Wearable Biopotential Technologies:

An Exploration of Textile Based Biopotential Sensing Electrodes for an ECG Wearable Device

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Abstract

Technology for the long-term monitoring of heart conditions in moving everyday environments has yet to be developed to a clinical standard for consumer users. This leaves a large gap in the ability to effectively diagnose certain heart conditions that present infrequently and outside of clinical settings. Increasingly, wearable technologies have developed to a point where they can begin to address this need. This research concerns the designs and fabrication of a wearable electrocardiogram (ECG) device using electronic textiles for long term monitoring of heart conditions.

The wearable device uses different configurations of e-textiles to serve as both electrodes for signal monitoring and conductive traces and pads for interconnecting hard and soft components. These materials were used for their ability to be integrated into clothing and offer dry sensing, in lieu of the gel electrodes used in hospital settings. Additionally, processes like vacuum forming, injection moulding and overmolding were used in conjunction with these materials to produce novel forms and offer new ways to integrate materials. This research involves a multifaceted approach to design that is framed by a larger narrative around wearable design considerations and the interdisciplinary challenges that relate to them. Practice is grounded by a research through design approach, a form of research also known as action research, that offers an appropriate methodology for practical and collaborative elements of the research.

While the practice did not produce a fully functional wearable ECG system, it did generate several promising functional component prototypes that could be further explored and integrated. These included innovations like embossed e-textile electrodes with moulded silicone gripping elements, and machine knitted belts with integrated soft circuits and overmolded silicone/e-textiles electrodes. These innovations address several challenges and considerations elaborated in the research.

The overarching interdisciplinary discussion considers both group and individual phases of the research. It suggests that, in this example and more generally, the tension between wearability and technical efficacy remains a stumbling point in the research and design space. Considerations around how wearable projects could be planned and actioned more effectively are offered in the form of explicit design processes guides that account for both the scientific

method and creative process as it relates to wearables. Suggestions are made on how these models might develop further to account for the level at which e-textiles are being integrated.

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

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Positioning Statement

This research was completed in fulfilment of a Master of Creative Technologies Degree. The research was funded in part by the Medtech CoRE Smart Biopotential Sensors project and guided in the first instance by a team project completed with the Auckland Institute of Biomedical Technologies (IBTech). Despite the team portions of the project being contracted, considerable elements of the extended master's research project were conducted independently of IBTech for no profit. Locating my practice relative to the larger team effort is helpful in understanding the nature of the research and difference in approach.

My approach as a creative technology designer is grounded in hands-on making and digital fabrication, with a focus on end users and collaboration. This approach contrasted with the highly specialized nature of the other members of the IBTech project team. My research, while part of an engineering project, was guided predominantly by creative design processes rather than scientific processes. It is important to clarify this, as the technical nature of IBTech group research and medical wearables often requires discussion around engineering and specialized fields. Due to this difference in approach, substantial effort was made to become more aware of the challenges and considerations associated with the various disciplines of the people involved in the team.

My practice as a creative technology designer has, for the last several years, focussed on developing wearable technologies and hard-to-soft interfaces. Given my approach and emphasis on creative process, testing was handled by the engineering team and findings provided as guided feedback. There is an obvious benefit in having access to specialized knowledge in the field of medical wearable development and utilizing this was a focus of the IBTech group phase of the project. However, developing the wearable project beyond the group stage allowed me to become more cognizant of the differences in approach, and better focus my own skillset.

I continued to amend designs beyond the sponsored phases of the project. This meant greater freedom of choice and being able to pursue more integrated designs, but being limited by my technical knowledge and assumptions around hardware. While I embraced reading widely and making connections between different disciplines and methods, in practice this individualised approach is liable to running into mistakes, easily predicted by a specialized practitioner or team. However, a broader disciplinary approach can be helpful in a wearable design space, as there are many parallel developments that are interrelated. Designing in the wearable space can often require making broad connections between concepts or technologies and leveraging advantages from a variety of disciplines and practices. Locating and developing these connections is the aim and main outcome of this research.

This research was conducted from April 2019 to February 2021. It was subject to significant disruption through the entirety of 2020 and early 2021 due to challenges in access during the various COVID-19 lockdowns. This limited access to fabrication tools and facilities in this time, and uncertainty around timeframes made planning difficult. This had a significant impact on the scope of the individual practice.

Introduction

For over a hundred years clinical environments have been the predominant setting for reliable diagnosis of heart conditions using the electrocardiogram (ECG) (AlGhatrif & Lindsay, 2012, p. 3). However, diagnosing heart conditions in a moving, non-clinical environment still proves challenging (Kennedy, 2013, p. 131). Recently wearable devices like smart watches have been able to acquire heart signals with an increasing degree of accuracy, to the point of being considered reliable for diagnosis of arrhythmias (Isakadze & Martin, 2020, p. 5). Arrhythmias are a condition where the heart beats in an irregular fashion (Nattel, 2002, p. 1). However even the latest devices are still only able to accurately detect abnormalities while the arm is in a rested position (Koshy et al., 2018, p. 126). There is still an unresolved diagnostic space for at-home, daily use, ambulatory/moving ECG diagnosis.

Several alternative approaches to wearable ECG diagnostics have been explored using electronic textiles (e-textiles) with some success (Paradiso & Pacelli, 2011, p. 1-3). Despite considerable advances in this area, wearables using this technology have yet to see significant consumer success (Agcayazi et al., 2018, p. 1). There are a number of reasons for this, many of which are discussed in a growing field of research and literature around wearable design. The cutting-edge nature of much of the research in textile engineering and materials development means advancement in the design space is usually secondary to technical concerns (Motti & Caine, 2014, p. 2). Despite this, a growth in user centred design has helped guide the wearable design process, and literature and research has developed around designing for both the user and body (Ferraro & Ugur, 2011).

In this research, a wearable ECG using e-textiles was explored with the goal of detecting atrial fibrillation (AF) in ambulatory, everyday use. AF is a type of heart condition that can go undiagnosed due to symptoms presenting infrequently, and often outside the necessary clinical setting (Nattel, 2002, p. 1). The proprietary technology used in this research, created by IBTech, makes it possible to acquire ECG signals and filter out undesirable signal noise related to ambulatory monitoring.

The practice and concepts described in this research involved two distinct periods of development: the first and longest was the ECG development that occurred as part of the sponsored IBTech group project, and the second was amendments made personally after the group project.

Of Auckland Institute of Biomedical Technologies and Project Goals

The innovative circuitry at the heart of this research was created by the Auckland Institute of Biomedical Technologies (IBTech): an organisation focused on advancing health technologies with smart sensing. The novel circuit allows for reducing or cancelling of motion artefact, a type of electrical interference created by movement of the body or skin when acquiring ECG. It was created with the intention of being able to diagnose atrial fibrillation (AF), a potentially fatal type of heart condition (Nattel, 2002, p. 1). Further explanation of atrial fibrillation is presented in Section 1.4.1 of the literature review (pages 22, 23).

IBTech's proprietary circuit is aimed at competing with gold standard clinical ECG diagnostic systems for walking diagnosis. Acquiring a clinical level of signal fidelity during ambulatory monitoring from 2- or 3-point ECG systems, as opposed to usual 12 lead ECG systems (Goldberger, 1999, p. 21), was the primary electrical engineering challenge of the IBTech project. However, this engineering problem sat outside the scope of this master's research as it was the responsibility of the engineers in the team.

The research presented in this exegesis, as it relates to the IBTech project, was concerned with the design and implementation of the actual wearable system; the creation of a garment, the integration of e-textiles for sensing and the interconnections that integrate hard and soft components. To achieve this, a working relationship was established with the engineering group from IBTech in the form of weekly meetings, testing technical/electrical components and providing feedback. Over the course of the project with the team, designs often required compromise between technical efficacy and functionality that would prove difficult to negotiate without impacting on wearability.

Design for IBTech Wearable and Beyond

Wearable technology development already presents several difficult and varied design challenges (Robinette & Natsume, 2019). Given the IBTech project focus was a healthcare wearable targeting the diagnosis of atrial fibrillation, technical efficacy was critical. However, if a design ignores user concerns such as comfort and wearability, which have been shown to be critical to the adoption of wearables, a challenging tension is created (Francés-Morcillo et al., 2018). Wearable design research has grown to encompass a number of valuable considerations for achieving the goals of this project. Despite this the developmental stage of the ECG wearable project made these considerations difficult at times, as there were several technical hurdles that needed to be overcome via frequent changes to hardware. Wearable design ideals were also difficult to communicate as I was not in the position to inform how others approached their work.

As the IBTech group project aimed at implementing a novel ECG technology in a wearable, challenges arose as the project developed. A key challenge for ambulatory ECG monitoring identified by the IBTech team early in the project was motion artefact. Motion artefact is when movement of the body or skin causes electrical interference in the ECG signal. This can be affected by many different forms of motion, from movement of the person wearing the device to movement of people or objects near the wearer. Additionally, the movement and pressure of the electrode itself was identified as an issue in reducing motion artefact.

Questions were formed around addressing these specific aspects of motion artefact and the effect they have on the electrode; How could the movement of skin underneath the electrode be reduced? How could electrode slippage, movement of the electrode from its intended position, be addressed? In addition to the mechanical and electrical challenges of motion artefact presented by the IBTech research group, there are also specific questions and challenges presented in using e-textiles for sensing and transmitting ECG. Amongst the main challenges in using e-textile for dry sensing, acquiring an ECG without an electrolyte gel (described in Section 1.4.2, p. 33), is how to maintain a consistent level of sweat at the site of the e-textile electrode. Finding the appropriate material for the e-textile electrode was also its own challenge.

Additionally e-textiles and wearable hardware present several challenges in how they are designed and created for the body. Primary among these are the integration of hard and soft components, and how components are interconnected in medical wearables. Wearability issues are often specific to the nature of the device and how and where it is attached to the body, but several considerations are presented in the literature review for addressing these difficulties (Chapter 1).

The wearability and comfort of the device were also part of a focus on wearable technology design that extended beyond the scope of the IBTech group phase. Research done on wearable design was independent of the IBTech group project but was critical in informing how designs were approached and how questions were framed around the end-user. While some of these challenges are framed in the literature and methodology, many are presented in the practice as that is where they arose.

Given the separation between the team project and later individual efforts, the documentation of practice in the research is presented first in terms of practice as it relates to the team project, then as it relates to individual practice. The initial team component is broken down into sections categorized by the major components involved in the design: Enclosures, Electrodes, Belts and Interconnects. These are explained further in each section in terms of major iterations. This is to delineate the complex and interwoven development of the project, and to present design and reflection in a cohesive way. The following literature review frames and locates this practice, discussing the development of the field of wearable technology and the specific technical challenges in ambulatory ECG and using e-textiles.

Chapter 1: Literature Review

In this literature review several challenges in wearables development are explored. Context is provided for the development of the field of wearable technology and the different types of wearables, the interdisciplinary challenges in creating wearables and the explicit consideration around designing wearables. While this locates and contextualizes the research in this exegesis, these aspects were not a focus of the IBTech research team.

1.1: Wearable Technologies as a Field

1.1.1: Overview

Wearable Technology can be broadly defined as any technology that can be worn on the body (Ferraro & Ugur, 2011). These devices can be either passive or active and take a variety of forms, such as clothing or accessories. Although the recent success of wearable devices like smart watches have begun to inform the consumer market for wearables (Jung et al., 2016, p. 1-2), the field has a rich and broad history of development predating current trends. (Guler et al., 2016, p. 1-7)

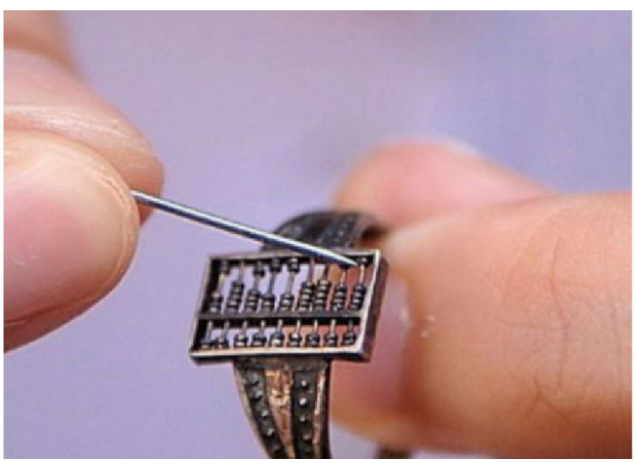

Figure 2

17th Century Qing Dynasty Abacus Ring.

Figure 2

Oura health ring.

Wearable technology has been innovated in a number of ways across different societies. The 17th century Qing Dynasty in China made rings embedded with an abacus to help traders make quick calculations (Guler et al., 2016, p. 2), (see Figure 1) and now companies are designing rings that can sense and communicate biometric information to the wearer (Kwon et al., 2019, p. 1-2) (see Figure 2). This example mirrors a trend of growth in wearables that follows the miniaturization of processing components and the introduction of new, smaller technologies (Hughes-Riley et al., 2018, p. 9). Beyond ever smaller components, the emergence of smart textiles (conductive yarns, soft sensors and smart fibres) has opened pathways to new concepts and technologies. (Hughes-Riley et al., 2018, p. 1-3)

1.1.2: Advancement of Field and Commercial Growth

The field of wearables has seen increasing growth over the last several decades. With the commercial success of applications like smartwatches and health monitoring devices, the field has blossomed to feed a steadily growing consumer market. The global wearable technology market was valued at USD 32.63 billion dollars in 2019 and is projected to expand at a compound growth rate of 15.9% from 2020 to 2027 ("Wearable technology market size | Industry report, 2020-2027," 2020). Wearable technologies follow a general trend of integration and miniaturization to consolidate items or functions into ever smaller and more effective devices. In the past several decades integrated circuits (ICs) have continued to shrink while offering significantly more computational power (Guler, Gannon, & Sicchio, 2016, p. 4). This trend creates opportunities for wearables to move beyond accessories to become more completely embedded within clothing.

A paradigm shift in the development of wearables has seen the development of technical yarns and fabrics, affording new and exciting opportunities in creating smart, reactive clothing with soft electrical components (Agcayazi et al., 2018, p. 1-3). In addition to novel uses afforded by conductive textiles and smart materials, work is also being done to re-imagine current electrical components at the yarn level to create fully embedded soft processing (Wicaksono et al., 2020).

1.1.3: Integrating Technologies

In 1996 the first ‘smart shirt’ was created. The American Department of Defense (DARPA) organised a workshop titled ‘wearables in 2005’. This workshop brought industrial, academic and military technologists together to work together towards delivering computing to individuals (Guler, Gannon, & Sicchio, 2016, p. 9-10). This is one of the earliest known large-scale efforts to create an embedded wearable system (see Figure 3). The shirt was developed with the mandate of ‘textiles as the computer’ and integrated engineering, textile and health applications. The shirt had capabilities like fibre optic weave able to sense bullet holes, and sensors able to provide valuable information on a soldier's health, like heart rate.

Figure 3

1996 DARPA smart shirt.

While initially focused on military applications, the project grew to focus increasingly on civilian applications due to the novel opportunities created for the health sector. This example represents one of the earliest instances of wearable biomonitoring for personal use in an integrated system. The close proximity to the body and “always on” nature of wearable technology, along with the low burden placed upon the end user, made the technology desirable for clinical monitoring of core biological functions such as heart rate, breathing, sweat levels and more.

As integrated systems like the smart shirt have developed, they have afforded numerous novel applications. Health care in particular has seen the development of a number of lifesaving benefits. However technological limits and highly variant application needs have created a vast array of wearable technologies integrated at different levels in different areas. The sheer number of outputs has driven a need for further definition.

