Development and Evaluation of Textile Actuators

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Abstract

Existing actuators in robotics are noisy, rigid and not very lifelike in their movements. There is a need for actuators in especially limb prosthetics and exoskeletons that are silent, softly moving and preferably operating on low currents. One such solution is the conducting polymers. Textiles are well researched and there is a wide variety of patterning. Even more important is their reproducibility and how easily they are mass-produced.

This thesis work combines conducting polymers with textiles to achieve linear textile actuators. The textiles are coated with the conducting polymer Polypyrrole which has the property of volume change, when a voltage is applied and there is a reservoir of ions accessible. The volume change, expansion and contraction, results in a linear actuation. The force and strain are measured while changing different parameters and the results are evaluated in this thesis.

Keyword
Conducting Polymer, Textile, Actuator, Soft Robotics
1. Introduction
   1.1 Actuator for robotics
      1.1.1 Current actuators in robotics
      1.1.2 Future actuators in robotics
   1.2 Smart textiles
      1.2.1 Conductive fibres and fabrics
      1.2.2 Strain sensors
      1.2.3 Textile muscles
      1.2.4 Wearable antennas
   1.3 Conducting polymer actuator
      1.3.1 Properties
      1.3.2 Fabrication
      1.3.3 Devices
      1.3.4 Conducting polymer performance

2. Method for yarns
   2.1 Schematics of method for yarns
   2.2 VPP
   2.3 ECP
      2.3.1 Software settings
   2.4 Electro mechanical characterisation
      2.4.1 Measurement
      2.4.2 Data processing
   2.5 Researched parameters
      2.5.1 Effects of polymerisation time
      2.5.2 Effects of core materials

3. Method for textiles
   3.1 Schematics of method for textiles
      3.1.1 Differences between yarn and textile sample preparation
   3.2 Researched parameters
      3.2.1 Lyocell Weft Tricot knit
      3.2.2 Lyocell Ne 24/1 Pattern 2:1 20x20
      3.2.3 Polyamide-Lycra dtex 78/78 Pattern 2:1
   3.3 Chemical list

4. Results
   4.1 The effect of the polymerisation time
   4.2 The effect of the core material
      4.2.1 Non-conducting core materials
      4.2.2 Conducting core materials
   4.3 The effect of the textile patterns
      4.3.1 Lyocell Weft Tricot Knit
      4.3.2 Lyocell Ne 24/1 Pattern 2:1 20x20
      4.3.3 Polyamide-Lycra dtex 78/78 Pattern 2:1

5. Discussion
   5.1 Polymerisation times
   5.2 Non-conducting core materials
5.3 Conducting core materials
5.4 Lyocell Weft Tricot Knit
5.5 The effect of the textile constructions

6. Conclusion
7. References
8. Acknowledgement
1. Introduction

1.1 Actuator for robotics

1.1.1 Current actuators in robotics

In the world of robotics only a few types of actuators are commonly used. One of these is the DC (electric) motor powered actuator, which can be found in hand prosthetics (see figure 1) on the market now [1-2] and also in exoskeletons [3] (see figure 2). The other common actuator is the pneumatic one, such as the McKibben artificial muscle [4] also called McKibben PAM (Pneumatic Artificial Muscle) [5]. DC motors are easily integrated and controlled, have a high power output and can be manufactured at a low cost [6]. PAMs have high power output, inherent compliance, relatively lightweight and have somewhat similar properties when compared to an organic muscle [7-8]. There are, however, many drawbacks with the aforementioned actuators. They are bulky, hard, have rigid segments and use structures that are not lifelike and it is costly and difficult task to mimic lifelikeness [9]. Other major drawbacks are the noise both types of actuators make and the lack of smooth motions [10-11].

Figure 1: Existing working prosthetic hand made by Johns Hopkins Applied Physics Lab. [12]
1.1.2 Future actuators in robotics

The new advances in robotics are normally referred to as the soft robotics. There are a number of attempts to make actuators that are different in nature from the ones mentioned above. Whitesides’ multigait soft robot is made containing different chambers that can be filled pneumatically and individually controlled [14]. Depending on which chambers are filled and what the design of the robot is, different shapes and tasks can be achieved and performed respectively [15]. Furthermore, there are the dielectric elastomers, with which a voltage is applied to two compliant electrodes in the direction of the thickness of a membrane. This membrane will then increase its area when the voltage is applied and at the same time decrease in thickness [16]. There are also actuators that use carbon nanotubes. Two electrodes made of carbon nanotubes and conductive polymers are sandwiching a layer of electrolytes and when a voltage is applied the whole structure will bend [17]. A different concept exists with the shape memory alloys, which deform with light or heat, but will revert back when the stimulus is released [18]. Hierarchically arranged helical fibres or HHF tighten their helical shape when exposed to vapour stimuli [19]. Moreover, there are pneumatically activated PDMS microtube tentacle actuators [20] and many more examples of actuators that could possibly be of importance in the future of soft robotics.
1.2 Smart textiles

To refer to smart textiles is to refer to a wide group of textile products. What they have in common is that they are in one way or another upgraded fabric that can interact, either with the user or with its surroundings. An even more narrow definition, is that of e-textiles, which is what the name suggests, a merge between electronics and textiles. There is a long list of advantages like wearable components which can move better than if one were to wear the existing alternatives, which can often be entangled. This is for example true for cables and tubes in the medical world. Another positive effect is that they become less perceptible. All in all, there is great hope for smart textiles and e-textiles. A few additional mentions of advantages with smart textiles are the following: Flexible, easy to integrate, low on power consumption and ergonomic. [21]

