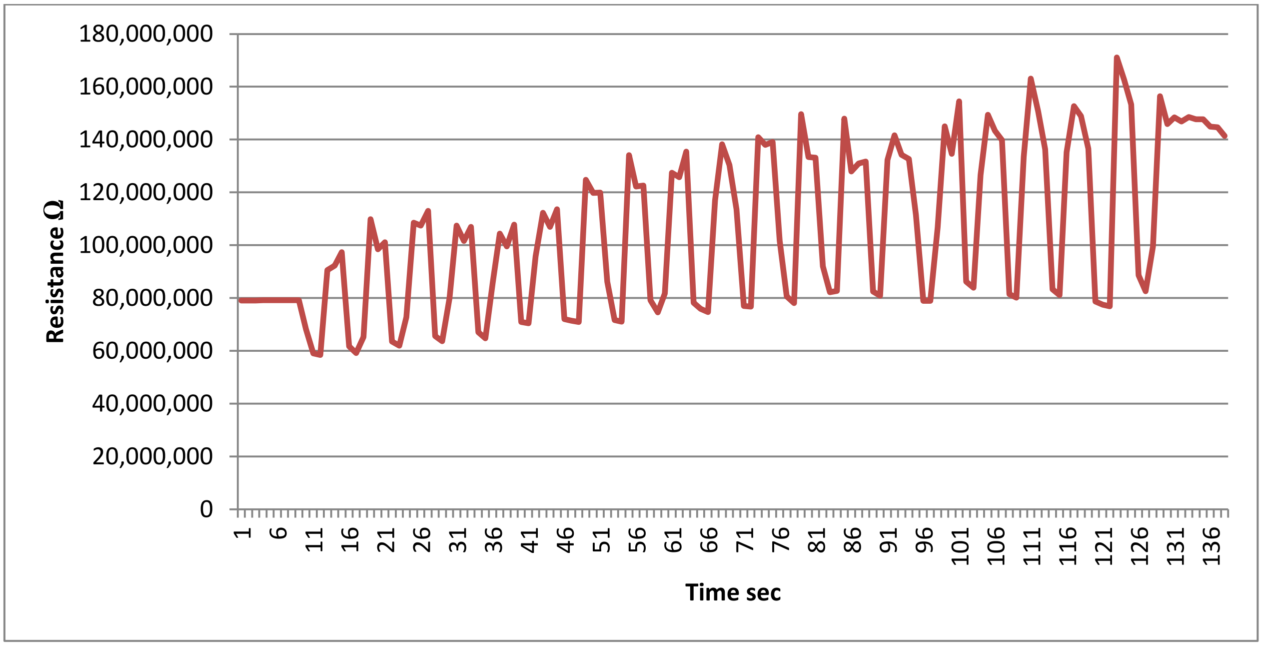

Figure 31: Resistance measurement for interlock knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed

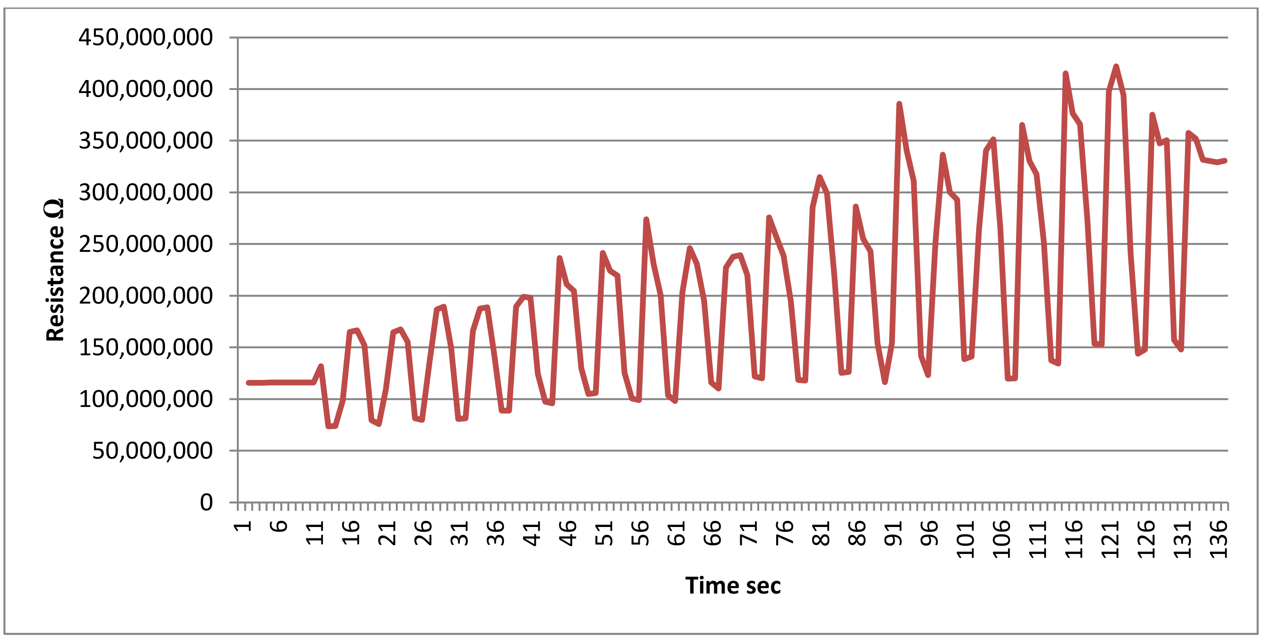

Figure 32: Resistance measurement for floating knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed

Both the results from the plain and ribbed structure are not stable enough for stretch sensors. The results form interlock and floating structures are better as shown in figures 31 and 32 respectively and are more or less the same to single yarn results in figures 27 and 28.