Various attempts have been made to classify the different types of wearables. Berkeley categorizes each smart accessory differently, the IEC (International Electrotechnical Commission, 2019) distinguishes categories based on proximity to the body. Many categorisation efforts appear to make the clear distinction between wearable accessories and smart clothing. Hughes-Riley, Dias, and Cork further clarified the different pathways to integration as distinct generations (Hughes-Riley et al., 2018, p. 2). The authors sought to categorize wearables into three generations based on the level at which technologies are integrated. The first generation adds electronics or circuits to a garment. The second generation integrates functional fabrics such as sensors or switches in the garment. The third generation involves the development of functional yarns (Hughes-Riley et al., 2018, p. 2) (see Figure 4). This master's research sits between the first and second generations of integration as it has on body components in addition to embedded conductive textiles.

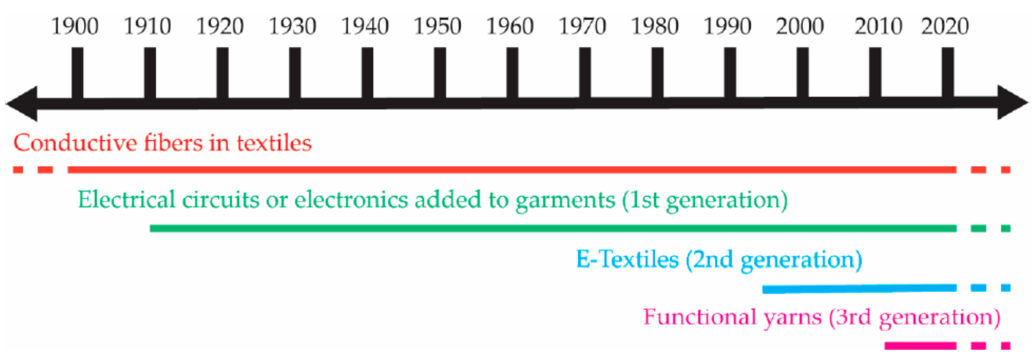

Figure 4

Timeline of E-Textile Integration. The level at which electronics are integrated with textiles are shown as generations.

The increasing levels of integration and development of wearables often demand highly specialised practitioners. The degree of specialization depends on the project, but the multidisciplinary nature of wearables produces a number of conflicting considerations. Difficulties in classification, along with the limited development of interdisciplinary design models for smart clothing are contributing factors in electronic textiles largely being relegated to R & D, and not achieving significant consumer success (Agcayazi et al., 2018, p. 1). The issues of interdisciplinary design models and the problems of component integration have been key areas of focus in this master's research project.

1.2: Interdisciplinary Nature of Wearables

1.2.1: Disciplinary Inputs in Developing Wearables

Given the complex technical problems presented by integrated hard and soft systems, it is expected that technically focused disciplines would be contributing most heavily in this field. Engineering is crucial to advancing material outputs and solving many of the challenging technical hurdles that arise, drawing from a range of specializations. Electronic textiles alone required input from a broad cross section of engineering including textile engineers, electrical engineers, chemical engineers, system engineers and material scientists. Advanced materials are frequently generated in research settings and later integrated for a commercial output. However, a core and difficult facet of creating wearables is the necessary compromise between what is technically possible, what is wearable, and what is desirable to an end user. This requires a degree of compromise between the optimum technical solution and subjective comfort. This can be difficult to reconcile when working from a formal engineering background as subjective values around comfort and desirability do not lend themselves to quantitative assessment (Bodine & Gemperle, 2003), especially when held next to quantifiable metrics for efficiency.

Challenges persist in addressing this compromise between disciplinary inputs. If a developing technology is focused primarily on optimizing for metrics such as electrical noise, or sensitivity, this can result in large scale retrofitting or redesign to make the technology usable for end users, at great cost to manufacturers. It is in this area that some of the greatest difficulties in deploying wearable products persist. This compromise between electrical or mechanical performance and useability/wearability is of particular interest as user adoption often hinges on the result.

1.2.2: Interdisciplinary Challenges in Wearables Design Teams

Technical research and design signoff are typically handled by a team of engineers who set the direction. To progress beyond research and development institutes, an explicit understanding of the respective disciplinary focuses and challenges is crucial in generating viable designs. Part of the interdisciplinary challenge is contextually specific to the research at hand, and in part is generated by underlying disciplinary emphasis on different stages of design and validation (Tenuta & Testa, 2018).

To address these potential challenges, I investigated the differences in disciplinary processes by comparing design cycles of what I perceived to be the relevant disciplines. Primarily I explored engineering design processes and fashion design processes. This is extrapolated on further in the methodology where recent research is presented that better articulates these comparisons and offers a developed model to potentially address interdisciplinary challenges in the design process.

1.3: Designing Wearables

1.3.1: Designing for the Body

Considerable headway has been made in establishing tenants and aspirations specific to wearable technology design, however challenges still persist. The case-by-case nature of designing for the body, in addition to variable levels of hard-soft integration has made it difficult to make absolute statements around how wearables should be designed (Robinette & Natsume, 2019). Still, the usability of wearable devices has shown to be critical to adoption; if a wearable device has poor usability it is unlikely to be used at all. The commercial success of a wearable technology can be attributed to how likely it is to be worn (Chang, Lee, & Ji, 2016).

In 'Designing Wearable Technologies Through a User Centered Approach' (Ferraro & Ugur, 2011), the authors use a series of anatomical models to suggest several important considerations around designing for the body. This approach is based on considerations of user centred design (UCD), a broad term that describes a design process in which end users influence how a design is formed (Norman, 1986). Ferraro et al. focus on Langer's lines (see Figure 5), in tandem with research by Carnegie Mellon that denoted areas on the body they found to be most unobtrusive for hard components (see Figure 6) (Gemperle et al., 1998). Carnegie Mellon based this on wearability parameters provided by the Institute of Complex Engineering Systems that include Attachment, Size (cross section variation of the human body), Human movement, Low Obtrusion and Body motion (Gemperle et al., 1998). Ferraro et al. attempted to overlap the two models to improve wearability and attempt to create a necessary shared language for design. Langer's lines describe the natural alignment of collagen within the tissue and correspond to the direction of maximal tension within the skin. These are typically used by surgeons, to ensure minimal scarring from incisions by cutting parallel to the load bearing collagen fibres rather than across them.

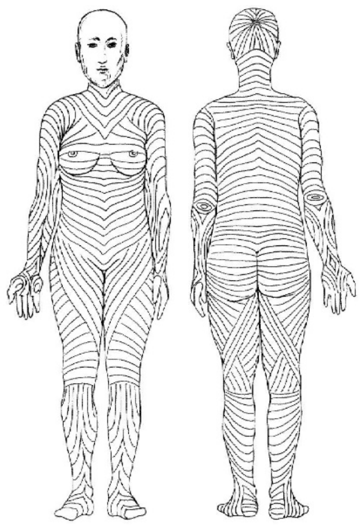

Figure 6

Langers Lines.

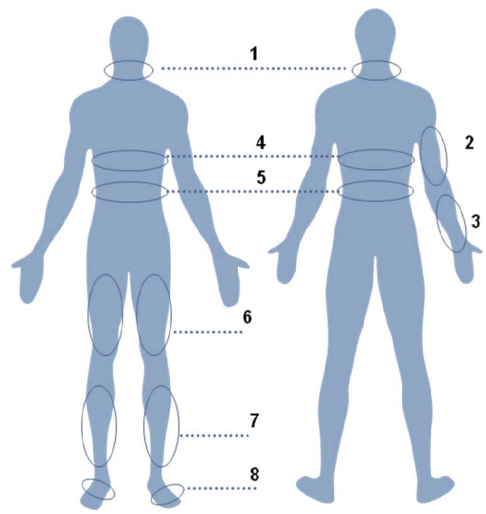

Figure 6

Areas of low obstruction on the body for placing hardware.

This provides a means for understanding areas on the body that might best facilitate the positioning of hard components. Additionally, considerations are offered for objects being attached to the body with a focus on 'humanizing' the form. This is often intuitive when considering the placement of hard electronics on the body; however, Gemperle et al. offer several considerations for these forms by combining elements of concavity against the body (see Figure 7a), convexity (Figure 7b) on the outside surfaces of the form, tapering (Figure 7c) as the form extends off the body, and radii (Figure 7d) softening up the edges, in order to create a humanistic form language (Gemperle et al., 1998).

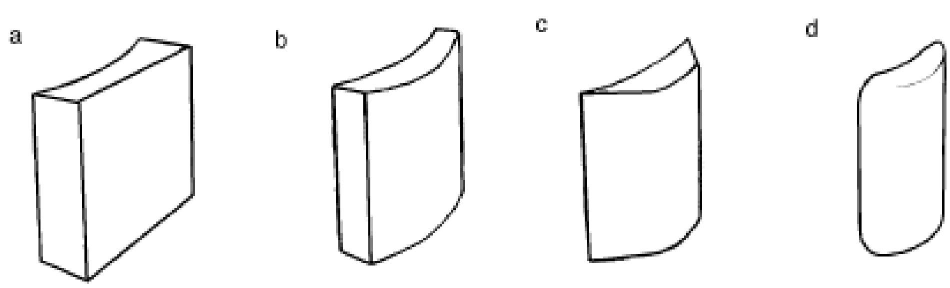

Figure 7

Form considerations for creating hardware that will sit comfortably against the body.

While consideration has been given to hardware on the body for quite some time, there is a lack of literature around the practical considerations of design and fabrication of soft circuits for the body, particularly as it relates to second generation integrated e-textiles and the use of e-textiles in garments. In previous design work I presented a potential mapping strategy for soft circuits (Anderson, C., 2018). This was based on research completed by Arthur Iberall on Lines of Non-Extension (IBERALL, 1964). These are lines running along the body that do not stretch, regardless of body position, as seen in Figure 8. These were initially proposed as a means of increasing mobility in full pressure suits, but I found they provided an ideal platform for placing soft circuitry on a garment. Using lines of non-extension in a way made the garment less subject to the electrical interference created by mechanical stress from stretch and movement (see Figure 9). This body placement information is valuable as current soft circuits offer a novel but electrically inferior means of signal transfer when compared to traditional wires. This is in part due to chemical and metallurgical instability in conductive fibres, manufacturing processes for e-textiles, and being heavily affected by body motion that creates mechanical stress on the conductive elements in the garment (Heo et al., 2017, p. 1-4).

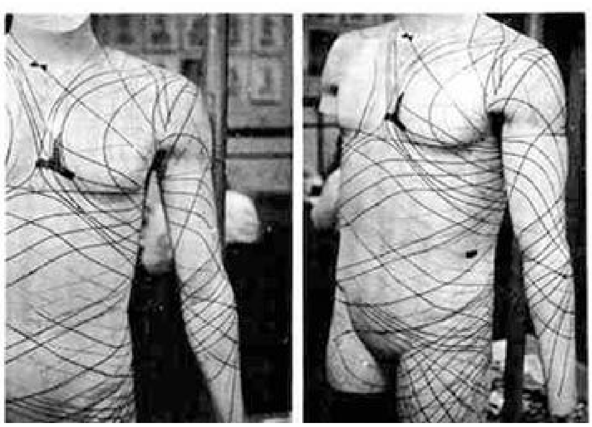

Figure 9

Lines of Non-Extension (LoNE).

Figure 9

Compression short smart garment with soft circuit based on LoNE.

1.3.2 Usability and Comfort

Technological issues such as the fabrication of novel devices or unique systems is often the focus of wearables research (Agcayazi et al., 2018, p. 28), comfort can quickly become a deciding factor of whether a wearable will be used or not (Chang, Lee, & Ji, 2016). Given the subjectivity of comfort though, this can be difficult to account for in the design process (Bodine & Gemperle, 2003). This is an important consideration for this project as a healthcare wearable's comfort and usability are critical to user adoption.

To address this deficiency around the role of comfort in wearable design, a study was performed on the role of user centred design in smart wearable systems (Francés-Morcillo et al., 2018). The study identified wearability considerations from a range of disciplinary literature and provides a map of design requirements for wearable device design. The research takes its base from ergonomics, as such its design requirement classifications detail physical ergonomics, cognitive ergonomics, and emotional ergonomics (Francés-Morcillo et al., 2018) (see Figure 10).

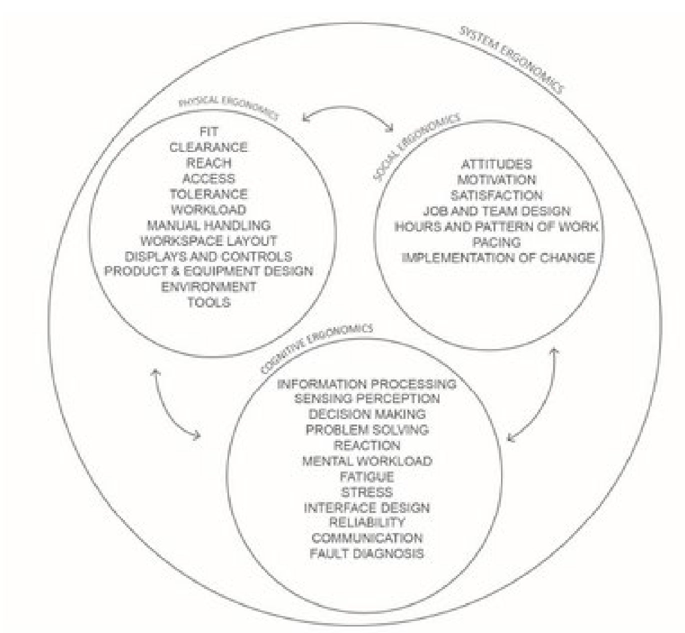

Figure 10

Ergonomics considerations.

The authors chose to use these categories as they consider them to be most suitable given the holistic nature of wearables. The study also identifies boundaries in approach presented by disciplinary vocabularies. They identify several terms that have different definitions in different studies: a common differentiation was the word comfort, for instance, some studies consider only physical ergonomics, but others include aspects like emotion.

Francés-Morcillo et al. present a well-designed mixed methods approach (2018). This involves an extensive literature review identifying crossover terms used between disciplines and validating strong and weak connections. Interestingly this method proved ineffective at drawing any solid conclusions, so the researchers posited the question: “Is it genuinely possible to quantify the criteria related to design parameters?”

They proposed a new wearable design method that separates design parameters by layers, again being based on the physical, cognitive and emotional aspects of designing for the user as seen in Figure 11.

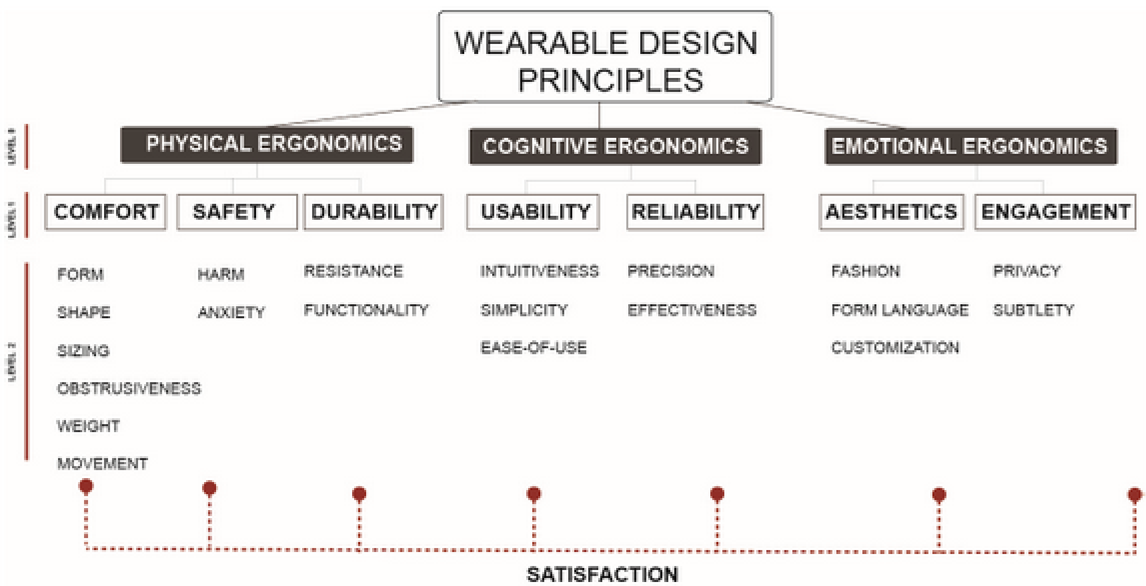

Figure 11

Wearable Design Principles derived from ergonomics.