1.2.1 Conductive fibres and fabrics

In order for e-textiles to be realised there needs to be conductive materials integrated somehow into the textiles. It is often done in two ways. One is to have metallic filaments or a metallic wire interlocked together with the rest of the yarn, resulting in a conductive yarn. The second option is to coat the yarn, making it conductive. The coatings normally come in the form of naturally conductive metals. [21]

There are inventive ways of integrating these conductive yarns into textiles. Post et al [22] were stitching patterns of conductive thread into circuits on clothes with the help of embroidery (e-broidery). They made for example a musical jacket with a keypad, which enabled the user to play chords, rhythms, notes and chose from a variety of musical instruments. The musical jacket can be seen in figure 3.
One does not necessarily need individually conductive yarns to make clothes or textiles conductive. Another way is namely conductive ink, which is not limited to textiles as a substrate. Although it is essential to have a conductive material, most of the time it is a metal with conductive capabilities, which is a component of the conductive ink. It is easier to pattern than if conductive yarns were used and since ink printing is well established it is also easier to mass produce than the yarns. Conductive inks are also more flexible and versatile. There are a number of requirements that need to be solved first however. The ink needs to have the right viscosity, high enough conductivity, oxidation resistance and it needs to dry in a certain fashion etc. [21]

1.2.2 Strain sensors

The integration of strain sensors into textiles and clothes will likely give rise to new applications. It can for example be in sports where the bending of joints can be measured, for similar reasons it would be useful in rehabilitation and for correcting posture [24]. Strain sensors can be integrated by placing a sensor thread on a silicon substrate, which is then attached to the fabric and connected to conducting fibres, that are also attached to the fabric
with adhesives, as done by Mattmann and colleagues [24]. Another group that tried to integrate strain sensors was Belforte and co-workers [25], who utilised the fact that conductive fibres have a change in electrical resistance when the length is changed. This would then lead to that the bending of for example an elbow will lengthen the conductive fibres which are integrated in the fabric and this changes the resistance, which can be sensed by the sensor [25]. There are also pressure sensors which work by changes of the piezoelectric resonance frequency due to the applied pressure [21]. Furthermore, there are electrochemical sensors that can be integrated [21].

1.2.3 Textile muscles

In the world of textile muscles or actuators, which is still relatively small, textile actuators with the pneumatic solution seem to be mostly tried. Various people are trying to integrate PAM into textiles [26]. One way hypothesized is thread-like micro-sized tubes that can be pneumatically expanded and inflated and then integrated into textiles [27]. Another being the bellow muscle [26], which is essentially a PAM made almost exclusively out of textiles. It has four identical chambers connected to one another and at the edges, rigid discs are placed for connection purposes. The chambers expand when the muscle is filled with air, leading to a linear actuation. The materials used are laminated fabrics in several layers in order not to break apart due to the applied pressure of the compressed air which is trapped inside of the device.

Magnetic fibres is an idea considered and studied in computer models [28]. Magnetic fibres can be made when the fibres are manufactured by adding a nanoparticle-sized powder with magnetic or ferromagnetic properties. The magnetic parameter is proportional to the amount of powder in the fibres but there is a limit to how much powder can be embedded and that is why researchers have simulated the powder amount and particle sizes [28]. Magnetic fibres enable both textile sensors and textile actuators, since magnetic circuits are part of electromagnetic circuits [28]. It would for example be possible to use the magnetic properties to make electromagnetic actuators.

1.2.4 Wearable antennas

There are quite a few new smart textile applications appearing and a very interesting one is the wearable antenna. It has already been integrated into life-vests so as to be a beacon for
rescue parties [29] for example. Another area of interests is the military where mobility and lightweight equipment is essential. The idea for integrating an antenna into clothes is not dissimilar to what has been previously mentioned, the substrate is a textile integrated with either conductive fibres or coloured with conductive ink or even e-broidery is possible. There are a few requirements for the material to be considered usable, one such is to withstand harsh environment. [30]

1.3 Conducting polymer actuator

1.3.1 Properties

An actuator that is based on conducting polymers (CP) is actuating due to a volume change of the polymer when a potential is applied to it. The potential applied causes a redox reaction and the volume changes according to if the redox reaction is an oxidation or a reduction, see figure 4. To change the direction of the redox reaction, one simply changes the potential from a negative to a positive voltage or vice versa. For this to be possible the actuator has to have access to an ion reservoir, an electrolyte. Since the movement of ions in and out of the material is the cause of the volume change, moving in means an increase in volume and vice versa. The movement itself is due to the fact that charge neutrality must be conserved. When there is a change in electronic charge there must also be a change in the ion charge. There are two reactions that can be considered (1) and (2). Reaction (1) contains small anions which will move in during the oxidation and move out during reduction. The problem with reaction (1) is that the second reaction (2) might also occur, which counteracts the volume change of first reaction. Since in (2) the mobile cations enter the polymer when reduced and leave when oxidised. The reason the second reaction is more often desired, is that it only contains big immobile anions which will not move due to their relatively big size. [31-35]

Equations:

\[
\begin{align*}
(1) \quad P^+(a^-)+e^- & \leftrightarrow P^0+a^- (aq) \\
(2) \quad P^+(A^-)+C^+(aq)+e^- & \leftrightarrow P^0+(A^-C^+) 
\end{align*}
\]

P is the polymer, A is the large anion, a is the small anion and C, the cation. [31-35]
1.3.2 Fabrication

Deposition of the polymer onto a substrate can be done in various ways, like spin coating and dip coating from solution [32-33], but more of interest in this report is vapour-phase polymerisation (VPP) and electrochemical polymerisation (ECP). In both cases a monomer is needed. Two monomers of interest for an actuator are pyrrole (Py) and 3,4-Ethylenedioxythiophene (EDOT) [31], especially of interest for bio-integratable aspects is Py since it is electroactive within the pH range of the human body [34]. The monomers will after the polymerisation be interlocked and in chains as polymers. In their polymerised state they are referred to as PPy and PEDOT.