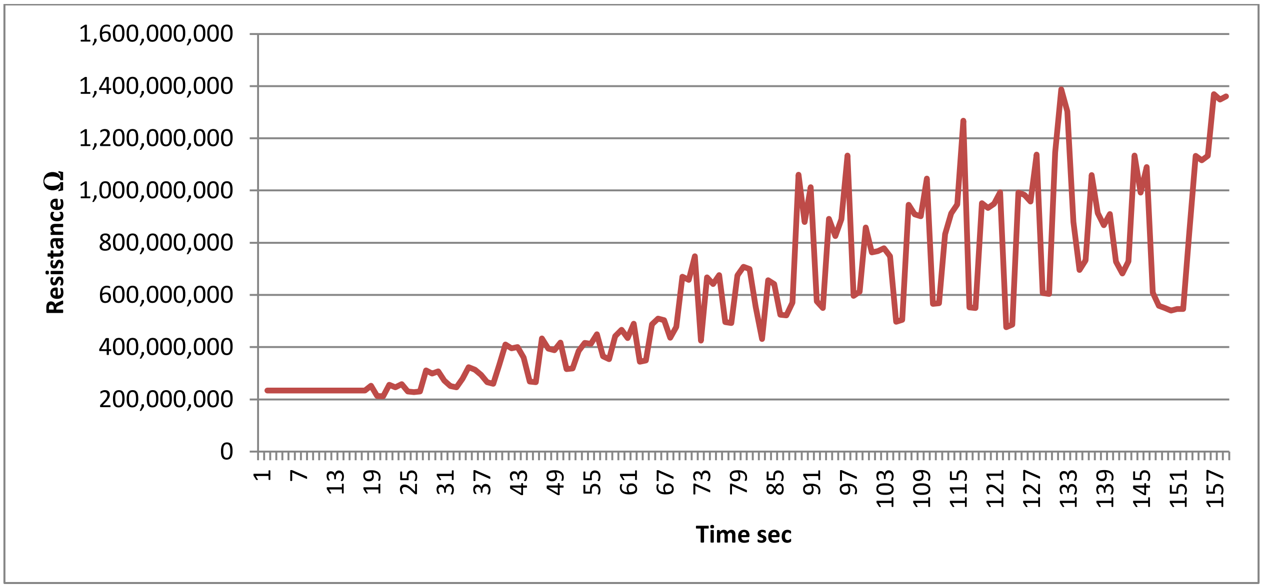

Figure 33: Resistance measurement for tucking knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed

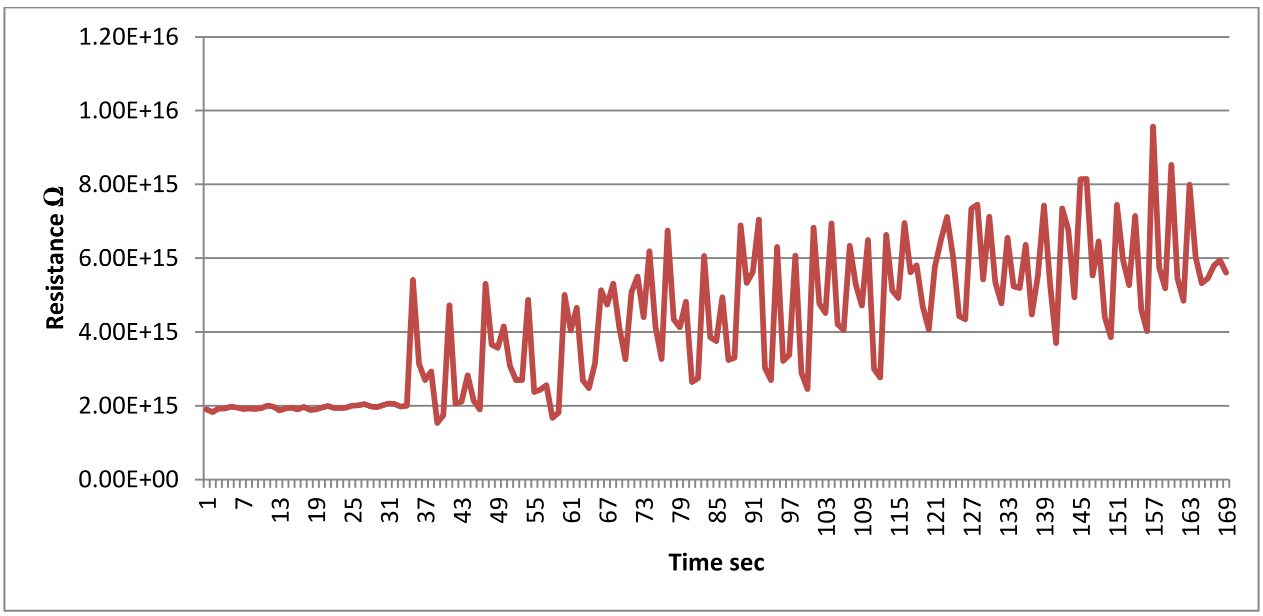

Figure 34: Resistance measurement for terry knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed

Tucking structure was proposed earlier in this project but it was left out due to non-desirable results. Figure 33 shows the results for tucking structure. Similar to tucking, terry was another structure which was not used due to its insignificant results as shown in figure 34.

After these results it is clear that Bekintex is the best conductive yarn to be used for stretch sensors and interlock and floating are most suitable structures to be used. We had to use these sensors for daily life so; different breathing rates should be used for testing these sensors.

Therefore we tested these sensors at different speeds to simulate different breathing rates. The initial speed was 20mm/sec for stretching. The results with 10mm/sec stretching speed are shown below.