This provides a tiered map for wearable design principles. Despite its focus on a holistic approach, it is limited in its consideration of the macro subjectivity of comfort. The researchers frequently return to comfort due to it being presented differently by different disciplines but make little allowance for how comfort is affected in gender, social or cultural contexts. This becomes critical in the development of health projects like that of this research, as it becomes clear that perception of comfort can differ greatly between worn items from context to context.

In a 2003 symposium, Bodine and Germperle analysed the effects of functionality on the perception of comfort (2003). They also make note of differences in perception according to gender, but temper the results with the caveat that, due to not expecting variance, they did not distribute the participants of the study equally by gender. This is a limitation of the study as it would inevitably affect the results. The study tested two wearable devices under the guise of different use cases. In this way the same device is judged on its comfort as well as social acceptability depending on the context of use. The use case contexts of Bodine and Gemperle's study were police use, medical use, and party use. They assessed each wearable on a number of features, including rating the desirability and comfort of the device, as well as how useful it was to friends and how functional they found it.

In all cases the comfort of the devices was viewed differently depending on their use case, for instance, in police use all participants expressed negative views on comfort, while in the party use case wearers were happy their device would serve them and their friends, and subsequently reported higher levels of comfort. This shows that, despite considerable effort to do so, even the notion of defining exactly what comfort means to a particular discipline can become fraught when social and use context can significantly change the perception of comfort.

Subsequently, a key component of everyday wearables is the user experience, and usability of wearables. Bodine and Germperle suggest that social context of use has a critical effect on user experience (Bodine & Gemperle, 2003). Considering not just the immediate user needs, but also the nature of their social circumstance can positively affect user engagement.

Taking into account the above considerations, the wearable outcome of this research should be designed to be user centric in nature, recognising how the device may be used and in what contexts. This should be emphasised further if it is an outward facing wearable device, easily visible to others. In this case the device will likely not be seen, so this emphasis shifted to creating a low-profile device that can be comfortably worn underneath other clothing. Additionally, the frequency of expected use should be held in relation to the previously mentioned factors to better understand situations the end user may be faced with. Designing with these considerations in mind is likely to improve comfort and adoption of the wearable outcome of this research for end users.

1.4: Technical Issues and Challenges

This section of the review addresses the technical and project specific issues and challenges that underpin this research. The following sections provide context and technical explanation around atrial fibrillation, the acquisition of biopotential signals and potential e-textile solutions for acquiring biopotentials in daily use.

1.4.1: Atrial Fibrillation and Long-Term Health Monitoring

Detecting atrial fibrillation (AF) is a primary focus of the larger research project of IBTech. This is in response to the difficulty of diagnosing it in clinical settings (Lip & Tse, 2007, p. 1). Atrial fibrillation (AF) is a condition which causes an irregular and often rapid heart rate and can lead to stroke and heart failure (see Figure 12). It is part of a larger group of conditions called arrhythmias (Nattel, 2002, p. 1).

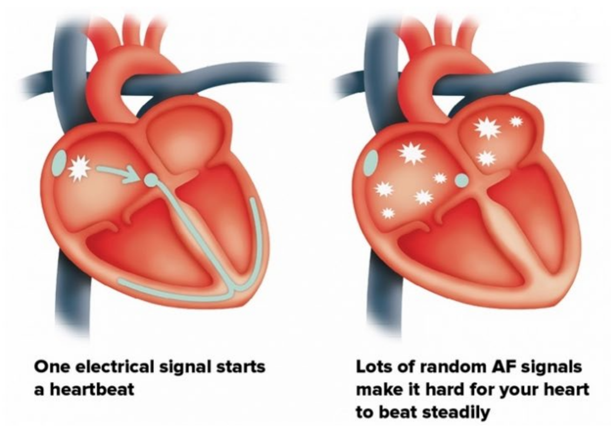

Figure 12

Comparison of a heart with a typical rhythm and a heart with atrial fibrillation.

The causes of AF are not always clear, and AF can often go undiagnosed. The challenge in diagnosis is in part due to Paroxysmal AF, a variant that comes and goes sporadically, presenting in around 25% of patients with self-terminating, recurrent atrial fibrillation (Lip & Tse, 2007, p. 6). When coupled with the fact that only a third of patients with AF present to hospital (Lip & Tse, 2007, p. 1), this makes effective diagnosis in everyday settings exceedingly difficult. Diagnosis for arrhythmias is typically performed by an Electrocardiogram (ECG) in a hospital setting by using electrodes to detect biopotentials (Lip & Tse, 2007, p. 1).

The process involves attaching an array of 12 (see Figure 13), or sometimes more, silver chloride gel electrodes (AgCl) (Goldberger, 1999, p. 21). However, silver (Ag) and AgCl electrodes are toxic and cannot be used for extended periods on living tissues (Grimnes & Martinsen, 2014, p. 183). Additionally, as the electrolyte gel dries, the signal quality decreases and degrades the data quality, this problem is present in acquiring many different types of biopotential. (Grimnes & Martinsen, 2014, p. 185-187).

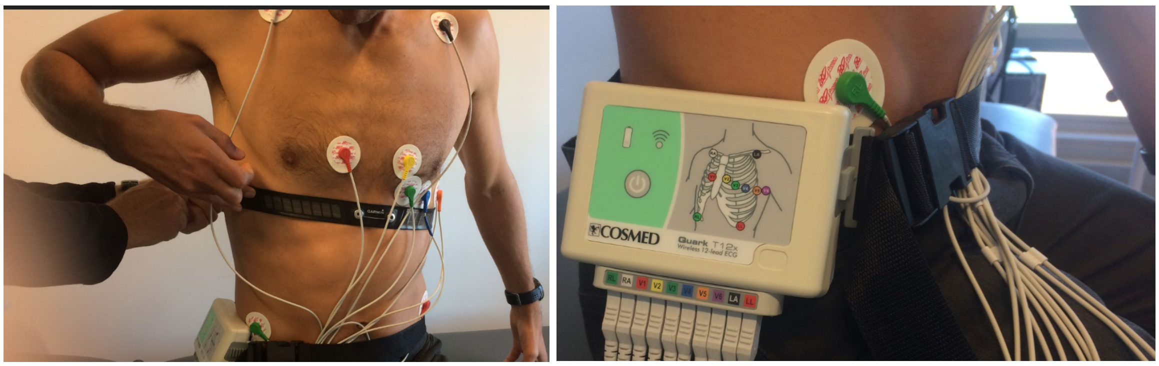

Figure 13

A clinical ambulatory 12-lead ECG monitoring system. Leads are coloured to assist set up.

1.4.2: Acquiring Biopotentials

A biopotential is an electrical potential that is measured between points in living cells, tissues and organisms, and which accompanies all biochemical processes (Sazonov & Neuman, 2014). Biopotential currents are generated when cell membrane stimulation exceeds a threshold of roughly 20 mV. When this occurs, the permeability of the cell membrane to various ion changes, ion flow from intracellular spaces to extracellular, and vice versa creating a chemical difference that generates an electrical potential (Sazonov & Neuman, 2014).

This potential can then be measured as an electrical signal (see Figure 14). Different functions in the human body generate different levels of biopotential signal, for instance, the ECG signal has an amplitude of 1-5mV and a bandwidth of 0.05-100Hz. This makes it one of the larger amplitude signals in the body which also allows for ECG diagnosis from points on the body distant from the heart (wrist, feet etc).

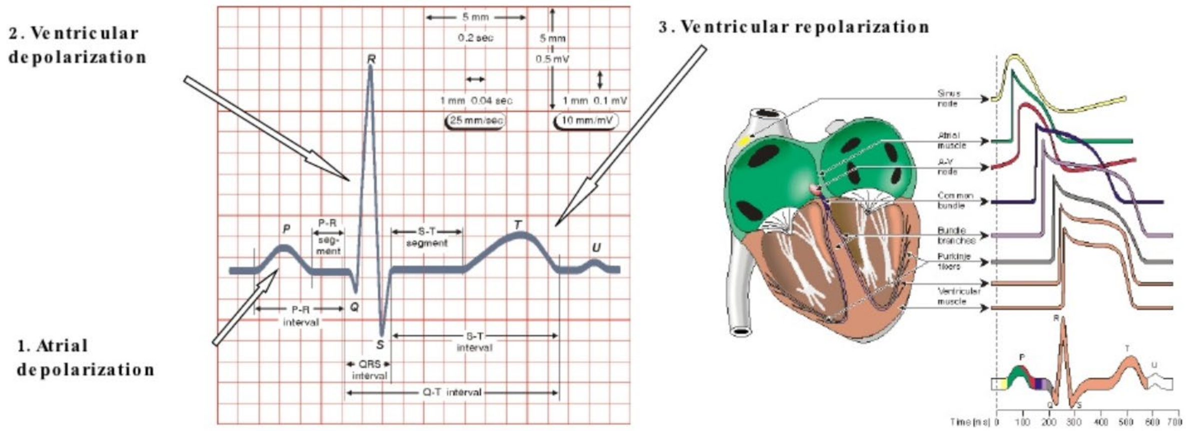

Figure 14

Anatomy of an ECG signal, the graph runs left to right. The image on the right shows the direction of charge as it travels across the heart from upper left to bottom right.

Other biopotentials like brain waves are tiny in comparison, these are measured via Electroencephalography (EEG). EEG signals are much more difficult to acquire accurately than ECG signals. EEG signals measure between 0.001-0.01mV with a bandwidth between 0.5Hz and 30Hz (Sazonov & Neuman, 2014). As discussed in the previous section these signals are acquired externally via AgCl gel electrodes that are prone to drying out and causing skin irritation if used long term (Grimnes & Martinsen, 2014, p. 183-187). This makes them ill-suited for long term, at home monitoring. Additionally, clinical systems often require specialised setup and maintenance by a technician (Goldberger, 1999, p. 21). By utilizing the unique opportunities afforded by e-textiles, this research aims to address a number of these issues.

1.4.3: E-textile Methods and Materials for Sensing Biopotentials

AgCl is used frequently as an electrode substrate due to its favourable balance of capacitance and resistance (Grimnes & Martinsen, 2014, p. 180). However, a metal alone cannot provide the necessary transferal of charge from ion to electron, this process is facilitated by an electrolyte gel, or in e-textiles, sweat. “When a metal with electrons as charge carriers comes in contact with an electrolyte with ions as charge carriers, an electric double layer is formed at the surface of the metal plate in the electrolyte. The double layer is very thin and depleted of charge carriers. This is where the conversion from electron to ion (or vice versa) charge carriers take place” (Grimnes & Martinsen, 2014, p. 179-180).

It is possible however to acquire biopotential signals by using similar metals in textile form, like stainless steel or silver e-textiles, that in conjunction with sweat (instead of electrolyte gel) promote ionic/electron flow (Paradiso & Pacelli, 2011, p. 2) (see Figure 15). By doing this the wearer can acquire serviceable biopotential signals while avoiding electrolyte gels given their poor suitability for long term monitoring. Instead using an e-textile affords long term, home use signal acquisition and in this way offers a clear advantage over clinical ECG in the detection of paroxysmal arrhythmia. Additionally, having a nonpermeable backing, such as a plastic or foam (see Figure 16), to an e-textile electrode allows sweat to gather and soak the textile electrode more effectively, improving signal quality (Paradiso & Pacelli, 2011, p. 3). Signal quality remains secondary to hospital standards, but this can be mitigated somewhat with appropriate signal processing hardware and software like that developed by the IBTech team.

Figure 16

Product using E-textile electrode.

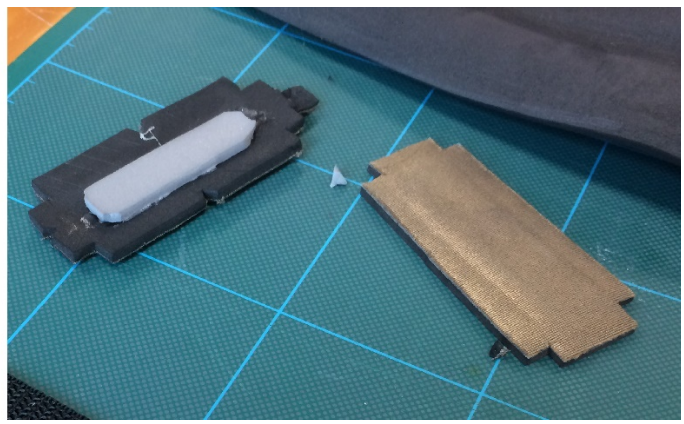

Figure 15

E-textile electrode created in this research with foam backing.

1.5: Summary

Understanding the historical developments of wearables and current trends is helpful in locating this research as an e-textile, or smart clothing project as opposed to hardware wearables like smart watches. This is noteworthy as currently e-textiles offer a number of benefits to the user, like long term monitoring (Fleury et al., 2015), but are electrically inferior to hard conductive alternatives (Agcayazi et al., 2018, p. 3). This is being mitigated by engineers and material designers pushing integration of electrical components to a fibre level (Hughes-Riley et al., 2018, p. 2). However, this technology is not yet available, so many integrated e-textile projects occur in the second generations of integration, where e-textiles are integrated in the garment as sensors or soft circuits (Hughes-Riley et al., 2018, p. 4). Due to the deployment of e-textiles at this level, the electrical system they provide is subject to the mechanical stresses of the fabric/garment. This presents a challenging tension as conventional garment and clothing designs/concepts can offer mechanical/electrical solutions. This balance between function versus form and the related disciplinary discussion is discussed in various forms in the literature review, method, practice and conclusion, as it underpins the challenge of executing 'best practice' wearable design considerations in a team environment and individually.

The larger view of wearables as a field helps in placing the specific challenges of the research around atrial fibrillation and biopotentials, specifically as they relate to e-textiles. Potential considerations around design goals are offered. To implement these goals in practice, despite relying on creative process, required some means of grounding the research in an established methodology. Action research (AR), or research through design, offered a developed theoretical framework for reflection on practice. Reflection, specifically a reflection cycle presented by David Kolb (Kolb & Kolb, 1984) is singled out as the primary tool in experiential learning as it relates to this research. It offers a considered approach to practice when paired with consistent documentation and reflection. Additionally, a macro/micro view of reflection offers a reference for my personal practice as it goes from a team environment to an individual one.

Chapter 2: Methodology

In this chapter, theoretical and practical frameworks are discussed for grounding research in practice. The project did not have a pre-set plan outside of the broader research goal of developing an ECG wearable using e-textiles. Instead, the research plan evolved as specific challenges became clear, for example designing around the sternum area or reducing slip/motion artifacts on the electrode. These challenges were prone to change and design documentation benefitted from a developed model of reflection and action.

The disciplinary context in which this wearables research takes place, and the interdisciplinary challenges related to that are then discussed further. Considerations are offered to promote interdisciplinary engagement in a team design space. However interdisciplinary elements became less focal once design amendments continued beyond the IBTech team project. The ability to action or enforce design models presented in the literature review should initially be considered in relation to the team setting, as my position within the team did not afford the decision-making power to push certain designs or affect how others completed their research. However, the team afforded technology, expertise, and specialised knowledge to develop ideas further, this collaboration was a key aspect of the research.