VPP is a polymerisation technique which works well for polymerisation of a thin layer of PEDOT onto a substrate [36]. When performing a VPP with the monomer EDOT, the substrate is covered in oxidising agents [36] and the monomer is introduced to the chamber, in which the VPP is carried out. The chamber consists of a hot plate and a glass lid. The results are relatively fast and a homogenous deposition is achieved [37], assuming that the deposition site is even. The VPP works by introducing vacuum into the chamber and the hot plate, which the encapsulating glass lid stands upon, is heated up to appropriate temperature [37]. The chamber is saturated by EDOT and subsequently the substrate, which was covered in the oxidising agents, is covered with a thin film of PEDOT [37].

[Figure 4: Volume change of the polymer due to redox reaction, causing out- and influx of ions.]
ECP is deposition of the polymer, which in these cases often is PPy, onto a substrate, often gold because of its good conductivity. It is done by making an electrochemical cell with an aqueous solution containing the Py monomers and a salt, NaDBS is commonly used, which becomes the dopant [31]. The substrate is attached to the working electrode and submerged into the electrolyte. Also introduced are a counter electrode and a reference electrode [32]. A low voltage is then applied via a potentiostat [35], commonly around 0.5-0.6V, a longer time or a higher voltage results in a thicker polymer layer but the layer tends to be less homogenous [32]. The same cell and setup, but without the monomer in the solution, can be used for actuation once the sample is complete.

1.3.3 Devices

There is a demand for actuators in biomedical applications such as artificial organs, micro robots and humanoid robots [38] and also a future within biomimetic undersea vehicles [39]. That is why there is a lot of research in actuators and specifically for conductive polymers applications in micro-systems are envisioned [38]. However, there is still a lot of work presented on the improvement of the actuators, while work on future applications and possible devices is not as common. There are some examples of applications that have been tried, such as biomimetic jellyfish, robot faces that can generate expressions and braille displays that can help the blind [39].

One group has constructed two biomimetic robotic fishes, WANDA [40] and NEMO [41-42]. WANDA is designed to autonomously move around, in water, and detect pollutants or other substances harmful to the environment. It is propelled with its polypyrrole actuated tailfin [40]. NEMO has a very similar design, also with polypyrrole actuated tailfin propulsion [41]. The actuators, in both cases, were designed as trilayers, making it possible for the fins to move back and forth [40-41].

Because of PPy actuators’ biocompatibility, small size and that they only require small currents [43] it seems likely that a large part of them will be used for biomedical applications. One such example is the neural probe made by Daneshvar and Smela[43]. It has an electrode which extends away from the probe into healthy tissue. This is because once the probe is inserted into the brain tissue it causes damage. The much smaller electrode does not cause the same damage and can enter healthy tissue to record from the healthy neural network [43].
There are still further possibilities for medical devices. Such as the microanastomosis
connector created by Micromuscle AB, which with the help of PPy actuation connects two
ends of a broken blood vessel [44]. Once this is done the two ends can heal once more.
Another application under research is a steerable catheter. It has a conducting polymer on a
part of its exterior and when a potential is applied the catheter bends due to the characteristics
of the polymer, resulting in a steering of the catheter [44].

1.3.4 Conducting polymer performance

The force per area unit generated by the conductive polymer activation is higher than that of
the skeleton of a human (~0.35 MPa) for example, at >5 MPa. The strain is normally 1-10%,
if the load is small. The numbers for a thin PPy layer ranging between 1-10 micrometre have
been shown to decrease in strain and strain rate the thicker they are. Likewise, the absolute
expansion increases in the same manner, but the expansion rate decreases. For example, the
reversible strain was changed from about 47% to 25% with increased film thickness (1 to 10
micrometre). The reversible expansion changed from 0.87 micrometre to 3.47 micrometre,
when the thickness was changed from 1 to 10 micrometre. [45]
2. Method for yarns

2.1 Schematics of method for yarns

![Schematics of method for yarns](image)

Figure 5: The yarn gets soaked in an oxidant solution followed by VPP and ECP performed in succession.

The core material is first made to soak up the oxidant solution. This is followed by VPP, which ends with the material acquiring a PEDOT coating and finally after the ECP the sample gets a thicker PPy coating. The changes the material takes can be seen in figure 5.

2.2 VPP

This step is only necessary if the substrate used is not conductive. VPP stands for vapour phase polymerisation and the setup consists of a hot plate with a glass dome on top, which makes a chamber. Within the chamber, the chosen yarn substrate is placed. The yarns are coated with a ratio of 0.15 PEGM, 0.15 PEGDM and 0.7 Fe(TOS)$_3$-BUOH, which make up an oxidant solution, before being placed in the chamber. Also placed within the chamber are two or three drops of the monomer EDOT. The hotplate has been heated up beforehand and the air in the chamber is empted with a pump and the pressure is decreased to approximately 0.01 atm, which results in the saturation of EDOT in the whole chamber. Once the EDOT is saturated it reacts with the oxidant solution on the yarn substrate and consequently a thin
layer, or coating, of the polymer PEDOT is deposited onto the yarn substrate. The VPP duration was kept constant at 45 minutes and the temperature of the hotplate was kept constant at 40°C for each deposition to limit the number of varying factors. Figure 6 shows the actual setup for the VPP and the pump used.