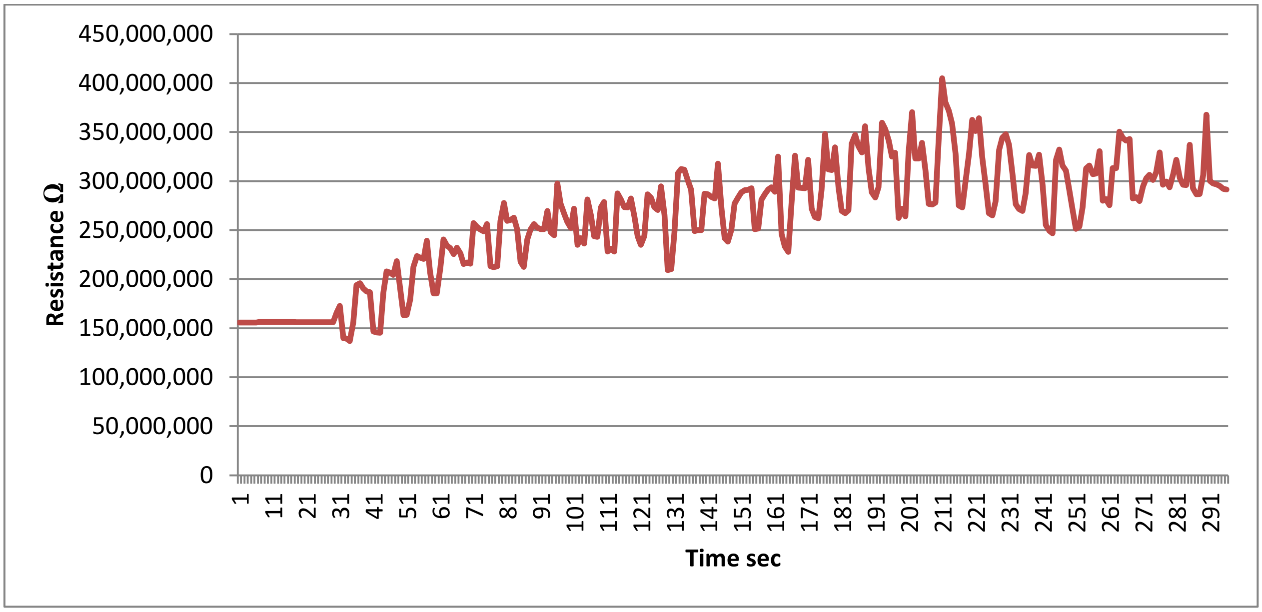

Figure 35: Resistance measurement for ribbed knitted Bekintex with P.E.T. in 20 cycles with 10mm/sec stretching speed

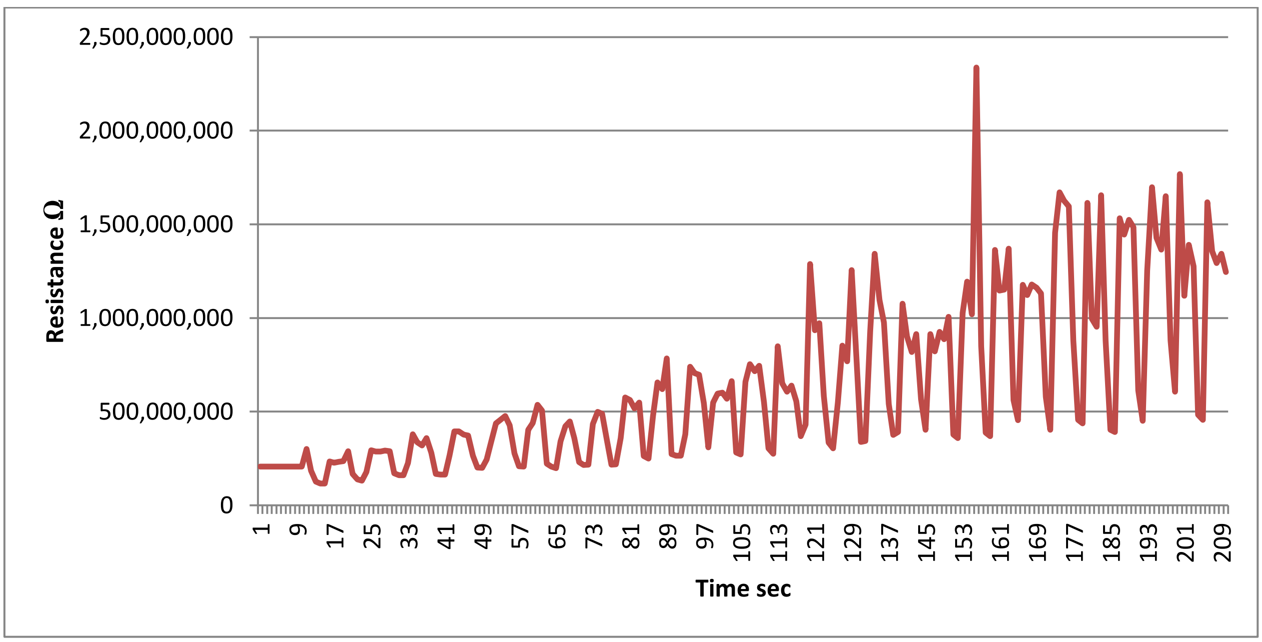

Figure 36: Resistance measurement for floating knitted Bekintex with P.E.T. in 20 cycles with 10mm/sec stretching speed