Beyond the theoretical framework, tools and processes used in practice are introduced to provide a basic context for some of the methods and processes discussed in the practice. The practice itself is framed in the research design, where the breakdown and presentation of the design process is discussed. A timeline is also presented to provide further chronological context and show the interrelatedness of the components in the design.

2.1: Framework

2.1.1: Action Research

Having defined several important wearable design considerations (discussed in the designing wearables section of the literature review), it was important to establish a theoretical framework in which design research and practice could be developed. Action research (AR) was identified as an ideal approach for this due to a natural fit with iterative development. Though relatively new in comparison to more established disciplines like science, research through design is still decades old.

Historically, the emergence of action research coincided with a period dubbed a "crisis of confidence in the professional" (Swann, 2002, p.49) in which established disciplines (medicine, law, engineering etc.) were being subject to increasing scrutiny. This period forced the emerging design disciplines to reflect more heavily on their practice, in turn establishing a focus on reflection as a means of grounding practice (Swann, 2002, p. 51-54).

Specifically, Swann draws attention to Schon as a key contributor to the formulation of novel epistemologies around reflection in practice:

> Central to this, in *The Reflective Practitioner*, Schon formulates an epistemology of practice based largely on an examination of the way in which practitioners reflect on their actions during and following their work. Reflection "in action" and reflection "on action" are key concepts in Schon's scenario. Schon talks about how problems are framed, how a situation can be changed, what norms are given priority and what possibilities are offered, quite intentionally showing a relationship to the design process. (Swann, 2002, p. 50)

Swann summarizes the sentiment further, stating "Reflection 'in action' and reflection 'on action' lead to 'action research'" (Swann, 2002, p. 50) (see Figure 17). Reflection in action is based on how one judges a situation and acts accordingly. This is useful in practice as it offers a means of learning on the fly but requires a degree of mindfulness. Reflection on action describes thinking about larger systems, and how to affect them.

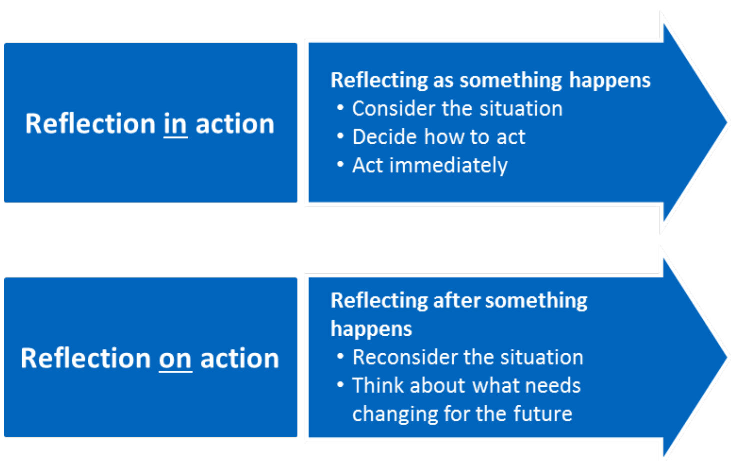

Figure 17

Defining the difference between reflection in action and refection on action.

Design practice in this research project was done heuristically, or in a 'hands on' iterative manner. This approach allowed for adapting accordingly as new challenges arose. In this way, reflection on processes and systems, as well reflecting on the methodology being used occurred recursively to try to improve at every step. The importance of a flexible practical approach was validated by the number of unknown challenges in wearable development. Specific challenges are discussed further before each relevant section of the practice.

Frequently changing constraints made it difficult to factor a planned making approach. This often required quick reworks, at times called for complete pivots in direction. Given the changing and iterative nature of the project, action research presented a relatively consistent approach provided documentation and reflection is done throughout the development. Reflection was independent of the wider group discussion as it related to making. A visual model created by David Kolb provides an explicit breakdown of the reflection process (see Figure 18), this process is further characterised as experiential learning.

2.1.2: Reflections on Experiential Learning

Kolb offers a visual model for Experiential Learning Theory (ELT), as a means of visualising the reflective process involved (Kolb & Kolb, 1984).

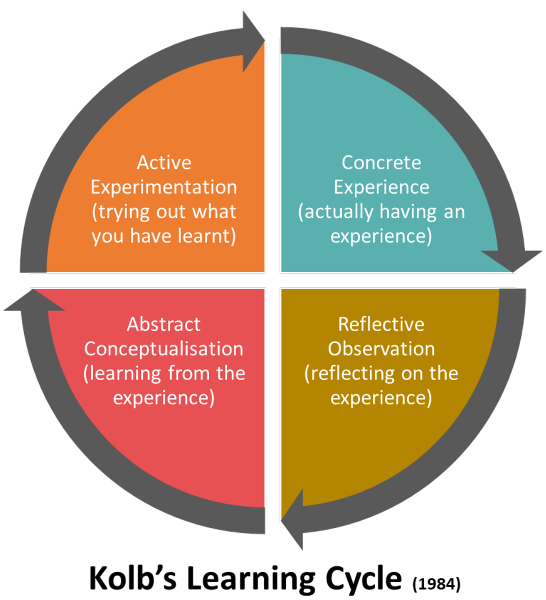

Figure 18

Kolb cycle of reflection and action.

> The ELT model portrays two dialectically related modes of grasping experience— Concrete Experience (CE) and Abstract Conceptualization (AC)—and two dialectically related modes of transforming experience—Reflective Observation (RO) and Active Experimentation (AE). Experiential learning is a process of constructing knowledge that involves a creative tension among the four learning modes that is responsive to contextual demands (Kolb et al, 2005).

This model helped solidify the grounds by which reflection was conducted throughout the course of this project. This was aided through documentation like writing, drawing, taking pictures and video. Additionally, Kolb's learning cycle offered a potential means for exploring the interdisciplinary challenges in this research. To help better understand the interdisciplinary aspects important in this research, a comparison of disciplinary design processes is presented as a personal attempt to better understand the involved practitioners in the early stages of this research. Subsequently, research was identified that supported these efforts and is presented in the following section as a potential method of approach for future practitioners.

2.1.3: Design Process Models

In the literature review, interdisciplinary challenges in wearable design teams and the corresponding problems are addressed. However, the perception of these challenges was limited by a lack of personal understanding around specific disciplinary approaches.

To further understand the approaches and relationships between the involved disciplines for my own practice, several disciplinary design processes were visually compared by placing them side by side, colouring their phases and comparing the differences in structure (see Figure 19). Although interesting, a lack of knowledge around the practical applications of each process meant the approach was limited. In this way it is more representative of ongoing personal efforts to understand and better work with disciplines involved in wearable projects.

In a larger interdisciplinary wearable project, assumptions around the disciplinary processes could result in missed opportunities, wasted resources, and potentially generating outcomes that cannot successfully be integrated.

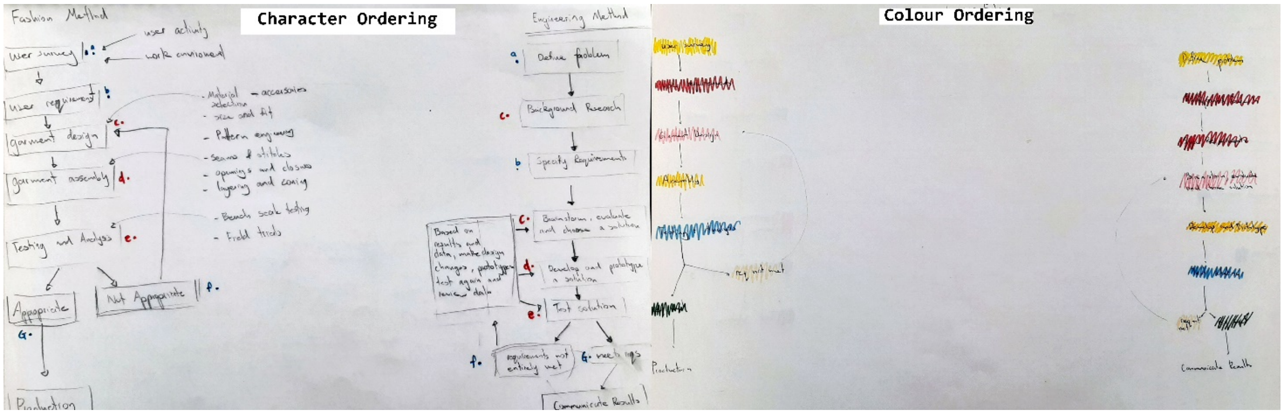

Figure 19

Draft visual comparisons of design processes.

Late in this project, research was discovered on this topic that focused solely on interdisciplinary issues and took a far more rigorous approach based on both industry and academic engagements. Granted it was the sole focus of their research, the authors, Tenuta and Testa (2018), were able to better identify problems and present solutions in this space. Tenuta and Testa introduced validation and user input at different levels of the design process as a means of adding end user input earlier on in the design process (2018). The researchers accounted for factors like late, or poor integration by validating concepts earlier. The researchers also provide a concise overview of how this process might play out and suggest its relevance for both academics and industry. The nuanced model offered by Tenuta and Testa was the most complete wearable design method identified during this project. Tenuta and Testa also offer a more succinct comparison by moving away from specific disciplinary design processes, rather comparing scientific method to creative process in general (2018) (see Figure 20).

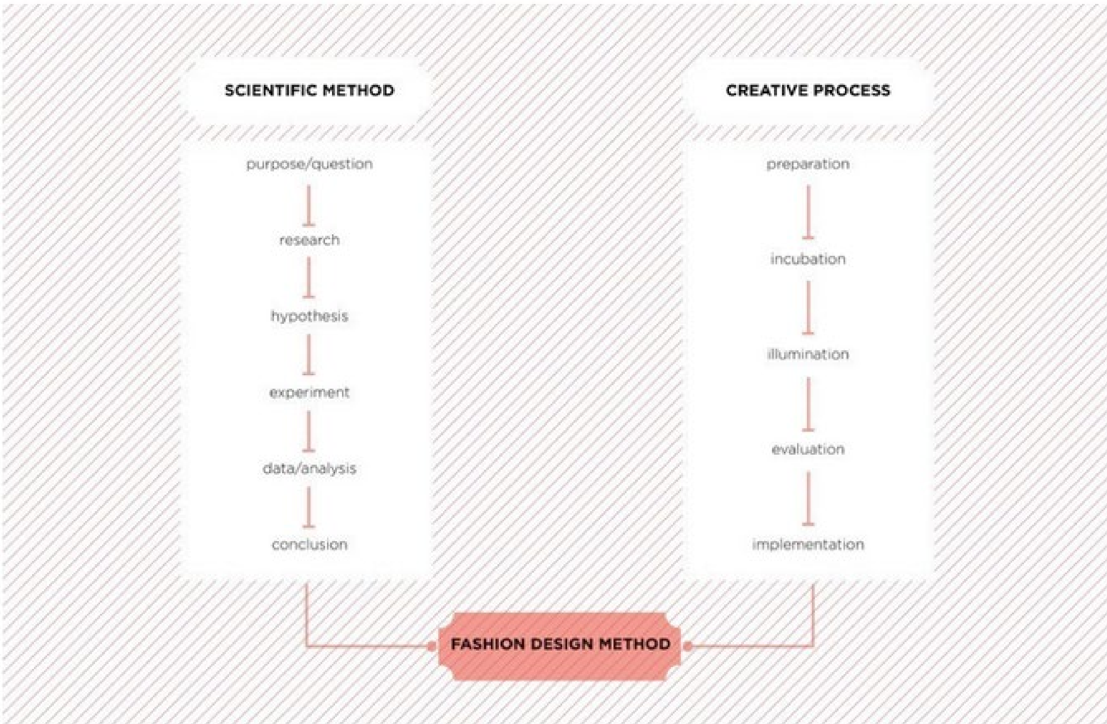

Figure 20

Visual comparison of scientific method and creative process toward a fashion/wearable design method.

This model was only identified in the later stages of the project after the team aspect of the design and making for this research had been completed. It would have been valuable to have had a model like this to guide the collaborative part of the research process for this project. Despite this, in terms of interdisciplinary focus, the efforts of this research were validated by Tenuta and Testa's (2018) findings. They established a clear need for a shared design process that could better account for different disciplinary concerns related to wearable technology design.

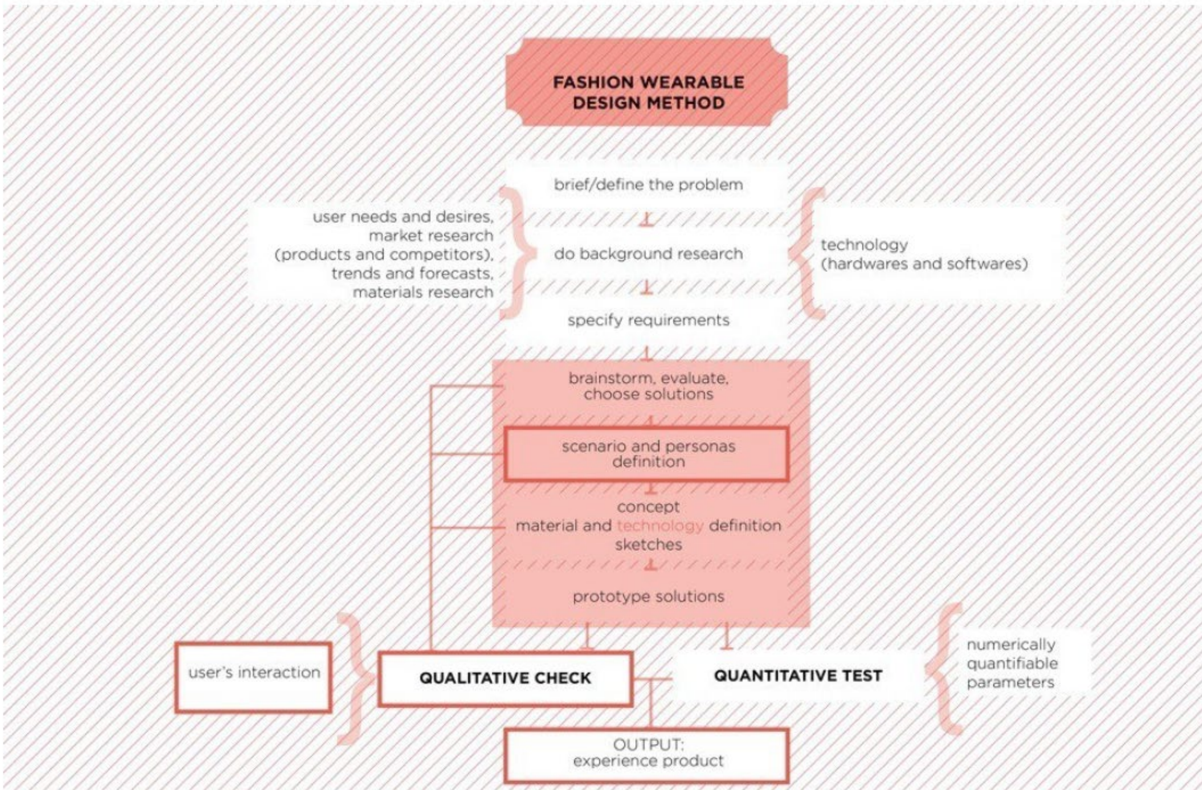

Figure *21*

Proposed method for fashion wearable design.

Design process models present a structure for approaching wearable design by marrying fashion industry processes and scientific method as seen in Figure 21, it does not provide any information around the actual practices of involved disciplines. An additional conceptual approach based on Crouch and Pearce (2013) was experimented with over the course of the research as a means of better understanding disciplinary considerations that might affect the wearable design process.