![Figure 6: VPP consists of a glass dome and a hotplate, within this chamber the samples are put. To the right is the pump used to create the vacuum.](image)

### 2.3 ECP

Once the sample has been prepared by VPP or if it was already conductive, it is then polymerised by electrochemical polymerisation, ECP. An electrolyte consisting of 0.1 M LiTFSI in 100 ml propylene carbonate and the addition of 0.1 M of the monomer Py. These are the components in the electrochemical cell. The aforementioned electrolyte/Py solution is placed within a beaker, sized 100 ml. This beaker is then connected to a 3-electrode system, with working electrode, counter electrode and reference electrode (Ag/Ag+). The counter electrode is connected to a piece of steel, which is submerged and the working electrode is connected to the yarn substrate. The yarn substrate is taped at one side with copper tape for greater contact surface with the working electrode. The yarn substrate, except for the copper tape, is also submerged into the electrolyte/Py solution, as is the reference electrode. To reduce the deposition speed of the ECP process, the cell is put into a freezer, which is set to -20°C and this is constant for each experiment. The setup and the electrodes are connected to a potentiostat, which in turn is connected to a computer. The settings of the potentiostat are set in the software. The complete setup can be seen in figures 7 and 8.
2.3.1 Software settings

The software used is Iviumsoft and in the software chronopotentiometry option is used, which is a subcategory to transients, although only one level is used. Chronopotentiometry sets a chosen current constant throughout the process, whereas the voltage changes according
to the situation and is recorded. The current is chosen according to the condition 0.1 mA/cm², which was desired and therefore it depends on the diameter and the length of the sample. However, since all of the yarn samples are of more or less the same size, the current is estimated to 0.03 mA for all the yarn samples. The option of pre-treatment is also included with the same current and a duration of ten seconds in order to see that nothing goes wrong.

2.4 Electro mechanical characterisation

The characterisation is done in order to measure how well the samples work. The sample yarn is taped with copper tape on both ends for conducting purposes and to make it easier to attach. One end is connected to the working electrode via a metal plate. The reference electrode and counter electrode are short circuit-connected to a gold sheet. The gold sheet and the working electrode end of the sample are then submerged in an electrolyte consisting of 0.1 M LiTFSI in 100 ml propylene carbonate in a cell. The connections for both the working electrode and the counter/reference electrode are not touching the liquid directly, but via the metal plate and the gold sheet respectively. The other copper end of the sample is attached to a lever system, which can measure force and length displacement, the latter is used to calculate the strain. The electrodes as well as the lever system are connected to a potentiostat. In figure 9 the working electrode is connected by the metal plate that pierces the lid at the bottom of the setup, the counter/reference electrode is connected to the gold sheet at the left side and the lever system is black box like structure above. The lever system is the series 300B Model from Cambridge technology, Inc.
Figure 9: The characterisation is performed in homebuilt cell while the sample is attached with a hook to a lever system. The right image shows the main part of the lever system.

2.4.1 Measurement

The measurement is performed by cycling between two potentials with the chronopotentiometry method. In these experiments -1 V and 0.5 V were chosen as the alternating voltages using a square wave pattern. Half the period of square wave was most of the time set to 200 seconds and for a few selected experiments 800 seconds. For the measurement results to be deemed satisfactory at least two whole cycles had to be completed without disturbance. Figure 10 shows the software Iviumsoft, while a measurement is being performed. All the options can be seen on the left hand side of the image, whereas the right hand side shows the output from the lever system and the current passing through the sample.
Figure 10: The bottom graph is the current measured in the measurement setup and the top graph is the response from the lever system.

2.4.2 Data processing

Figure 11 is an example of what the resulting graphs look like from a measurement after the data has been processed in Excel. The difference between the maximum and the minimum value for each cycle is what is of interest. The data is exported from Iviumsoft and put into an excel file, where the data is arranged and processed into graphs and the values for force and strain. The first step is to recalculate the incoming data into units that can be used. The data is always received in the unit volt. For force this value should, according to the lever system manual be divided by 0.2 to get the unit g and then multiplied with 9.81 to get the unit mN. Similarly, to get strain divide by 2 to get the unit mm and then this acquired length change is divided by the active length and multiplied by a hundred to get the strain percentage. The active length is the length of the sample that is submerged in the electrolyte and which therefore contributes to the change in length, by influx or outflux of the mobile cations and resulting in volume change.

The graphs tend to have creep, which is the increasing value on the y-axis even though the cycle is completed and should have returned to the same baseline. In order to handle the results despite the creep, the mean value of the neighbouring minima was compared to the maximum value in between those very same minima values. The value which is the
difference between the minima mean and the maximum is calculated in the same manner for both force and strain. This is done for each successful cycle found in the graphs and the mean of all these values is calculated to get a value that represents the whole measurement. Sometimes there would be a “jump” in the measurement, leaving the current cycle unusable and deemed an unsuccessful cycle. A “jump” causes, for unknown reasons, the next data point to be shifted greatly on the y-axis.