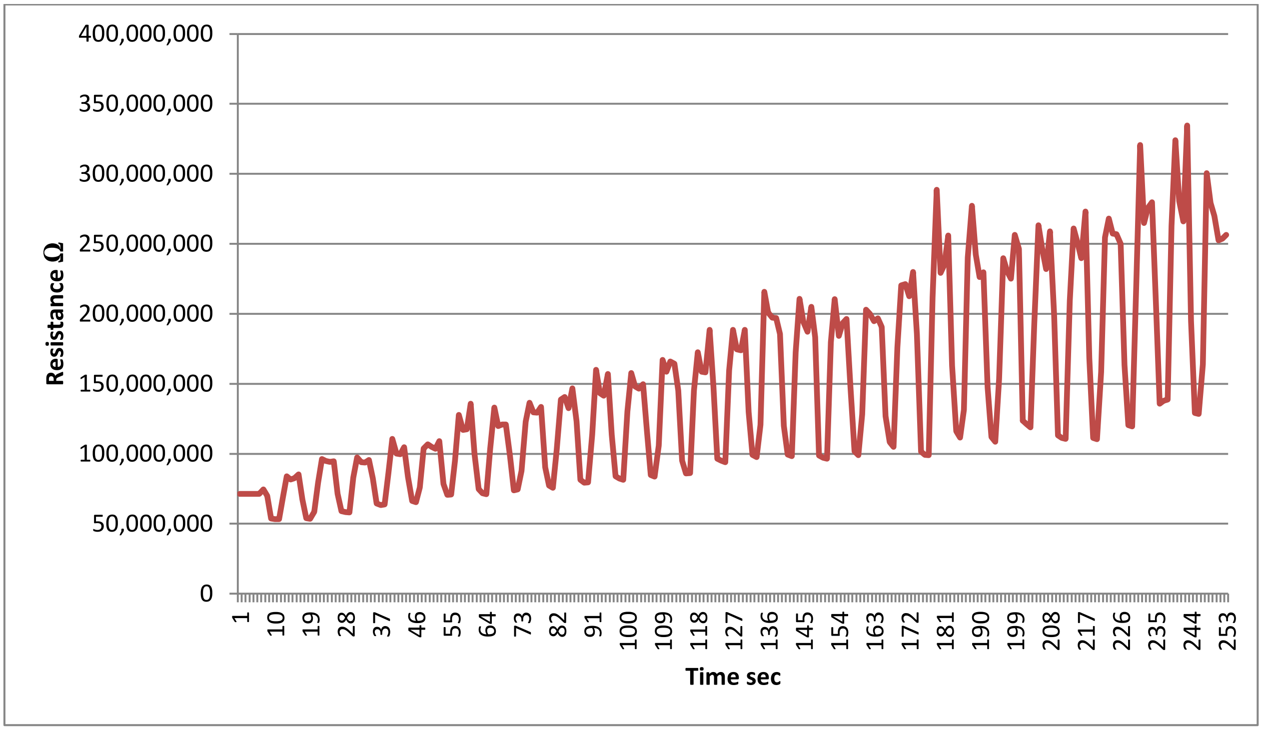

Figure 37: Resistance measurement for interlock knitted Bekintex with P.E.T. in 20 cycles with 10mm/sec stretching speed

As usual the ribbed structure produces wayward results but, unusually the floating structure also produces irregular results similar to ribbed structure as shown in figure 35 and 36 respectively. In figure 37 Interlock structure however gives the same good result.

Now, we take a look at results with stretching speed of 15mm/sec.

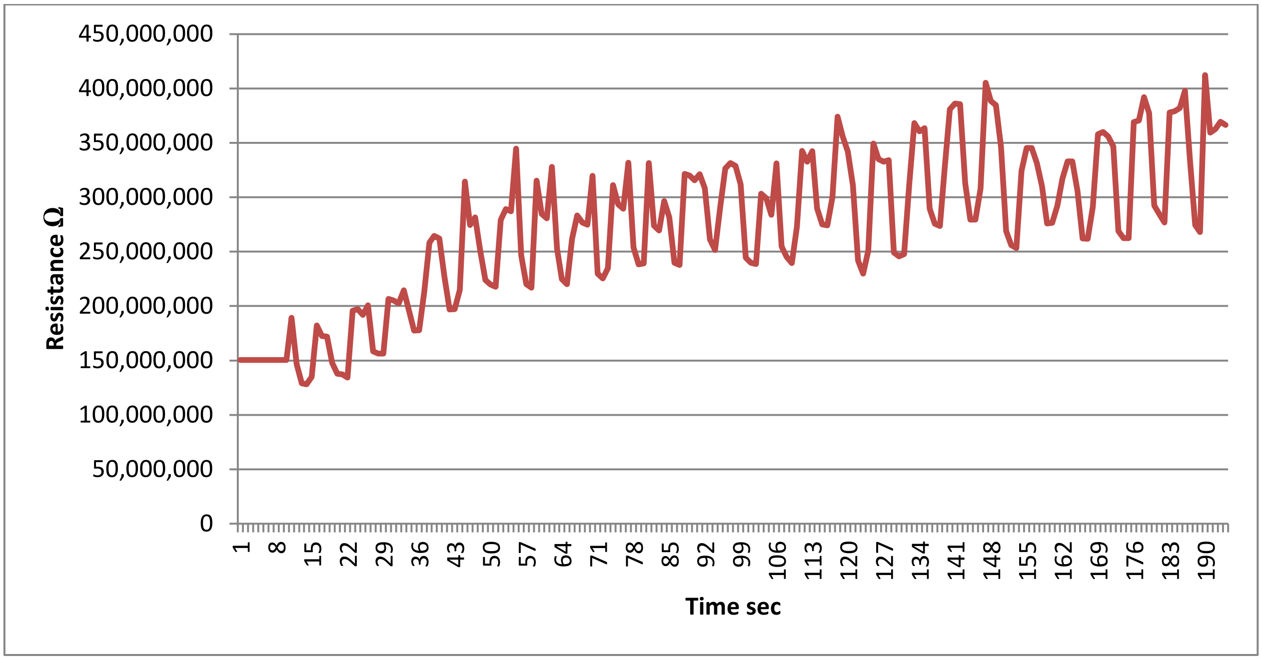

Figure 38: Resistance measurement for ribbed knitted Bekintex with P.E.T. in 20 cycles with 15mm/sec stretching speed