2.1.4: Addressing Interdisciplinary Challenges

In their book on design methodologies and research within design, Crouch and Pearce identify a conceptual position of designing through 'lenses' (2013). The concept explores the idea that, as we are unconsciously informed by all our previous life experiences as well as our disciplinarity, this is manifest in whatever we design. It would theoretically be possible to consciously apply these lenses to our design by developing a mindful approach to reflection in design.

As a working concept, the model on its own was not suitable as a formal approach and required an established, complimentary research methodology to experiment and work with. Action research provided an ideal method for exploring this concept as a formally established approach.

The lens concept is based on Crouch and Pearce's framing of a research position as; "The particular theoretical or conceptual lens through which we view the phenomena we are studying; our methods (Walter, 2010b)" (Crouch & Pearce, 2013, p. 53-54)

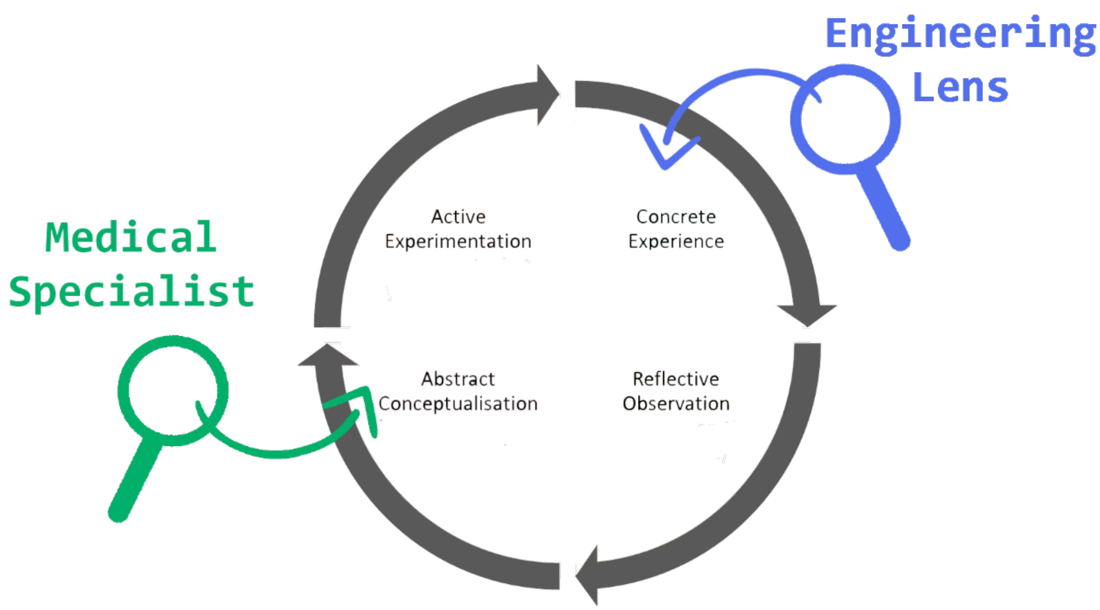

Figure 22

Example of how to potentially apply the dispensary lens concept in a cycle of experiential learning. In this example engineering feedback helps inform the initial making, while a medical specialist helps inform the post-reflection constructive ideation.

They explain that research positions, or in this case design challenges, are inherently informed by experientially determined biases (Crouch & Pearce, 2013, p. 55). This is a truism but presents an interesting idea in extrapolating the figurative concept to something more practical (see Figure 22).

It can then be said that unconscious biases are also informed by formal training or specialisation, and that this in turn becomes a ‘disciplinary lens’. It quickly becomes clear however that this is not an approach that can be considered in any literal terms, as one does not just see and think as an engineer by applying an ‘engineering lens’. Whatever lens might be applied would be characterised by designers' own understanding of the discipline and carry with it implicit assumptions and biases. Crouch and Pearce’s lenses offer little in the way of pre-emption, instead serving as a potential reflective tool. They might instead be better thought of as approaching a problem with all inherent experience, but with the goal of adding reflection via interdisciplinary input.

The conceptual nature of this approach was only loosely established at the beginning of the project, being iteratively developed as the nature of the team, design and subsequent challenges became clearer. This framework was used in initial attempts to try and make sense of the various approaches and assumptions made by various members of the research team. Conclusions about its efficacy and value in practice are left till the conclusions chapter *(113)*.

2.1.5: Collaboration

While this research contains both collaborative and individual elements, the bulk of the design and fabrication occurred while part of the IBTech team project. As such addressing the effect of collaboration and team hierarchy on the design process is valuable in placing the resulting wearable outcomes.

Throughout the IBTech portion of the research, weekly collaborative meetings with a team of engineers helped direct efforts towards producing a garment for long term ECG monitoring and the diagnosis of atrial fibrillation. While meetings were held weekly, work was often done in close collaboration with IBTech throughout the week, specifically with the electrical engineer on the team.

Team structure played a significant role in the planning and validation of designs. The overall directive for the research was a product output that could be tested against clinical ECG equipment. I was tasked with designing a working prototype that covered all facets of the design; hardware enclosures, e-textile electrodes, designing the garment as well as the interconnects between components.

I was responsible for ideating and creating designs, though any final decisions around the design would be deliberated on by the two lead researchers who headed the team. There was an expectation that designs would be adapted to meet the needs of the engineering team. It is important to note results around testing design outputs could not be provided for this research due to lack of availability when requested. At the time of the joint project, the engineering team was responsible for testing the mechanical and electrical elements of the design. These outcomes were communicated by team leads in the form of providing verbal or written considerations for designs. A breakdown of the team structure for the duration of my time working with IBTech is as follows:

- Project Supervisor: Professor from IBTech who, along with another senior engineer, created the proprietary technology that made the project feasible.
- Team Leads: Responsible for implementing the technology via designing PCBs, component selections as well as creating the backend code for the hardware. Also responsible for testing of hardware and designs. Managed by two postgraduate researchers from IBTech, AUT.
- Electrical Engineer: Tasked with developing, testing, and refining PCB's and electrical components. Managed by a fellow postgraduate student.
- Chemical Engineer: Contributed to the development of a substrate to be used for a potential testing phantom (A testing rig for electrodes that features electrodes connected to a bio signal generator and submerged in material that mimics the electrical properties of human flesh).
- Senior Engineer Consultants: Being a multi-institute venture, several advisors from different institutes were involved in weekly meetings.

2.2: Fabrication Methods and Processes

The practice in this research covered a variety of methods and fabrication techniques to produce designs. While many of these manufacturing processes are standard in terms of design research and product development, some were novel implementations of existing methods or processes, adapted to support the innovative nature of the project. The following section introduces the manufacturing methods and how they were used in this research. This provides a general understanding of processes covered and some of their inherent opportunities and challenges.

2.2.1 Digital Fabrication Processes

Computer Assisted Drawing (CAD)

While most design work in this research started with hand drawn sketches, they were ultimately recreated in CAD. 3D modelling was crucial for fabricating designs related to the research, such as electronic enclosures, connection methods and mould blocks. The primary software used for producing CAD models was Fusion 360 (Figure 23).

CAD offers a wide range of benefits in being able to design and test parts or components without having to make them. Additionally, parametric modelling affords the ability to have designs that can be easily adjusted or changed after they have been made. Within the modelling software there is an array of functionality, including the ability to program a computer numeric controlled (CNC) router (Figure 24).

Large open-source CAD libraries and electrical component libraries also offered a quick and effective means of laying out component footprints for designing enclosures around. Enclosures and moulds are also easily fabricated with 3D printing, another key method used in this research.

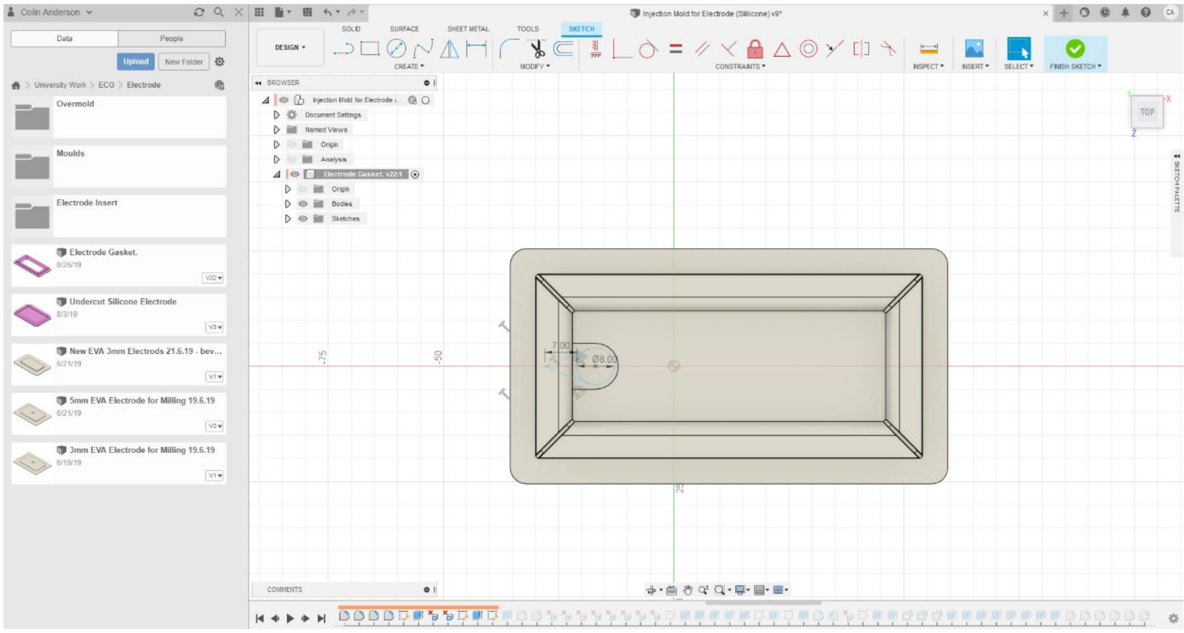

Figure 23

Fusion 360 sketch view in general CAD environment.

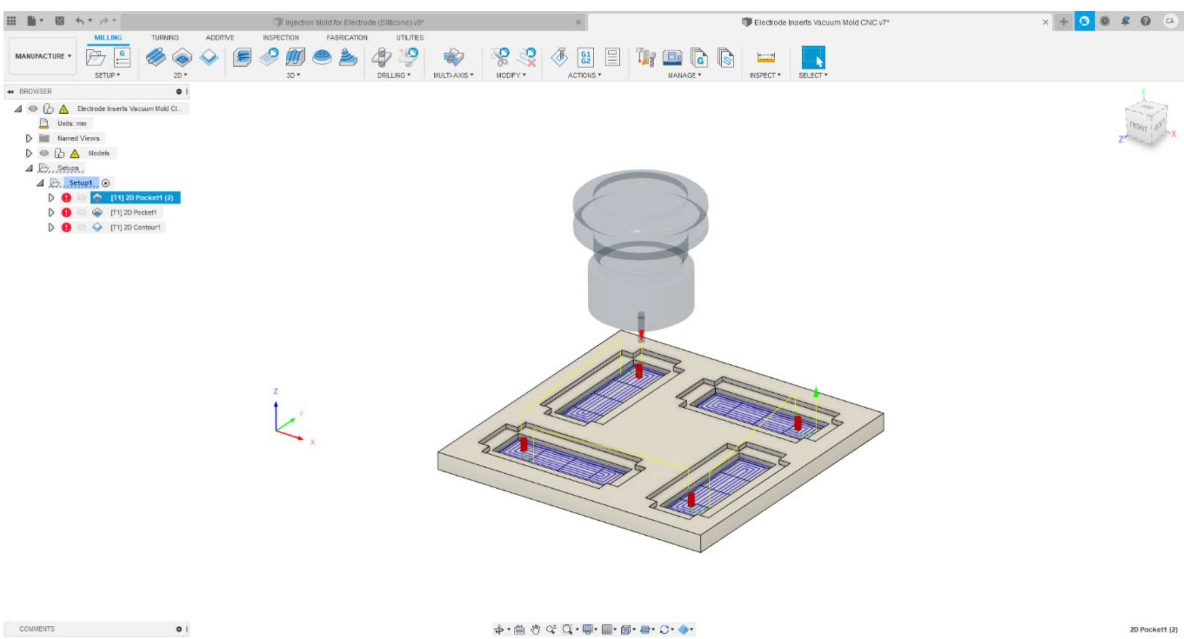

Figure 24

Fusion 360 computer assisted machining (CAM) environment.

3D Printing

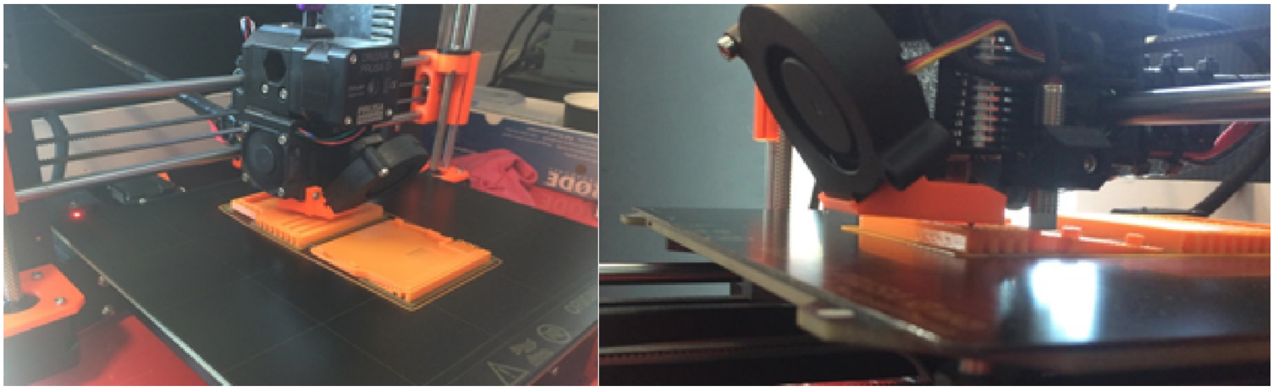

Figure 25

3D printer creating an enclosure.

3D printing was most often done via fused deposition modelling (FDM), the most common form of printing in consumer 3D printers. In this process a firmament is fed through a heated nozzle attached to a motorized gantry, this then lays the extruded material down on a heated bed (to stop extruded plastic cooling too quickly and then deforming). The printed model is built up layer by layer by the extruded material until the 3D model is completely fabricated. There are a number of challenges in fabricating in this way that require special consideration when designing the form to be printed. The main 3D printer used for this was a Prusa MkII, as seen in Figure 25. Considerations for printing involved:

- Reducing complex geometries: tight curves, over hangs etc
- Adjusting fit tolerances based on printing specifications ensures printed parts fit well, in addition to ensuring clasp mechanisms function correctly
- Build orientation: the way the part is printed can dramatically alter object fidelity
- Enclosure thickness: Determined by the optimal wall thickness of the printer (the width of the nozzle extrusion in multiples) eliminating the need for bridging material and strengthening parts.