![Figure 11: A typical curve acquired from either the force or strain measurement while cycling the potentials between positive and negative values (each cycle is 200 seconds).](image)

2.5 Researched parameters

The research is carried out by only varying one parameter at the time. This makes it possible to distinguish the parameters’ effects on the results. Therefore, the changing of different parameters is divided into researched parameters. That is, for each parameter that is studied the effect of the changing of a single parameter is examined. All the yarns had the same conditions. The same conditions mean that the samples had the same size, the VPP was 45 minutes, the ECP was 15000 seconds and that the electrochemical characterisation measurement was only performed in 200 seconds cycles. Except for certain yarns which also had the force measurement for 800 seconds cycles. In addition, the settings in the potentiostat software were the same.
2.5.1 Effects of polymerisation time

The first researched parameter was the polymerisation time of the ECP. The same material (single multifilament Tencell (Lyocell) Ne 24/1 yarn) was used for four different polymerisation times: 5000, 10000, 15000 and 20000 seconds, resulting in four samples. The polymer coating thickness increases proportionally with the length of polymerisation time and therefore different results are expected from the measurements of the different samples.

2.5.2 Effects of core materials

The second researched parameter was to look at the effects of having different core materials and to compare the results. The following materials were all put through the same preparation conditions and tests: Viskos Ne 60/2, Polyamide dtex 78/46/2, Polyamide-Lycra dtex 78/78 and Viskos-Lycra(44) Nm 70/1. In addition to the Lyocell Ne 24/1 sample, which was also used in the researched parameter of polymerisation time. These make up the five materials for the comparison.

Additionally, three different conducting metal yarns were examined: single multifilament copper yarn, single multifilament silver yarn (Shieldex) and double twined multifilament stainless steel yarn (Bekinox). All three conducting yarns were set to have polymerised samples for 10000 and 20000 seconds of ECP and all three did not undergo the VPP, since they were already conducting. The copper yarn and the silver yarn polymerisation were repeated two and three times respectively to make sure the results were correct.
3. Method for textiles

3.1 Schematics of method for textiles

![Figure 12: The textile is first soaked with the oxidant solution, then VPP and ECP coat the material with polymer. The core material in the figure is Lyocell weft tricot, Ne 8/2 CO.]

The textiles go through the same processes as the yarns do, see figure 12. This means first soaking in the oxidant solution, then VPP and thereafter ECP. Because of the larger size of the textiles their synthesis parameters needed to be adapted sometimes. The electrochemical characterisation also works in the same way and with the same parameters. In addition, the same instruments, software and setup are used for textiles as for the yarns.

3.1.1 Differences between yarn and textile sample preparation

There are a few things that differ when polymerising a textile and a yarn. When applying the oxidant solution, because of its size and shape, the textile cannot always be submerged into the solution. Instead a pipette is used and the solution is dripped all over the textile substrate, until the substrate has been evenly covered. During the VPP a textile needs to be flipped.
halfway through the polymerisation because of the way it is setup, see figure 13. This is to make sure the coating is polymerised as equally as possible on both sides, since the EDOT is placed inside a beaker which has the textile suspended on top of it and when it evaporates it reacts with the bottom side of the textile more than the top side. Furthermore, it proved that performing the VPP for the same amount of time as the yarns (45 minutes) was insufficient, since a larger amount of EDOT was necessary for the bigger textile sample and the short time frame was not enough to use up all the EDOT. In addition, it was visually possible to draw this conclusion, since the colour desired for a complete VPP sample was not achieved during the 45 minutes. For the ECP, the same conditions were used, namely 0.1 mA/cm². This does however mean that a tenfold or even twentyfold increase in current is likely, compared to the yarns because of their greater surface area.

![Figure 13: Preparation for VPP. Lyocell weft tricot, Ne 8/2 CO soaked in oxidant solution, suspended over a beaker, containing the EDOT monomer.](image)

3.2 Researched parameters

The researched parameters are essentially various materials in different patterns (textiles). What is of interest is the comparison with the results from the yarns. In other words what kind of results can one achieve if one has a specific pattern, made by knitting or weaving, but with the same core material as one of the yarns.
3.2.1 Lyocell Weft Tricot knit

The Lyocell weft tricot sample was prepared by pipetting the substrate with the oxidant solution and then the VPP was performed in two stages. The first sample batch was synthesised for two hours with a break in the middle for flipping the sample upside down. This was followed by a second sample batch, which had a synthesis time of three hours, this also included a break after 90 minutes to flip the textile. The ECP was also carried out in two steps. First, it was performed outside the freezer, at room temperature for a duration of 10000 seconds and with a 3-electrode system. Since the polymerisation happens faster at higher temperatures and the sample was large, it was deemed best to polymerise at room temperature, also this sample was not up for comparison with any other sample and therefore did not need to be prepared the same way. The sample was then characterised and then additionally polymerised for the same amount of time (10000 seconds) with the same setup and yet again characterised. In short, the electrochemical characterisation was performed twice, once for the 10000 seconds’ sample and once more for the 20000 seconds’ sample.