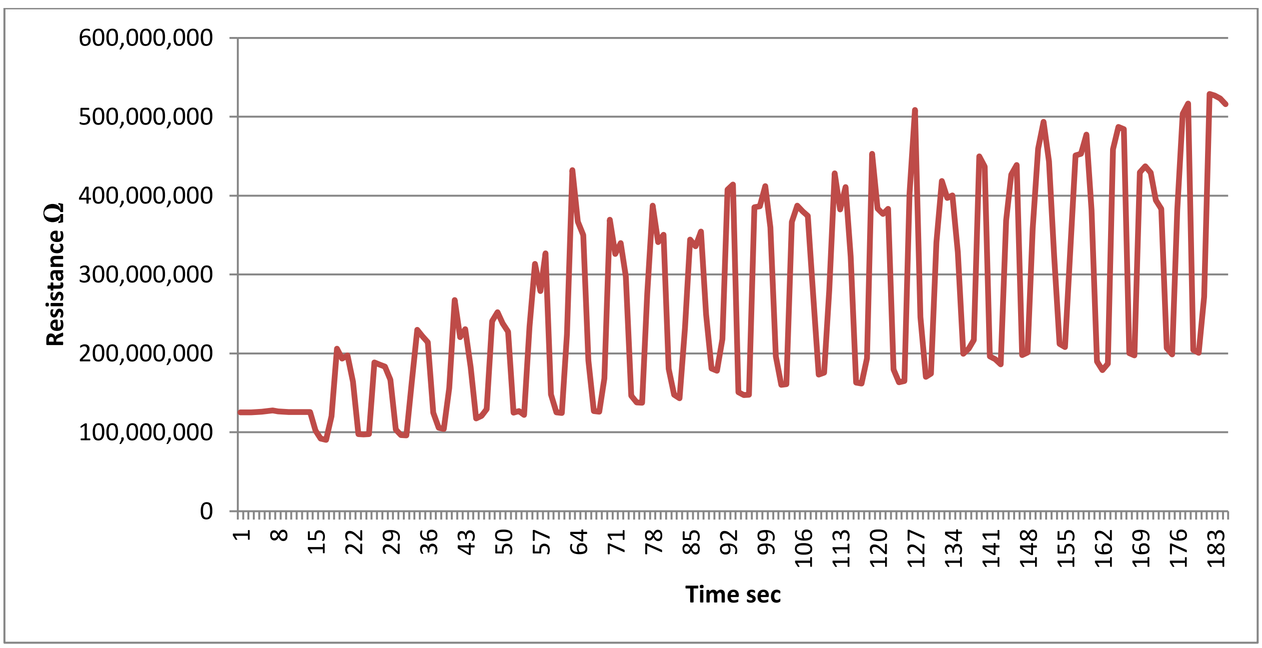

Figure 39: Resistance measurement for floating knitted Bekintex with P.E.T. in 20 cycles with 15mm/sec stretching speed

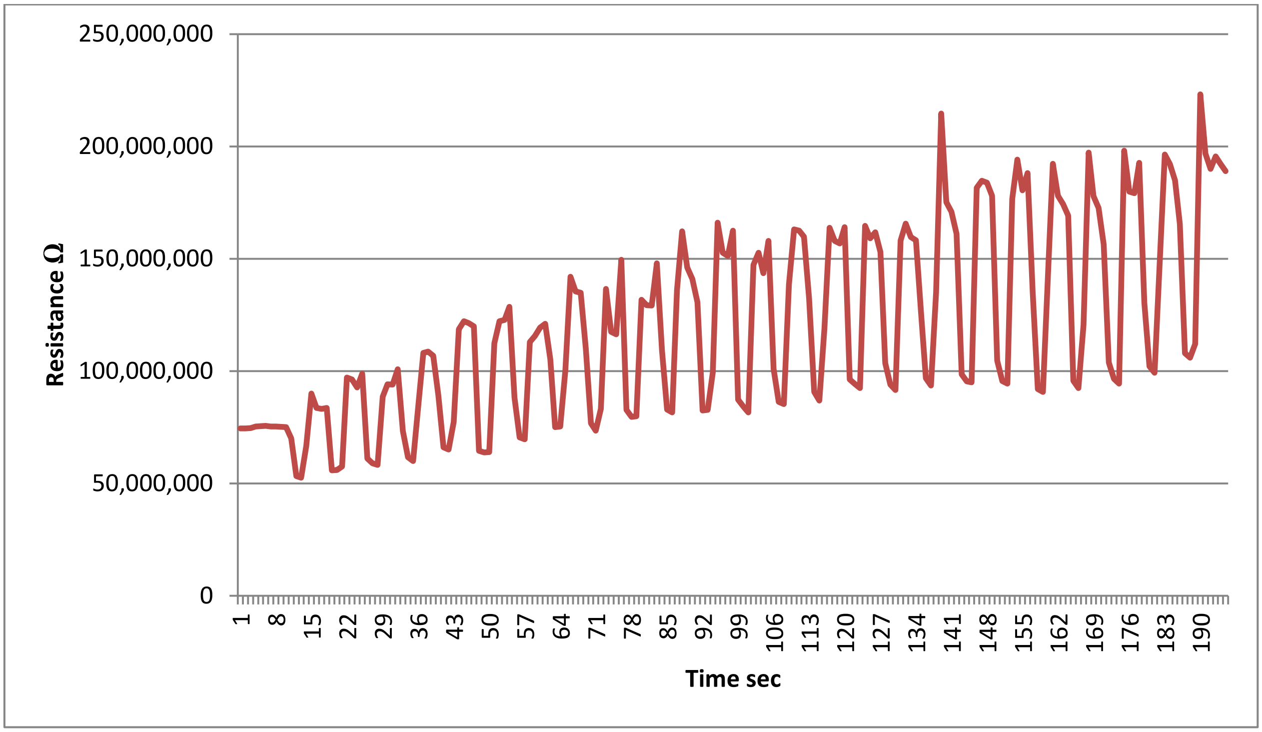

Figure 40: Resistance measurement for interlock knitted Bekintex with P.E.T. in 20 cycles with 15mm/sec stretching speed

These results in figures 38,39 and 40 also follow the pattern of the results with 10mm/sec stretching speed and as usual the results for interlock structure stand out as best among them.

Washing

These sensors should be able to withstand normal washes during daily life to make them reusable in daily life. To make sure their ability to measure resistance is not changed after washing, normal wash was performed on interlock knitted sample with Bekintex and P.E.T. and afterwards the similar test with *cyclic tester* was performed with 20mm/sec stretching speed. The results are shown below.

Washing was done at 60 C^{o} temperature for 50 minutes using normal detergent and sample was flat dried.