3D Printed Injection Moulding

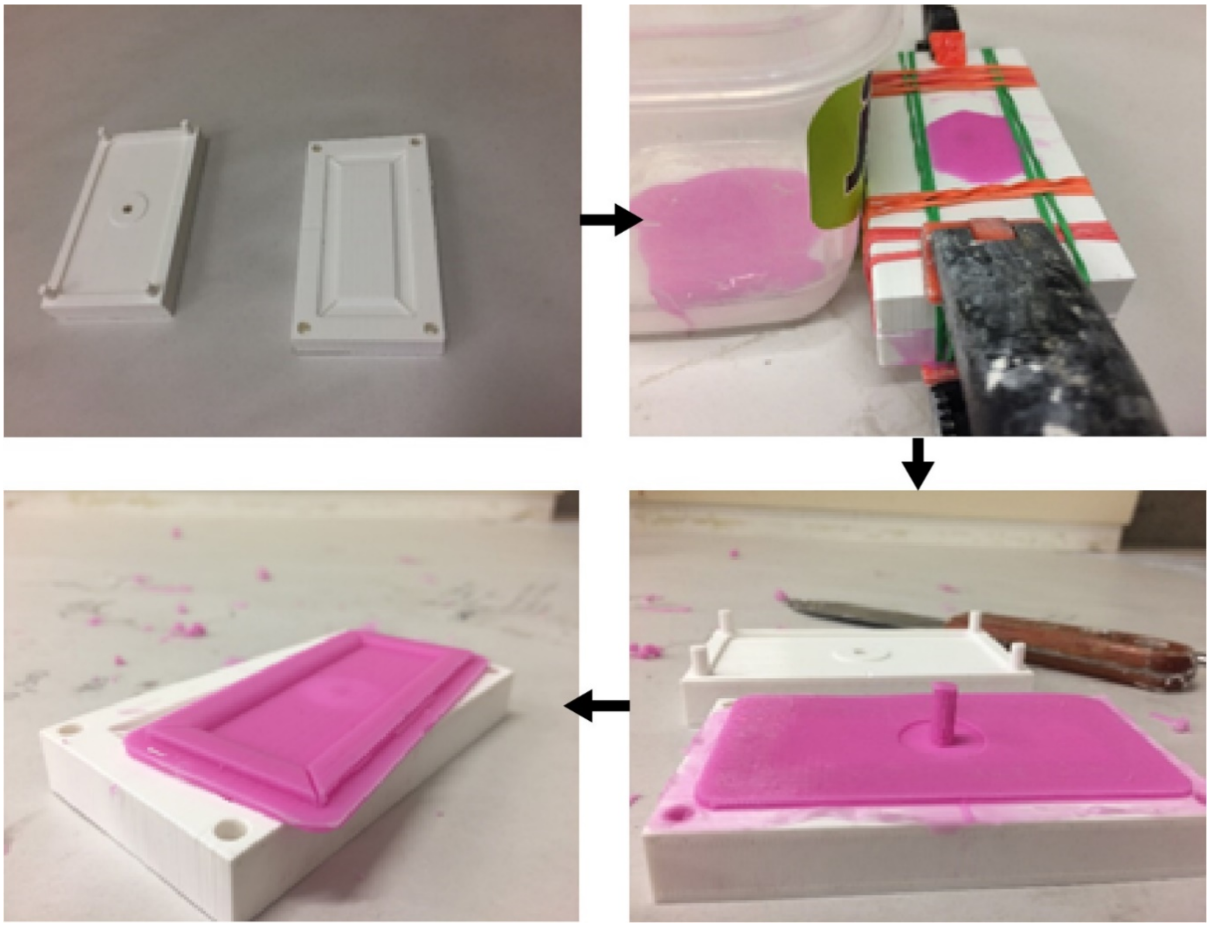

Figure 26

Injection Mould Being Created From 3D Printed Mould Block.

Due to the low exotherm and supple nature of silicone, the 3D printing of mould blocks was an ideal approach for producing complex silicon forms to interface with textiles and e-textiles in the research. In this process a mould block is printed containing a negative interior space. The block has one key opening, or gate, for silicone to be injected into. Silicone has a workable viscosity as soon as it has been mixed, but quickly hardens. Immediately after being mixed, the silicone is pulled into a large syringe and then injected into the mould block. This process is shown in Figure 26.

The actual fabrication of the mould blocks presented some challenges, moulds require post processing to be suitable for casting, the relatively low fidelity of FDM printing also meant that low resolution was transferred to the resulting mould.

Overmoulding

Over moulding was considered early in the research but only prototyped and developed subsequent to the IBTech portion of the project. In reality this is a mix of processes beyond just digital fabrication. The process involves injecting silicone into machine knit using 3D printed overmould blocks. This allows silicone to be cast directly onto the garment, forming a composite material as shown in Figure 27. Early prototypes cast onto a machine knit were suspended in Tupperware to test whether the materials would bond suitably. The more developed aspect involves a 3D printed mould that clamps the fabric section and seals the silicone in place.

Figure 27

Prototyping silicone overmould on machine knitted garments. Magnets embedded in silicone

Computer numeric control (CNC) Routing

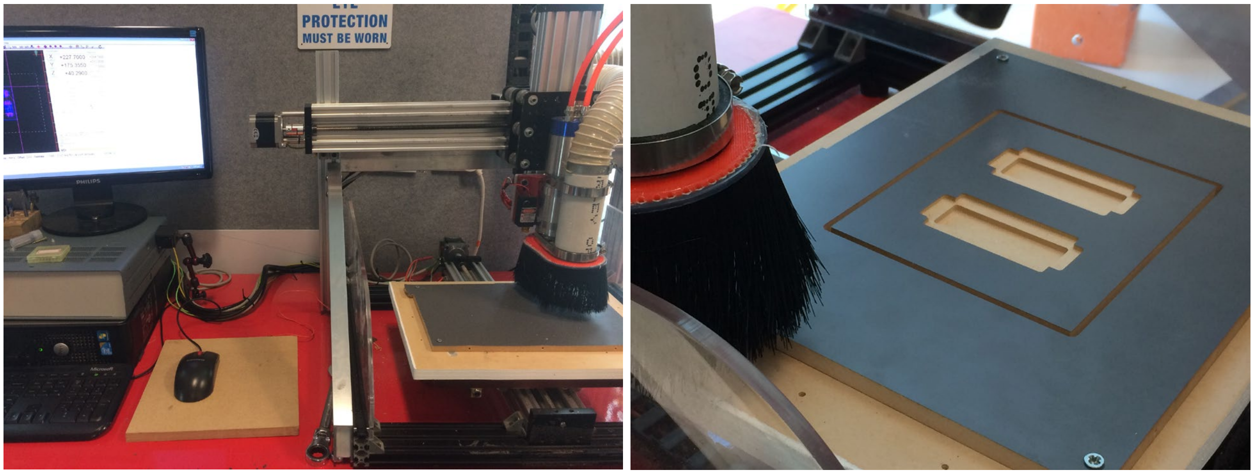

Figure 28

CNC router and machine block of vacuum forming.

CNC routing was carried out on a custom-built desktop CNC by the Creative Technologies mechatronics lab technician (see Figure 28).

CNC routing uses a computer-controlled routing piece to reductively manufacture shapes or forms from a piece of material like wood or steel. In this case it was used to create the mould plugs for vacuum forming. CNC as a process was far more time intensive and costly compared to digital fabrication processes like 3D printing or laser cutting. This is due to the machine needing specific programming to mill the object. These specific instructions are also known as g-code. This programming is an added step in the modelling software that requires creating a toolpath for the routing piece.

2.2.2: Vacuum Forming

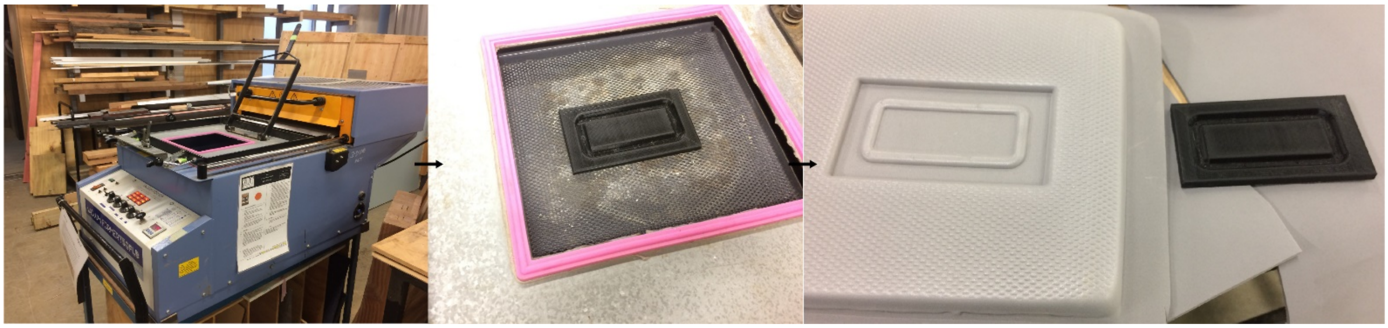

Figure 29

Vacuum Forming Process.

Vacuum forming ethylene-vinyl acetate (EVA) foam was completed in AUT's design workshop using a Vacuum Former 750 FLB unit. Primarily this was done with 3mm thick EVA. The vacuum functions by using a clamp and gasket unit to seal off the thermoplastic for the vacuum to be effective. The bed size for a mould plug sits around 10cm below the gasket brim and is raised with a lever on the side of the machine.

In this instance EVA was secured in the clamp and a CNC milled MDF block was used as a mould plug. The process was combined with e-textile attached to the EVA to generate a novel output for 3D formed conductive textiles as shown in Figure 29.

Chapter 2.2.3: Sewing

Sewing served to provide finishing for both the garment and electrode aspects of the wearable design. A less robust sewing machine was used for prototyping, while more skilled technicians provided expertise in operating specialised industrial machines for specific designs as seen in Figure 30.

Figure 30

Technician Sewing Silicone to fabric.

2.2.4: Machine Knitting

Machine knitting for this research was carried out at the Auckland University of Technology Textile Design Lab (TDL) (see Figure 31). For this the Shima Seiki WholeGarment SWG041, 14 gauge knitting bed was used for machine knit belt prototypes.

Machine knitting offers several unique benefits and powerful, novel outputs. Having had previous experience in developing e-textile garments with this technology, there was an awareness of the strengths and possibilities in the medium. One of the key strengths of machine knitting is the ability to produce 3D knitted forms in full garments. It also allows for the splicing and mixing of yarns and materials in addition. This a key strength for this research as it allows for the inclusion of conductive and more mechanically advanced yarns.

Figure 31

Full garment knitting machine.

2.2.5: Testing

For the duration of the IBTech team project, mechanical and electrical testing was performed by the lead engineers. In turn they would offer feedback around designs. This relationship was established at the onset of the project and carried on until ceasing work with IBTech.

Unfortunately, after the first phase of the research ended with the group, it appeared testing had not been performed. On enquiry, data could not be provided for the research in this thesis. After the team portions of making, some preliminary signal processing and electrical testing was performed using a Data Acquisition Module (DAQ) (see Figure 32). Testing in these incidences was subject to looser testing protocols and as such data from these results should be considered only for indicative purposes.

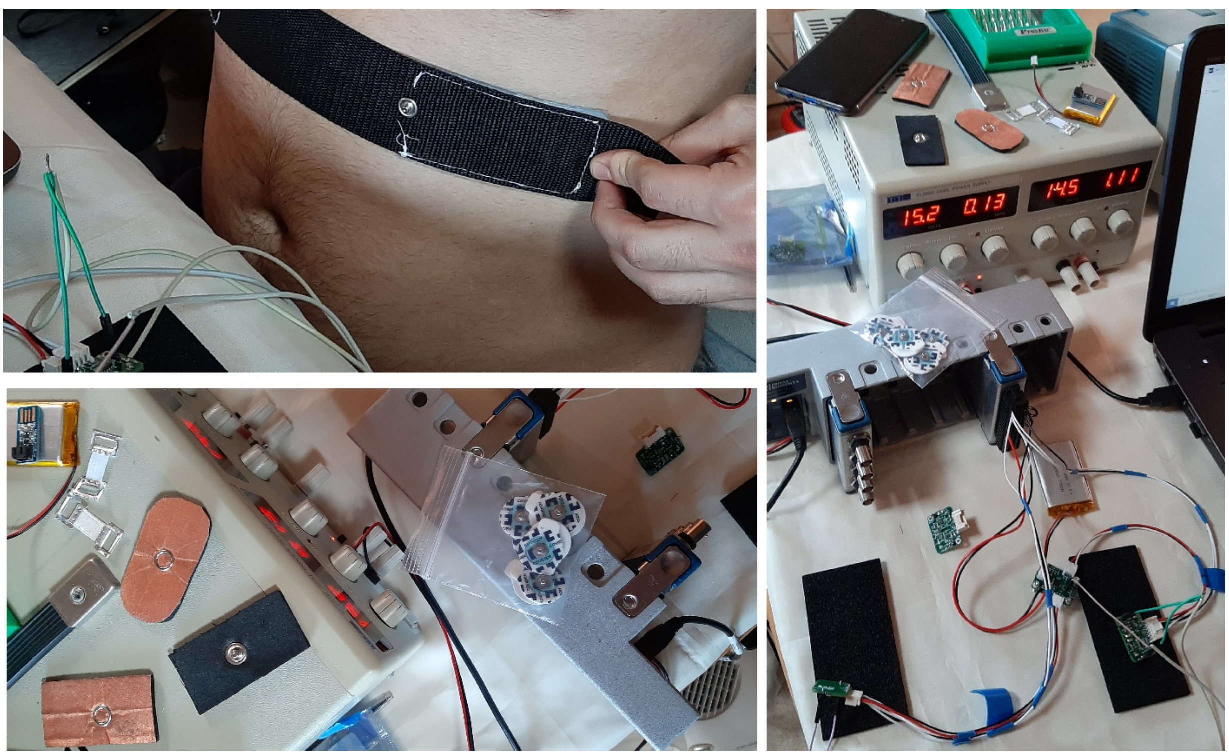

Figure 32

Testing e-textile electrode using a Data Acquisition Module (DAQ).

2.3: Research Design

In practice, it appears the development of the various components happened in sequential fashion as shown in Figure 33, but because the design involved so many components in parallel, but had only one designer/fabricator, there were often bottlenecks and disruptions in the process. This made presenting a cohesive step-by-step account of the process difficult. In response I chose to separate the documented practice into the major components of the wearable. Each component is discussed in its own section.

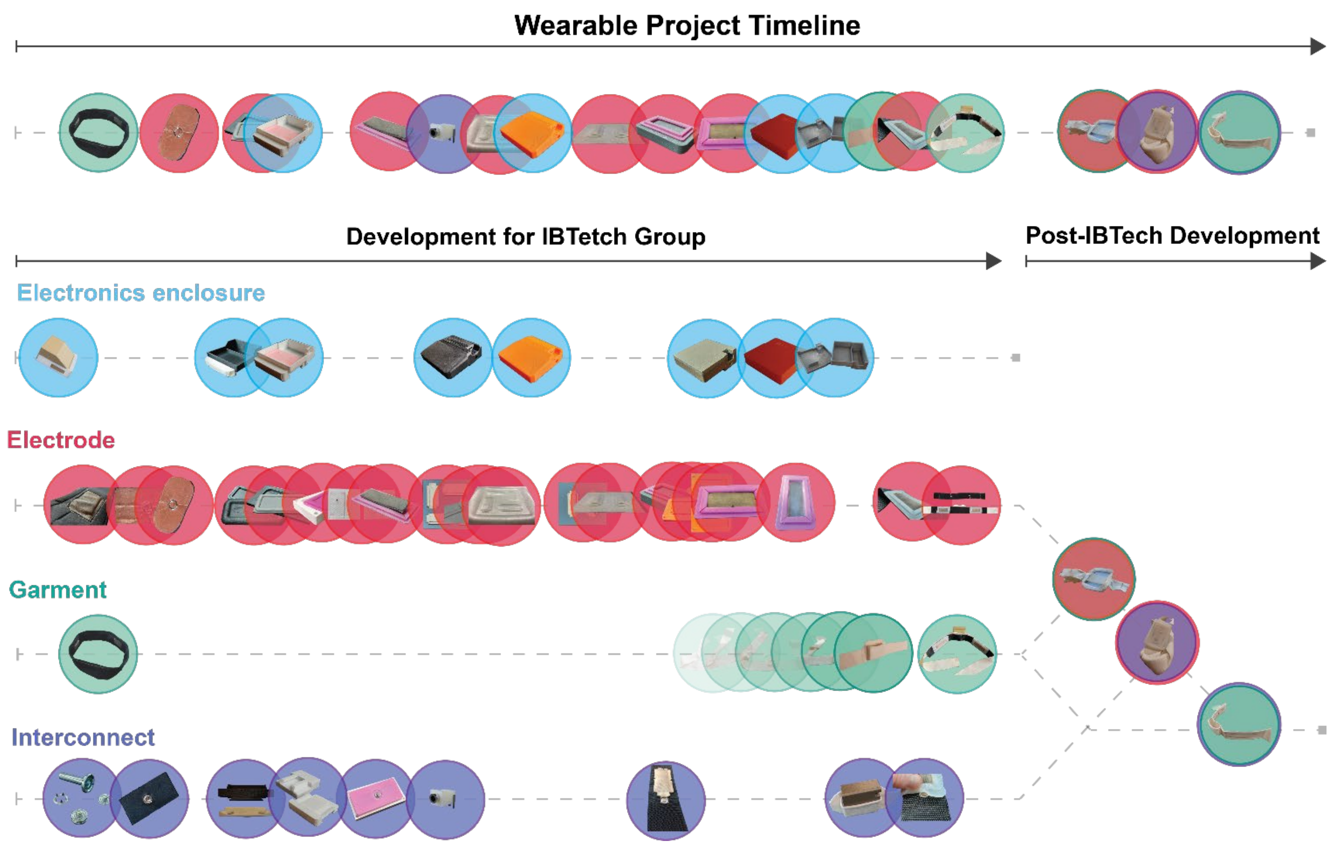

Figure 33

Project Timeline.