3.2.2 Lyocell Ne 24/1 Pattern 2:1 20x20

The Lyocell Ne 24/1 pattern sample was prepared by pipetting the substrate with the oxidant solution and then the VPP was performed for two times two hours, with the sample being turned over after two hours. Figure 14 shows what the material looks like after VPP with a small and a large stretch. Then the sample went through the ECP for 20000 seconds in the freezer with a 3-electrode system.
3.2.3 Polyamide-Lycra dtex 78/78 Pattern 2:1

The polyamide-lycra dtex 78/78 pattern sample was prepared by dipping the substrate into the oxidant solution, this was possible because the fabric was cut smaller than the Lyocell Ne 24/1 pattern and fitted into the container. This allowed for absorbing more oxidant solution. Then, the VPP was performed for two times two hours, with a flipping of the sample after the first two hours for equal exposure to the EDOT for both sides. Then the sample went through the ECP for 20000 seconds in the freezer using the 3-electrode system.

3.3 Chemical list

The following is a list of the chemicals that were used in both of the methods’ sections (yarns and textiles). Included, if possible, is the whole name, name of the company, CAS-number, chemical formula and the molecular weight.

PC: Propylene carbonate 99%, Sigma-Aldrich CAS:108-32-7, C₄H₆O₃, Molecular weight: 102,02 g/mol
LiTFSI: Bis(trifluoromethane) sulfonimide lithium salt, Aldrich CAS:90076-65-6, C₂FeLiNO₄S₂, Molecular weight: 287,09 g/mol
EDOT: 3,4-Ethylendioxythiophene 97%, Sigma-Aldrich CAS:126213-50-1, C₆H₆O₂S, Molecular weight: 142,18 g/mol
Pyrrole: Sigma-Aldrich CAS:109-97-7, C₄H₅N, Molecular weight: 67,09 g/mol
PEGDM: Poly(ethylene glycol) dimethacrylate, Aldrich CAS:25852-47-5, C₃H₇C(O)(OCH₂CH₂)ₙOC(O)C₃H₅
PEGM: Poly(ethylene glycol) methyl ether methacrylate, Aldrich CAS:26915-72-0, H₂C=CCH₂CO₂(CH₂CH₂O)ₙCH₃
Fe(TOS)₃-BUOH: Clevios C-B 55 V2, Heraeus Deutschland GmbH & Co.
4. Results

The graphs resulting from the tests have similar patterns as figure 11 for all force and strain measurements, as previously explained. For most researched parameters the average values that have been calculated, also previously explained, are put into comparative graphs.

4.1 The effect of the polymerisation time

The four different polymerisation times used for comparison were 5000, 10000, 15000 and 20000 seconds. The core material, Lyocell Ne 24/1, and all other variables were kept constant. The resulting values are shown in table 1 and the resulting graphs are shown in figure 15 and 16.

<table>
<thead>
<tr>
<th>Polymerisation Time (s)</th>
<th>ECP Force (mN)</th>
<th>Strain %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>0.29</td>
<td>0.0090</td>
</tr>
<tr>
<td>10000</td>
<td>0.32</td>
<td>0.0052</td>
</tr>
<tr>
<td>15000</td>
<td>0.44</td>
<td>0.0026</td>
</tr>
<tr>
<td>20000</td>
<td>0.70</td>
<td>0.0051</td>
</tr>
</tbody>
</table>

*Table 1: Force and strain values for polymerisation time*

*Figure 15: Force measurement of single multifilament Lyocell Ne 24/1 yarn for four different ECP polymerisation times.*
4.2 The effect of the core material

4.2.1 Non-conducting core materials

In this researched parameter, the core materials were varied from sample to sample, but all the other variables were kept constant. The resulting values are shown in table 2 and resulting graphs for force and strain are shown in figure 17 and 18. Polyamide-lycra was supposed to be one of the yarn substrates to be tested, but it tore with even the slightest pulling and the result of this can be seen in figure 19: fractured pieces of PPy-coated polyamide-lycra. Therefore, no measurement could be performed on the polyamide-lycra sample.

<table>
<thead>
<tr>
<th>Material</th>
<th>Force (mN)</th>
<th>Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyocell</td>
<td>0.44</td>
<td>0.0026</td>
</tr>
<tr>
<td>Viskos</td>
<td>0.40</td>
<td>0.0027</td>
</tr>
<tr>
<td>Viskos-Lycra</td>
<td>1.94</td>
<td>0.024</td>
</tr>
<tr>
<td>Polyamide</td>
<td>0.20</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

*Table 2: Force and strain values for core materials*
Figure 17: Force measurement for Lyocell, Viskos, Viskos-Lycra and Polyamide.

Figure 18: Strain measurement for Lyocell, Viskos, Viskos-Lycra and Polyamide.
4.2.2 Conducting core materials

Three conducting yarns were tested, stainless steel, copper and silver yarns. The stainless steel yarn (Bekinox) resulted in a good coating and the resulting values are shown in table 3 and resulting graphs are shown in figures 20-22. The force measurements include both 200 and 800 seconds cycling, while the strain measurement was only cycled for 200 seconds, a decision which was based on the lack of strain in the measurement.

<table>
<thead>
<tr>
<th>Stainless steel yarn</th>
<th>Cycling 200 seconds</th>
<th>Cycling 800 seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000 seconds ECP</td>
<td>1.13 mN</td>
<td>0.18 mN</td>
</tr>
<tr>
<td>20000 seconds ECP</td>
<td>1.31 mN</td>
<td>0.70 mN</td>
</tr>
</tbody>
</table>

*Table 3: Force values for stainless steel yarn*

Images of the polymerised copper yarn and silver yarn (Shieldex) are shown in figure 23. As can be seen they had a poor or non-existent deposition of conducting polymer, and therefore they were not characterised at all. The images’ brightness levels have been increased to make it easier to discern the lack of polymer on the sample.
Figure 20: Force measurement of stainless steel (Bekinox) for ECP 10000 and 20000 seconds in both 200 and 800 seconds cycles.