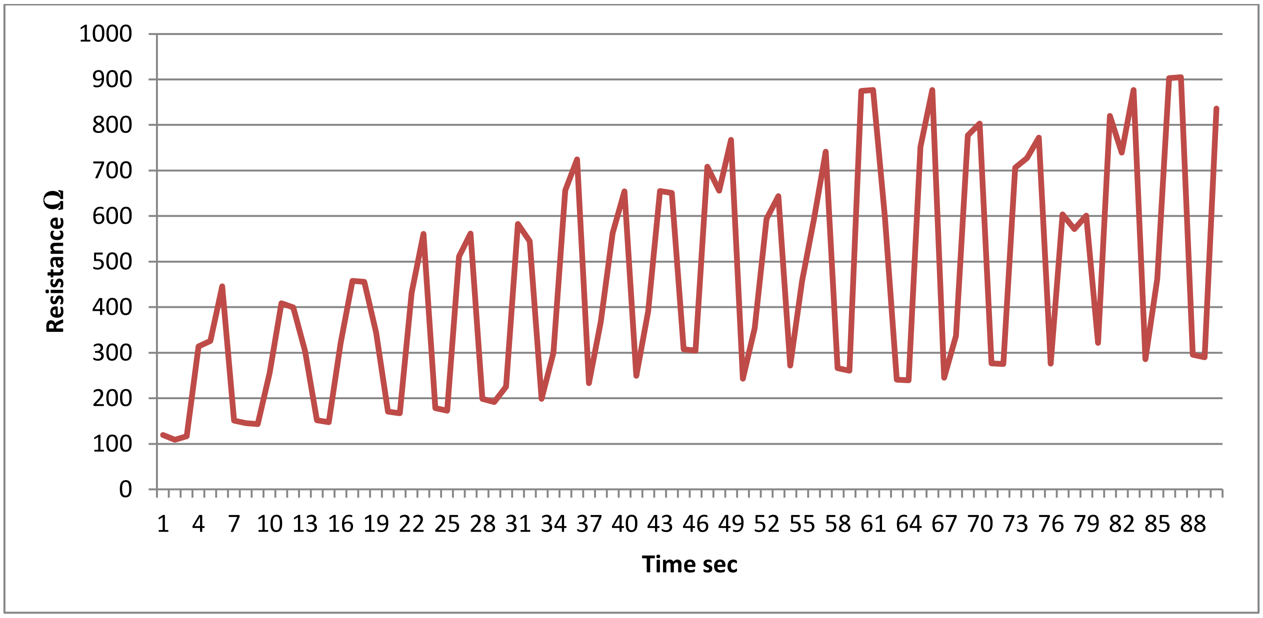

Figure 41: Resistance measurement for interlock knitted Bekintex with P.E.T. in 20 cycles with 20mm/sec stretching speed after washing

If we compare these results with the normal sample results in figure 31 we can see that at the starting point resistance has increased but the pattern is the same and we can clearly distinguish between breathe in and breathe out.

5. Discussion

There were a lot of efforts made to make this project possible. We had to change to change a lot of things from the project proposal that was first proposed. Right from the beginning, when we selected first batch of conductive yarns which we thought would be better for this project as shown in table 1, and we ended up using conductive yarns in table 2. We knew that it would be difficult to follow the line we had drawn.

First we changed the conductive yarns then we had to alter the knitting structures because some were not suitable for sensors and some yarns were not flexible enough to be used in knitting machine. Initially we selected the conductive yarns based on their properties on paper. When we compared their properties with some conductive yarns from our knitting laboratory, we knew that some yarns were more or less the same to Bekinox and some yarns which we selected earlier were out of production such as Trevia neckleman then, we decided to use the batch in table 2. Similarly, some structures such as interlock and ribbed were not made form stainless steel because of the knitting machine limitation. Some other structures such as tucking, fleecy and terry were also part of the project proposal but due to insignificant results; they were left out of this project. After these inconveniences we got the knitting samples we required.

Then comes the testing part where we used *cyclic tester* with a measuring device for resistance. First we used a multimeter for measuring resistance which was used for manual observation of resistance. There was no possible way of using this measuring device with computerized software. So, we did a bunch of tests with this device and used the values to plot some graphs. Then along the way a colleague from the engineering department proposed that it is possible to use an automatic device called Keithley, another resistance measuring device, with *cyclic tester* which can record and construct graph automatically using software for a given sample. After some tests with Keithley it was realized that even Keithley cannot be used for all the samples because only samples with high resistance values can be used with Keithley. The software used for operating Keithley was Lab-view and it cannot measure low resistance values. So, Keithley cannot be used for highly conductive fibers such as Bekinox and Shieldex. It was the limitation caused by Lab-view software which was used to operate Keithley. So; we could only use Bekaert Bekintex with high resistance values of 400Ω/m with it. However, apart from these limitations, the choice for using Keithely was very wise as the results are more detailed and can be interpreted in a different way. This can be seen in the results starting from figure 25 and onwards. Now, in these results we can actually observe the minor fluctuations and inconstancies in the peaks and the pattern for breathing can be clearly visualized. In these results it can also be discovered that interlock structure has the most stable results. Interlock structure is also the most resilient in terms of its elastic recovery than the other samples tested. It is interesting to mention that the limitation for Keithley was only dependent on the Lab-view software and there is a workaround for it but, it could not be done within the time-frame for this project.

There are no authentic standards available for washing textile stretch sensors. We used some instructions from ISO: 6330 for domestic washing and drying for textile testing. So, we performed a normal wash just to check the wash ability of these sensors and its effect on the results. The results were still good enough for daily life use but until or unless there are some international standards for washing textile stretch sensors, there is still doubt.

In the beginning we thought that we should test these samples for different breathing rates but due to the time limitation we could only test them for three different stretching speeds, which are 20mm/sec, 15mm/sec and 10mm/sec. For all these tests interlock structure performs very well in all of them and stands out in all the results. Likewise, we also thought we could test these samples after washing but, due to other troubles during this project time could not be spared for it.

6. Conclusion

People have been working on textile sensors for almost twenty years now and there have been progress in this field but, there has to be a considerable amount of development and substantive results to show that these sensors can be actually be used in practical life. Well, this project certainly is the foot in the right direction. I am sure with a little bit more work and by overcoming some of the limitations and restrictions proposed by the machines the results can be further improved. Using the textile sensors for breathing monitoring can be sensitive and the results of this project are well distinguished and meaningful so, we are certain that it can be achieved.