The component sections detail the primary concerns or challenges, and what was designed and fabricated with those considerations. Within each component section, major iterations were identified in the development process. These often overlapped or interlinked, as the components were frequently developed in parallel. The lower section of Figure 33 represents the timeline of the development process broken down into components, and their major iterations. The order the sections are presented reflects the initial order work started on each component, however interconnects are left till last as the enclosure, electrode and belt sections help provide context for interconnect development.

Beyond the IBTech group project, development of some components was continued. This was to improve the performance and functionality of some of the components developed with IBTech. This process occurred after the IBTech group project and is subsequently discussed after the IBTech phase of the research. The following chapter details the practical component of the wearable design as described in this section.

Practice: ECG Wearable Development

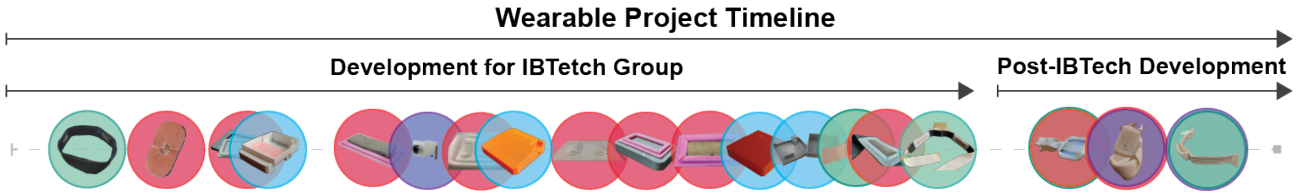

Figure 34

Main Timeline. Arrows indicate the two phases that occurred and their relative length to the project.

As outlined in the previous section on research design, the presentation of practice is categorized into four components, colour coded to help with separating developments that occurred in parallel. The components sections discuss practice in a linear fashion, going through major iterations, processes involved and the interlinking developments. As shown in Figure 34, the bulk of the practice occurred during the IBTech phase of the project. Given this is where the research began, it defined the direction of practice. Beyond the team phase of the project, time was spent developing, amending and integrating components created during the IBTech phase of the project. Due to being individually driven it takes on a more linear, personal narrative compared to the practice documented in the IBTech phase.

Chapter 3: IBTech Team Project

The following sections cover the development of designs and documentation of practice for the components in the following order: Electronics Enclosure, Electrode, Belt and Interconnects.

3.1 Electronics Enclosure

Figure 35

Timeline of enclosure iterations

3.1.1: Enclosure Goals

The design of the electronics enclosure involved creating a housing to safely hold the electronic componentry designed by the engineering team (see Figure 35 for iterations designed for IBTech). The main technical requirement was that the electronic components needed to be grounded to reduce interference noise in the circuit, such as those discussed in the biopotentials section of the literature review. In my role I considered factors such as the aesthetic, comfort and usability of the belt and its components. Ultimately any concerns of fit or form would be secondary to the electrical components chosen.

A key focus in my practice for producing the enclosures was form, aesthetic, fit and a pragmatic approach to interconnecting the different conductive parts. This required consideration of the body and how it moves. For instance, designs should be low profile, with the intention of positioning any enclosures smartly on body area dead zones (Ferraro & Ugur, 2011). To effectively achieve these goals, there needed to be some compromise between the form and the focus on the technical functionalities. This tussle would prove difficult to reconcile at times and is further discussed throughout the making.

3.1.2: Early Enclosures and Enclosure-Garment Interface

Provided the availability of open-source CAD models of the electrical components and with industry products as examples, this area required the least innovation in how it would be designed and fabricated. However, the added consideration of figuring out how the enclosure would intuitively interface with the garment in a robust way factored in heavily in early prototypes. This can be noted in the design timeline (Blue, Green, Purple) in the Research Design sections (Figure 38), showing the interconnect between belt and enclosure was not explored again until much later in the project. This was due to rapidly changing hardware requirements and the team requiring outputs for other aspects of the design.

From early product research we identified several locations on the body we could position the electronics. One ECG garment placed the electronic housing asymmetrically on the body; below the left ribs more to the side of the torso (Steinberg et al., 2019, p. 3). To interface the electronics, they used a series of clasp buttons to attach the hardware to the body (see Figure 36).

Figure 36

ECG product with button snap attachment.

Figure 37

Hard pocket on wearable ECG product.

A few products were considered by the team for the wearable. Among the potential form factors considered were belts, shirts, singlets, harnesses, and slings. All the potential garments offered strengths and weaknesses, but some could facilitate the different components involved in the design better than others. Based on what we had seen in industry products along with the smaller form factor and ease of development, the team chose a belt design at the time and moved forward on that basis. The alternative, a harness design, becomes complicated or impractical in a unisex design. Based on the 'designing for the body' section in Chapter 1, the dead zone in the centre of the sternum was chosen to place the enclosure. This is somewhat contrary to Ferraro et al. (2011) due to what was perceived as a lack of symmetry in offsetting the position of the enclosure over the rib. The position of the device over the sternum was still in line with considerations offered by Gemperle et al. (1998) and the enclosure weight would not pull awkwardly on the garment. This would have been ideal, provided we could keep the components small and the enclosure profile low enough.

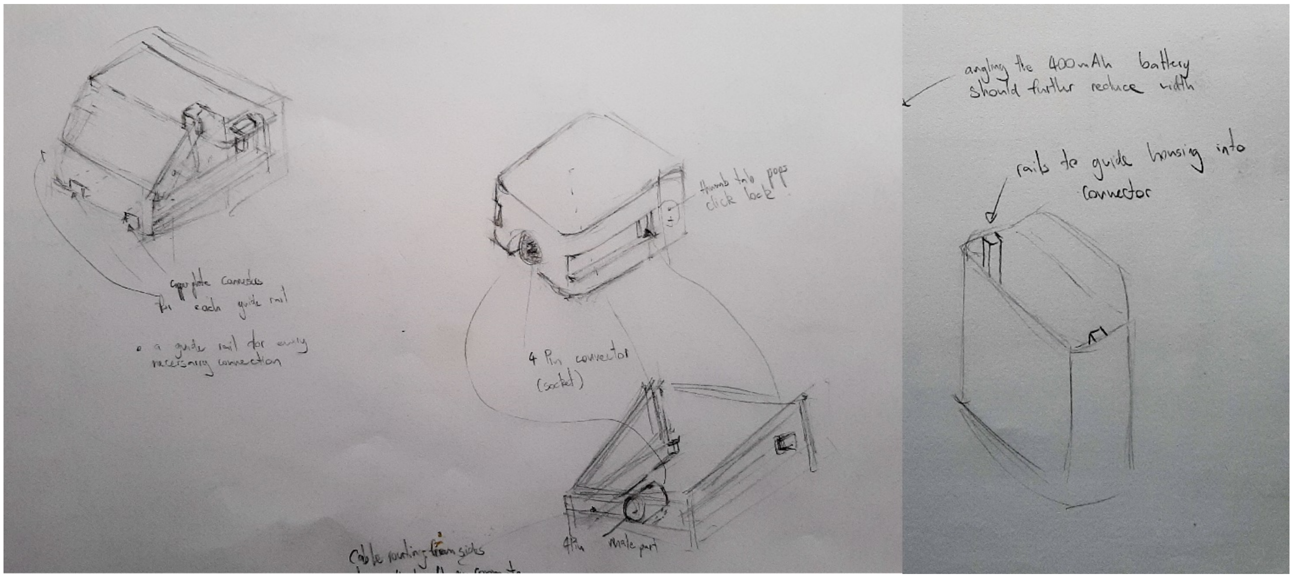

Figure 38

Concept Sketches for first enclosure.

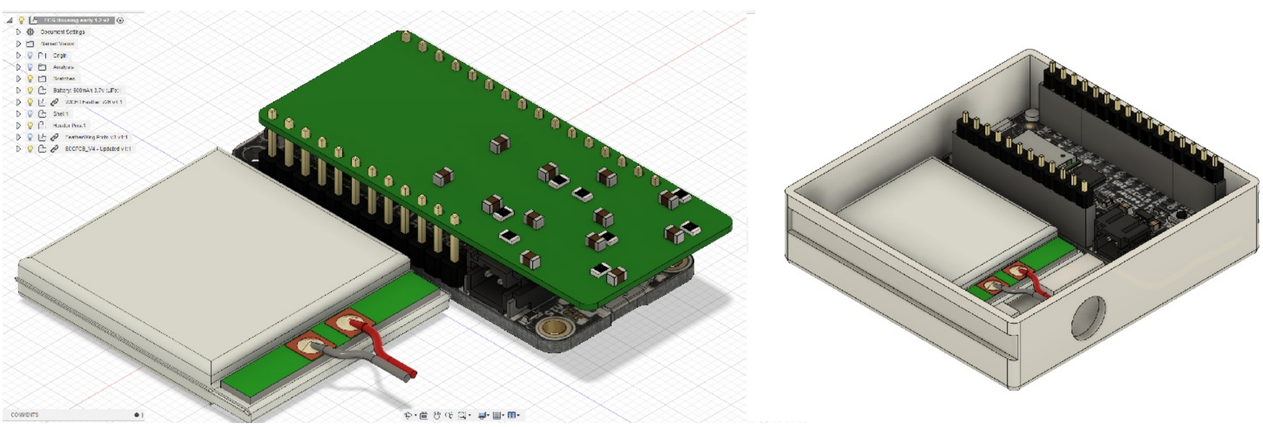

Figure 39

Internal electrical components arranged in smallest footprint

The first enclosure was created with inspiration from a product containing a hard sleeve/pocket that would guide the enclosure on correctly while ensuring a stable connection (see Figures 37, 38). To do this an enclosure was created that housed all the components in as small a footprint as possible (see Figure 39), but on its body facing side, had indented rails on either side (see Figures 39, 40). These interfaced with a hard chest piece with belt loops on the garment. The rails would serve to guide the enclosure onto the garment. The concept envisioned an interconnect at the centre base of the chest piece that would interface with the enclosure, as well as protect the garment side interconnects as shown in the Figure 38 concept sketches.

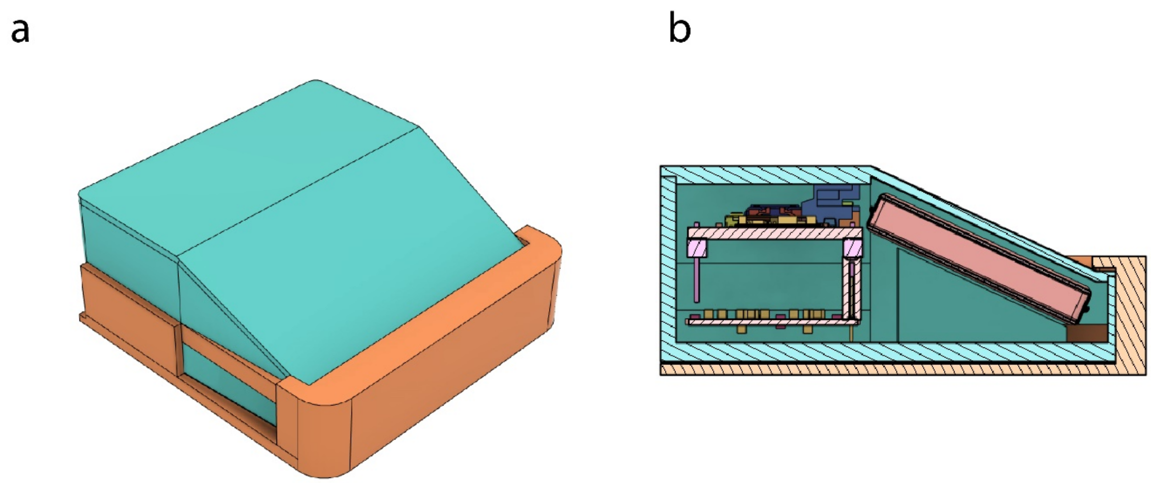

Figure 40

a: developing rail design concept for enclosure interface. b: CAD mock-up of first enclosure design.

At this stage the enclosure itself was rudimentary in design and focused mainly on matching the electronics footprint and interacting with the body (see Figure 40a). This plate would undergo two further revisions. Identifying that with the rails on the outside, the enclosure would likely pop off its rails if subject to excessive flex (see Figure 41), the design was re-imagined with a central rail on the chest piece. This would ensure a thin but robust connection to the garment while also protecting the interconnect between enclosure and garment (Figure 42). This also meant I could also leverage the thin battery to offset the awkward component footprint by raising it above the rail and creating a more uniform enclosure as shown in Figure 43. In addition to the interface redesign, the enclosure chest piece form was articulated for the sternum area.

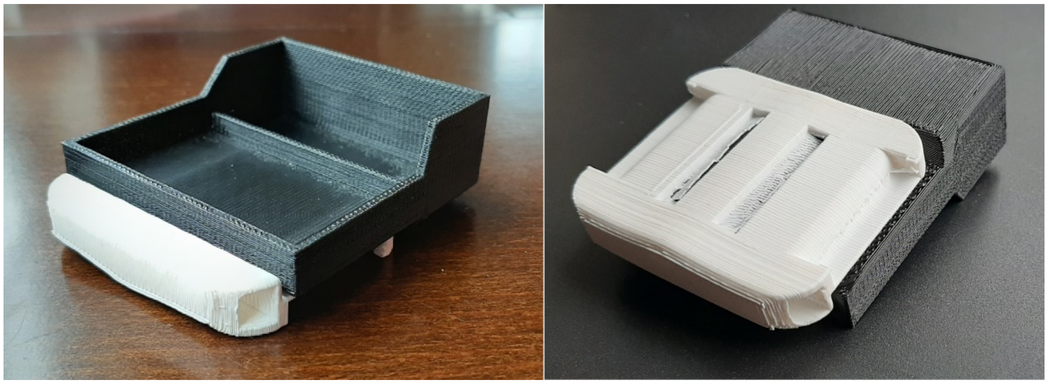

Figure 41

3D print for first developed enclosure with interfacing chest piece.