Figure 21: Strain measurement for stainless steel (Bekinox) ECP10000.
4.3 The effect of the textile patterns

4.3.1 Lyocell Weft Tricot Knit

The resulting force measurement graphs for 200 seconds cycling can be seen in figure 24 and 25. The two figures are for the two different electrochemical polymerisation times, 10000 and
20000 seconds of the Lyocell weft tricot material. No strain measurement was performed due to the lack of noticeable actuation (i.e. no periodic variations can be discerned) in the force measurement.

4.3.2 Lyocell Ne 24/1 Pattern 2:1 20x20

Like the previous samples, the Lyocell Ne 24/1 pattern 2:1 20x20 was measured for force and strain. For both the force and strain measurement, 200 and 800 seconds cycles were used. The resulting values are shown in table 4 and the resulting graphs of both cycles are combined and presented in figures 26 and 27.
<table>
<thead>
<tr>
<th>Lyocell textile</th>
<th>Cycling 200 seconds</th>
<th>Cycling 800 seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>0.50 mN</td>
<td>0.91 mN</td>
</tr>
<tr>
<td>Strain</td>
<td>0.040 %</td>
<td>0.070 %</td>
</tr>
</tbody>
</table>

*Table 4: Force values for lyocell textile*

**Figure 26: Lyocell Ne 24/1 pattern ECP 20000, force measurement for 200 and 800 seconds cycle.**
4.3.3 Polyamide-Lycra dtex 78/78 Pattern 2:1

Polyamide-Lycra dtex 78/78 pattern 2:1 was measured for force and for strain, like previous samples. For both the force and strain measurement, 200 and 800 seconds cycles were used. The resulting values are shown in table 5 and the resulting graphs of both cycles are combined and presented in figures 28 and 29.

<table>
<thead>
<tr>
<th>Polyamide-Lycra textile</th>
<th>Cycling 200 seconds</th>
<th>Cycling 800 seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>0.25 mN</td>
<td>0.51 mN</td>
</tr>
<tr>
<td>Strain</td>
<td>0.0015 %</td>
<td>0.014 %</td>
</tr>
</tbody>
</table>

*Table 5: Force values for polyamide-lycra textile*
Figure 28: Polyamide-Lycra dtex 78/78 pattern ECP 20000, force measurement for 200 and 800 seconds cycle.

Figure 29: Polyamide-Lycra dtex 78/78 pattern ECP 20000, strain measurement for 200 and 800 seconds cycle.
5. Discussion

5.1 Polymerisation times

Having used the same material Lyocell Ne 24/1 yarn and kept all the other variables constant for the first researched variable, the polymerisation time, it is easy to see that an increase in polymerisation time leads to an increase in force, according to the data (0.29 mN → 0.70 mN). This is likely due to an increased amount of polymer on the substrate, which results in a larger cross sectional area and thus larger force, since the force (strain x scale) scales with area. Effectively giving more volume change and in addition more force. The strain measurement on the other hand is not straightforwardly explained. There was a clear decrease in strain with increased polymerisation time, if one only takes into account the three lower polymerisation times (0.0090 % → 0.0026 %). However, the fourth and longest polymerisation time was on par with the second shortest in the strain measurement (0.0052 % and 0.0051 %). This can be because of various reasons. The third polymerisation time could have yielded poorer results than what was possible or perhaps the longest time measurement over performed. Since it is likely that an increase in polymer thickness on the substrate makes it more rigid and stiffer, it is easy to assume that the strain will decrease with increased amount of polymer. However, it might be the case that having a large enough amount of polymer actually changes the total stiffness and that once again the strain increases. The numbers from the strain measurements were very small and every small change might have a large impact on the result. For example, the exact active length of the sample, which is needed for the calculation of strain, is not easy to obtain since the sample soaks up the electrolyte and therefore some parts of the sample have access to ions even if those parts are not submerged. More research would be needed to more in detail understand this matter. However, 15000 seconds was still the time decided to be kept constant for the next researched variable, the non-conducting core materials.

5.2 Non-conducting core materials

The experiments of the different core materials used as the substrate showed that Lyocell Ne 24/1 and Viskos Ne 60/2 had quite similar results both for the force and for the strain (0.44 mN and 0.40 mN, 0.0026 % and 0.0027 %). Polyamide dtex 78/46/2 proved to give both a lower force and strain output, with about half the force output (0.20 mN) and with only
slightly more than half for the strain output (0.0018 %). Viskos-Lycra(44) Nm 70/1 had, by far, the best results (1.94 mN and 0.024 %). The force was approximately five times higher than Lyocell and Viskos and the strain was close to the ten times larger compared to the same materials. The Polyamide, being a very stretchable material, lost much of this stretch when it was polymerised and got stiffer. This is likely the reason it performed worse than the other materials. Viskos and Lyocell were both more rigid as core materials and they also performed with similar values. Viskos-Lycra had both the rigidity of Viskos and the stretchiness of Lycra and performed very well in the measurements. However, when one considers that Viskos and Viskos-Lycra had such different values for both force and strain, it is not unlikely that there might be other factors that played a part in achieving such a huge difference. Polyamide-Lycra dtex 78/78 was not possible to measure at all, because of its fragility when stretching it. However, since the Polyamide-Lycra pattern was possible to measure, it is possible that the preparation of the sample might have been poor and therefore Polyamide-Lycra should not be overlooked in the future because of the failed results of the yarn sample in the experiments in this thesis.