After testing these conductive yarns for breathing sensors we can conclusively say that, highly conductive yarns such as Shieldex and Bekinox are not suitable for use in textile breathing sensors. Now we know that these sensors can be used in daily life for monitoring of breathing for children with sleep disorders, athletes or patients who need special care at home. The purpose of this project was to make stretch sensitive fabrics for recording breathing and it is certainly fulfilled with these results in our hand.

7. Future Work

Most of the work is done but, the things we left out in this project is making a full prototype vest using these sensors for monitoring of breathing in a human body. Now, we can tweak the software for Keithley to test more conductive fibers with high conductivity. After that we can make full prototype vest and connect it with recorder and transmitter and test these sensors on a live human being and observe the results.

References

- Bickerton, M. (2003). *Effects of Fiber Interactions on Conductivity, within a knitted fabric stretch sensor.* In proceedings of the Eurowearable 2003, IEEE Press Birmingham UK, pp. 67-72.
- Carey R. Merritt, H. Troy Nagle, Edward Grant. *Textile-Based Capacitive Sensors for Respiration Monitoring.* IEEE SENSORS JOURNAL, VOL. 9, NO. 1, JANUARY 2009.
- Cedric Cochrance, Vladan Koncar and Maryline Lewandowski, (2008) *Development of a flexible strain sensor for textile structures*. In ambience conference proceedings.
- Chang- Ming Yang,Wen-Tzeng Huang, Tsu-Lin Yang, Mi-chi Hsieh,Chi-tso Liu. *Textile digital sensors for detecting breathing frequency.* In proceedings of 5th International Workshop on Wearable and Implantable Body Sensor Networks in conjunction with the 5th International Summer School and Symposium on Medical Devices and Biosensors, The Chinese University of Hong Kong, HKSAR, China. Jun 1-3, 2008.
- Charles Hautamaki, Shayne Zurn, Susan C. Mantell, Dennis L. Polla. *Experimental evaluation of MEMS strain sensors embedding composites.* Journal of microelectromechanical systems, Vol. 8, No. 3, September 1999.
- Choi and Powell, 2005 Wonseok Choi, Nancy B. Powell, 2005. Three dimensional seamless garment knitting on V-bed flat knitting machines, *Journal of textile and apparel, technology and management* volume 4, Issue 3.
- Cochrane C., Vladan Koncar, Maryline Lewandowski, Claude Dufour, 2007. *Design and development of a flexible strain sensor for textile structures based on a conductive polymer composites.* [online] Available at:
- Conductive yarns, 2011 Fiber2 fashion. *Conductive yarns and their use in technical textiles* [online] Available at: <http://www.fibre2fashion.com/industry-

article/15/1491/conductive-yarns-and-their-use-in-technical-textiles1.asp>[Accessed 22 March 2011].

- Corinne Mattmann, Frank Clemens, Gerhard Troster, 2008. *Sensor for measuring strain in textile.* [online] Basel, Switzerland. Available at: <http://www.mdpi.com/1424-8220/8/6/3719/pdf> [Accessed 15 June, 2011].
- D. W. Lloyd, D. G. Neilly and D. B. Brook. *Strain measurement in fabrics part1: general considerations and the development of an extensible strain sensor.* In RJTA Vol. 5 no. 1.
- Double filling knits, 2011 Weft knitting. *Double filling knits* [online] Available at: <http://218.189.210.187/ApparelKey/Document/Cate2/2.4/double_filling_knits.htm> [Accessed 24 March 2011].
- Dunne, L, E., Brady, S., Tynan, R., Lau, K, Smyth, B., Diamond, D., O Hare, G. M. (2006). *Garment Based Body Sensing Using Foam Sensors.* In proceedings of Seventh Australian User Interface Conference (AUIC 2006), Hobart, Australia.
- Edmison, J., Jones, M., Nakad, Z., Martin, T. (2002). *Using piezoelectric materials for wearable electronic textiles.* In proceedings of the 6th IEEE international symposium on wearable computers, 7-10 October 2002, Seattle, Washington, USA.
- Eds. Amsterdam, The Netherlands: IOS Press, 2004, vol. 108,Studies in Health Technology and Informatics, pp. 133–141, Nieuwe Hemweg 6B, 1013 BG.
- Fabrice Axisa, Pierre Michael Schmitt, Claudine Gehin, Georges Delhomme, Eric McAdams, and André Dittmar. *Flexible Technologies and Smart Clothing for Citizen Medicine, Home Healthcare, and Disease Prevention.* IEEE TRANSACTIONS ON INFORMATION TECHNOLOGY IN BIOMEDICINE, VOL. 9, NO. 3, SEPTEMBER 2005.
- Filling knits, 2011 Weft knitting. *Filling knit fabrics* [online] Available at: <http://218.189.210.187/ApparelKey/Document/Cate2/2.4/filling_knit_fabrics.htm> [Accessed 22 March 2011].
- G. Loriga, N. Taccini, D. De Rossi, and R. Paradiso, “Textile sensing interfaces for cardiopulmonary signs monitoring,” in *Proc. 27th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (IEEE-EMBS 2005)*, Shanghai, China, 2005, pp. 7349–7352.
- Hirooki AOKI, Yasuhiro TAKEMURA, Kazuhiro MIMURA, Hiroichi AOKI and Masato NAKAJIMA. *A non-contact and non-restricting respiration monitoring method for a sleeping person with a fiber-grating optical sensor.* Sleep and Biological Rhythms 2003; 1, pp. 249–250.
- Hung-I Kuo, Jun Guo, Wen H. Ko, 2007. *High performance piezoresistive micro strain sensors.* In proceedings of 2nd IEEE international conference, January 16-19, 2007, Bangkok, Thailand.
- Janusz Zięba, Michał Frydrysiak. *Textronics –Electrical and Electronic Textiles. Sensors for Breathing Frequency Measurement.* Fibres and Textiles, Eastern Europe, January/ December 2006, Vol. 14, No.5 (59), pp. 43-48.
- Li Guo, Lena Berglin. *Test and evaluation of textile based stretch sensors.* World textile conference, 26-28 May, 2009, Izmir, Turkey.
- M. Avenel-Audran, A. Goossens, E. Zimerson, M. Bruze, 2003. *Contact dermatitis from electrocardiographmonitoring electrodes: role of p-tert-butylphenolformaldehyde resin.* Denmark, pp. 108-111.
- M. Catrysse, R. puers, C. Hertleer, L. Van Langenhove, H. Van Egmond, D. Matthys. *Fabric sensors for the measurement of physiological parameters.* In proceedings of the

12th international conference on solid state sensors, actuators and microsystems, Boston, June 8-12, 2003.

- Mazzoldi, A., De Rossi, D., Lorussi, F., Scillingo, E. P., Paradiso, R. (2002) *Smart Textiles for Wearable Motion Capture Systems.* Autex Research Journal, Vol 2, No 4, December 2002.
- Mowbray, J., 2002. A quest for ultimate knitwear. *Knitting International*, 109 (1289), pp. 22–24.
- Mu-Huo Cheng, Li-Chung, Ying-Che Hung, Chang Ming Yang, Tzu Lin Yang. *A REAL-TIME HEART-RATE ESTIMATOR FROM STEEL TEXTILE ECG SENSORS IN A WIRELESS VITAL WEARING SYSTEM.* In proceedings of 2nd international conference on bioinformatics and biomedical engineering, 16-18 May, 2008.
- Munro, B. J., Campbell, T. E., Wallace, G. G., Steele, J. R. The intelligent knee sleeve: A wearable biofeedback device. Sensors and Actuators B 131 (2008) 541-547.
- P. Grossman, "The LifeShirt: A multi-function ambulatory system monitoring health, disease, and medical intervention in the real world," in *Wearable eHealth Systems for Personalized Health Management:State of the Art and Future Challenges*, A. Lymberis and D. de Rossi,
- Pacelli M, Loriga G, Paradiso R, N. Taccini. *Flat Knitted Sensors for Respiration Monitoring*. IEEE Industrial Electronics Magazine Fall 2007.
- R. Puers, M. Catrysse, B. Hermans, L. Van Langenhove, C. Hertleer, D. Matthys, H. van Egmond, A. Kalmar, M. Struys and P. Speleers. *A Smart Suit For The Monitoring Of Physiological Parameters.*
- R.I. Ross Russell, P.J. Helms. *Evaluation of three different techniques used to measure chest wall movements in children.* European respiratory journal, 1994, 7, pp. 2073–2076, UK.
- Tognetti, A., Lorussi, F., Tesconi, M., De Rossi, D. (2004). *Strain Sensing fabric characterization.* In Proceedings of IEEE Sensors 2004, Vienna University of Technology, Vienna, Austria, 2004.
- Tsang, H. Y. J., Leung, M. Y., Tao, M., Yuen, C. W. M. (2005). *Development of textile E-sensor and instrumented dancing garments.* In proceedings of ambience conference, Tampere, Finland, September 19-20, 2005.
- Van Langenhove, L., Hertleer, C. (2004). *Smart Clothing: a new life.* In International Journal of Clothing Science and Technology, Vol 16 No ½ 2004, pp. 63-72.
- Weft knitting, 2011 Weft knitting. *Filling knit structures* [online] Available at: <http://218.189.210.187/ApparelKey/Document/Cate2/2.4/weft_knitting.htm> [Accessed 24 March 2011].
- Wipfler, M., Raina, M., Gries, T. (2008) *Smart Textiles in automotive applications – An overview of present and possible future development activities.* In: Proceedings of 2nd International Conference Textiles of the Future, Kortrijk, Belgium, 13-15 November, 2008.
- Xiaoyin Cheng, Yang Li, Xiaoming Tao, Hing Yee J. Tsang, Mei Yi Leung, Pu Xue, Xiaoxiang Cheng and C.W.M. Yuen. *Polypyrrole coated fabric strain sensor with high sensitivity and good stability*. In proceedings of 1st IEEE international conference on nano/micro engineered and molecular systems, January 18-21, 2006, Zhuhai, China.

- Y. Li, X.Y. Cheng. J. Tsang, X.M. Tao, M.C.W. Yuen. 2005. *A flexible strain sensor from polypyrrole coated fabrics.* Synthetic Metals, Volume 155, Issue 1, 15 October 2005, pp. 89-94.
- SAS Articles: *The four base structure of knit*. [online] Available at:
- Answers.com. *Carbon Fiber.* [online] Available at: < http://www.answers.com/topic/carbon-fiber?cat=technology> [Accessed 20 August 2011].
- Softswitch and Peratech. Elektec and QTC technology [online] Available at: eleksen.com, peratech.com.
  < http://www.mdpi.com/1424-8220/7/4/473/pdf> [Accessed 10 June, 2011].
  < http://sas-articles.blogspot.com/2010/04/four-primary-base-structure-plain-rib.html> [Accessed 25 July 2011].
- *Knitted breathing sensor.* Melliand International, 5-6, 2010.

Images

Figure 2 *filling-knit fabrics*. [Image online] Available at: <http://218.189.210.187/ApparelKey/Document/Cate2/2.4/filling_knit_fabrics.htm> [Accessed 2011-03-24]

Figure 3 *double filling knits*. [Image online] Available at: <http://218.189.210.187/ApparelKey/Document/Cate2/2.4/double_filling_knits.htm> [Accessed 2011-03-24]

Figure 4 *The four primary base structure of knit.* [Image online] Available at: < http://sas-articles.blogspot.com/2010/04/four-primary-base-structure-plain-rib.html> Accessed 2011-05-03

Figure 5 and 6 *Unit 5: Knit stitches.* [Image online] Available at: < http://textilemania.textilefabric.com/u_5/u_5_3.html > [Accessed 2011-08-24]