5.3 Conducting core materials

The double twisted stainless steel yarn (Bekinox), with ECP 10000 gave the second highest force output (1.13 mN and 1.31 mN) out of any the samples that were measured. The ECP 20000 gave results closer to other samples tested (0.18 mN and 0.70 mN). One must keep in mind however that the stainless steel had two yarns twisted and also therefore approximately twice the surface area, which would thus give a higher output. The strain measurement gave no such results and this is likely due to its rigidity, both in the core material (metal) and in addition the added conducting polymer coating. The fact that VPP was not necessary, since it was already conductive thus simplifying the preparation and the fact that it had such a high force output makes the use of stainless steel yarn a positive result. However, the lack of strain is negative.

The poor polymerisation of PPy on the copper and silver yarns (Shieldex) showed that these are not good candidates as substrates. The copper yarn had some coating but it was very inhomogeneous and the silver yarn had no deposition at all. It is probable that the electrochemical polymerisation caused these materials to have some sort of reaction that was unfavourable in this case and therefore could not acquire a polymer coating partly or at all.
5.4 Lyocell Weft Tricot Knit

Lyocell weft tricot knit samples had no visible force output and therefore strain measurements were not even attempted. Both ECP 10000 and ECP 20000 samples were made and both of these had similar data from the force measurement showing no visible force output. It is most likely that the textile construction was not a good design for use as an actuator or perhaps that even 20000 seconds deposition time was not long enough to get a large enough conductive polymer coating. The textile’s fibre diameter was quite a lot larger than all the other yarns and textiles that were tested and that might simply be the reason for it not having any force output.

5.5 The effect of the textile constructions

The Lyocell Ne 24/1 pattern 2:1 20x20 textile when compared to the Lyocell Ne 24/1 yarn for ECP 20000 has about ten times larger strain for 200 seconds cycling (0.040 % vs 0.0051 %). The textile’s strain increases to almost the double for the 800 seconds cycle (0.070 %). There are however no 800 seconds measurement for the yarn, neither for force nor strain. The force on the other hand is slightly lower for the textile in 200 seconds cycling (0.50 mN), when compared to the yarn (0.70 mN), even though the force gets higher than the yarn with 800 seconds cycling (0.91 mN). A similar increase might have happened to the yarn if cycled for the same time. Interestingly, the textile increases to almost the double for both strain and force, meaning that it is true that the potential force and strain is a lot higher than what the 200 seconds cycling showed. This suggests that the yarns perhaps reach their potential a lot faster and 200 seconds is enough, whereas the textiles seem to need more time. It could also mean that the they do indeed have similar force output, but the strain is amplified with this Lyocell textile when it is compared to a Lyocell single yarn.

The comparison between the two textiles Lyocell Ne 24/1 pattern 2:1 20x20 and Polyamide-Lycra dtex 78/78 pattern 2:1 is a lot clearer. The Polyamide-Lycra has lower force and strain for both 200 (0.25 mN and 0.0015 %) and 800 seconds cycling (0.51 mN and 0.014 %), this implies that Lyocell is the better core material. However, the strain that Polyamide-Lycra achieves for the 800 seconds is one of the highest of the evaluated yarn and textile samples.

Finally, the comparison between the textile Polyamide-Lycra dtex 78/78 pattern 2:1 and Polyamide-Lycra dtex 78/78 yarn is not easily discussed because of the lack of data for the
yarn. The only thing that can be said, is that it might be possible that the yarn can be successfully polymerised and that the textile is definitely possible.
6. Conclusion

Regarding the researched parameter of polymerisation time, it can be concluded that the force increases with increased polymerisation time i.e. thicker polymer coating. The strain decreases when increasing the polymerisation time, at least from ECP 5000 up to ECP 15000, where after it increased again for ECP 20000.

The researched parameter non-conducting core materials made it evident that Viskos and Lyocell were comparable and Polyamide had poorer results than that. However, Viskos-Lycra was by far the best material in this comparison and had the highest force out of any sample, yarn or textile, in addition it had the second highest strain (0.024 %) out of any sample for 200 seconds cycling, only outperformed by the Lyocell textile (0.040 %).

The results from the conducting core materials showed that silver and copper yarns are not suitable substrates for textile actuators since they did not achieve good polymer coating, even after several attempts. The double twined stainless steel had the second best force output, only surpassed by the Viskos-Lycra, and that was with only 10000 seconds polymerisation time, but the force went down when the polymerisation time doubled.

The Lyocell weft tricot knit should be deemed not suitable, at least with the conditions that were tried here. The textile’s fibre diameter was simply too big for the limited amount of polymer deposited on it, resulting in no measurable force output.

Comparing the textiles Lyocell Ne 24/1 and Polyamide-Lycra dtex 78/78 proved that the two had similar looking comparative graphs, except for the fact that Lyocell had higher magnitude values for every comparison point, meaning force and strain for both 200 and 800 seconds cycles.

Polyamide-Lycra yarns were easily broken, however, functional textile actuators could be made by woven fabrics of the same material. Therefore, it is not possible to conclude that an actuator made of the Polyamide-Lycra yarn could not work.
7. References

10. Electric: https://www.youtube.com/watch?v=KfjOMfC9Miw and https://www.youtube.com/watch?v=tYgHdxmCcAl 2016-01-20


42. NEMO: https://www.youtube.com/watch?v=1FyF6Bac1fo 2016-02-17

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