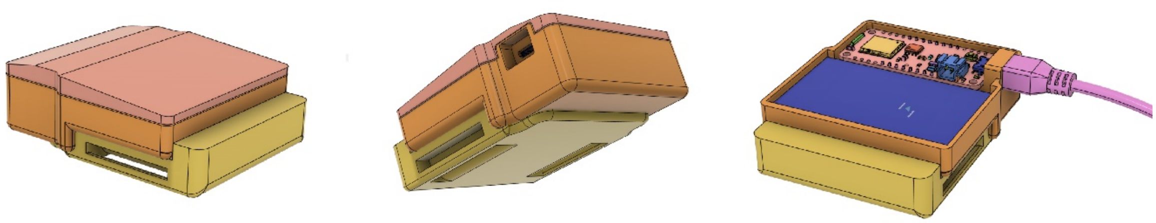

Figure 42

CAD for second developed enclosure, now accommodating micro USB.

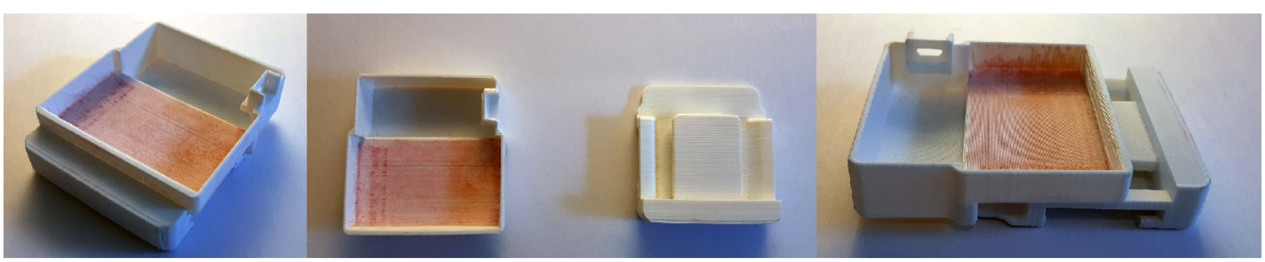

Figure 43

3D print of second enclosure

A consistent challenge in designing the wearable ECG/housing/enclosure was that the printed circuit boards (PCB) and electrical components being used were not ideal in that their size was not optimized relative to one another. The Feather and shield stacked together produced a processing unit almost 30mm in height, while in comparison the 400mAh battery was thin but had a wider footprint than the PCB stack. This meant initially settling on the wedge like form seen above as it produced the lowest profile. Redesigning the PCB to minimize vertical height and making better use of the relatively large dead zone on the sternum could be areas worth further research and are discussed in the conclusion.

3.1.3: Enclosure Redesign

At this stage, several changes had been made to the hardware, requiring the enclosure to be redesigned. Namely the team upscaled the battery multiple times, from 500mAh to 800 to 1200mHa and finally to 2000mAh (see Figure 44 for size comparison). This was due to the engineers being unable to use Bluetooth and low energy Bluetooth for data transmission. Subsequently they moved to Wi-Fi, a higher bandwidth transmission protocol but with a substantially more demanding power draw. The upscaling from 500 to 1200mAh presented new challenges in designing the enclosure. At the same time the battery was being upscaled, it was decided to shift away from the original idea of a belt and begin considering a range of different garment ideas such as the ones that had initially been discounted like t-shirts and vests. This was due to indecision around the best placement of electrodes on the body and the engineers desiring a garment that would let them adjust the electrode position. To do this the engineers decided to use readymade, off the shelf garments to prototype and explore ways to deploy electrodes on the garment in an ideal arrangement. Due to this, the design of the chest piece that would interface the enclosure was suspended and I was tasked with designing an enclosure optimized purely for profile and manufacturability. Time sensitivity for making in this regard was difficult to communicate as the team were largely unfamiliar with the details of most manufacturing processes. This contributed to several bottlenecks.

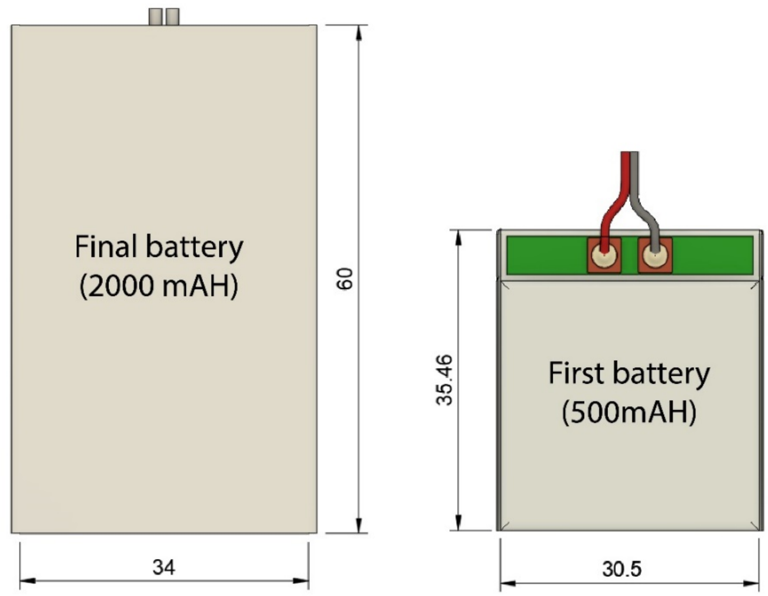

Figure 44

Example of battery size growth between first and last hardware iterations.

The transition from Bluetooth to Wi-Fi raised some difficult conversations around the ballooning size of the enclosure which made apparent that concerns of wearability were subordinate to the components and function of the enclosure.

For the new form of the enclosure, in addition to the enclosure now protruding from the body further and weighing more, the battery size differential meant that accessing the ports on the microcontroller required creating a notable inset in the housing to accommodate the micro USB connector (as shown in Figure 45).

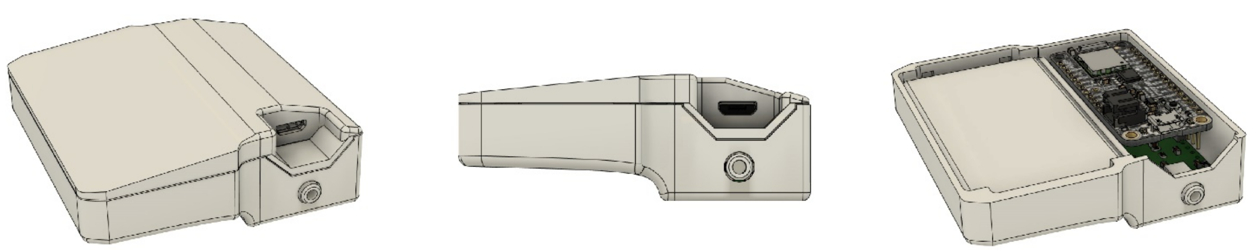

Figure 45

CAD of new enclosure without rail and including a 2.5mm auxiliary connector.

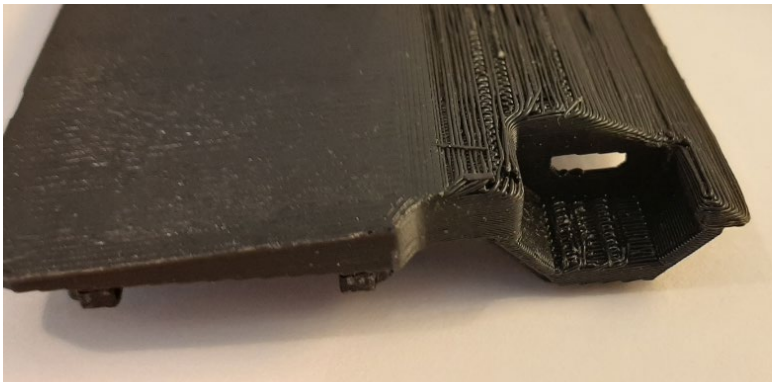

Figure 46

Example of complex geometries being difficult to fabricate accurately with 3D printing.

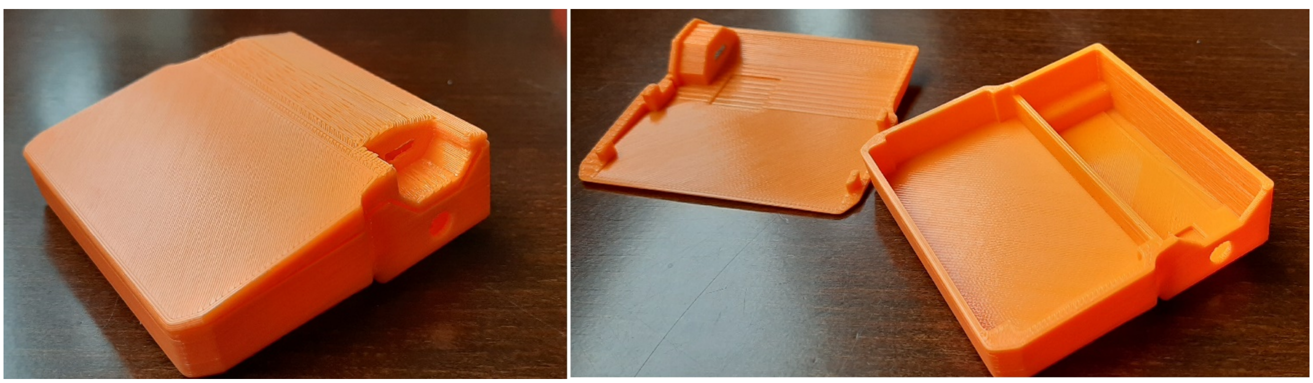

Figure 47

Refined third enclosure.

This introduced a far greater complexity in the geometry of the enclosure and its ability to be printed easily (see Figure 46), requiring several iterations and heuristic learnings on FDM printing design considerations to produce an accurate form to spec (see Figure 47). In this instance the design changed to increase the ease of printing, by reducing geometry complexity. This resulted in a simple, blockish enclosure that had port access for a 2.5mm jack and micro USB as shown in Figure 48. While this did not articulate well to the body, a compromise was made between the time available and the failure rate of prints when the form was too complex. Shallow angles or spline curves created awkward distances to step the extrusion over, increasing the failure rate (Figure 46). Despite the reduction in wearability this suited the teams needs at the time for prototyping modularity (See Figure 49).

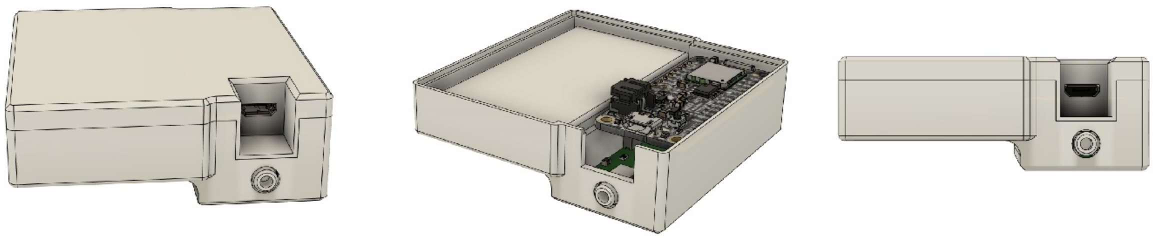

Figure 48

CAD profiles of final enclosure for IBTech.

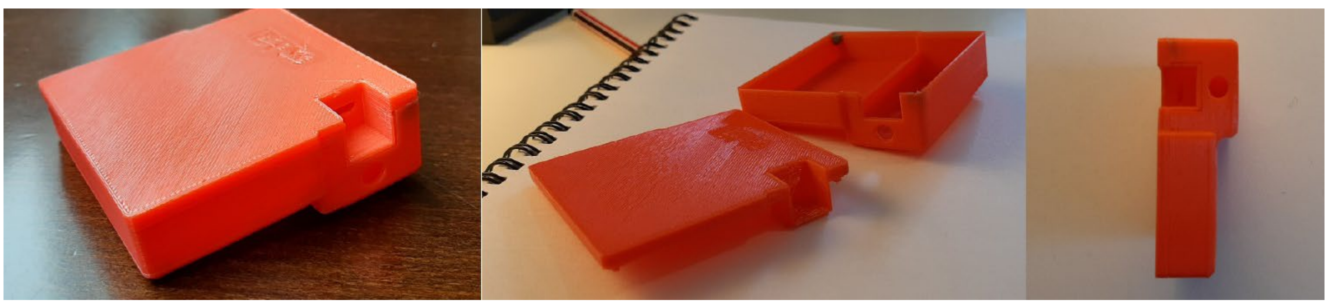

Figure 49

CAD and 3D Print for final enclosure. Simplified geometries guaranteed successful prints.

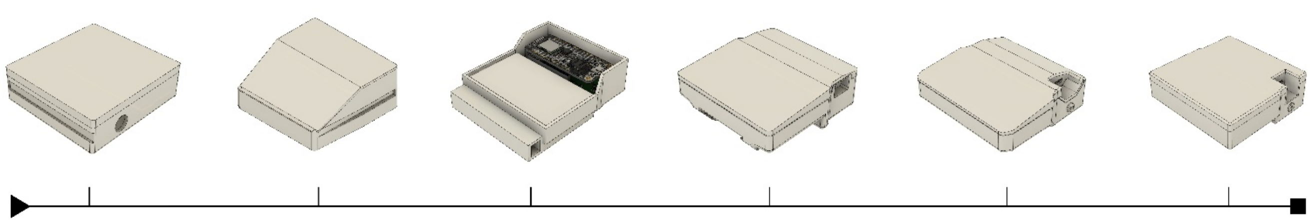

Figure 50

CAD timeline of enclosures.

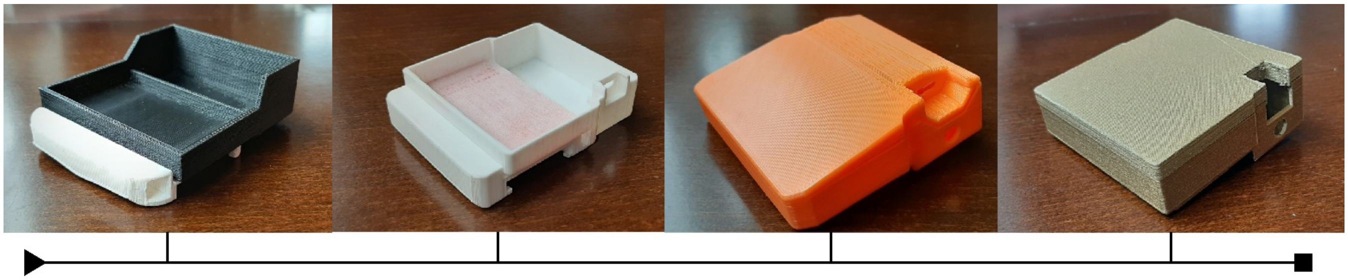

Figure 51

Timeline of enclosure 3D print development.

The entirety of this process was completed using two main methods, CAD (see Figure 50 for CAD timeline) and then fabricating with FDM 3D printing (see Figure 51 for printed enclosure timeline), as detailed in the practical approaches chapter. Reflecting on each iteration offered several valuable insights. These considerations are offered for generating enclosures for electronics: CAD for 3D printing as it relates to wearables design.

- Keeping the profile and footprint of the enclosure as small as possible: The smaller the components the better, but space should always be optimised to be as low a profile as possible.
- Make body-facing hard elements humanised: Making enclosures conform to body curvature increases comfort for the user, though it introduces difficulties in FDM manufacturing.
- Orienting hardware to prioritise easy and clear electrical connections: How does the enclosure interface with the garment side and how are internal PCB orientated to promote interconnection.
- Being mindful of the manufacturing process. This is critical in having successful outputs: FDM was limited in the fidelity and complexity of geometries that could be created.
- Cable routing and ports for connections: Allowance, or headroom, should always be made for cables and pin connectors inside the enclosure. Smart cable management requires thoughtful understanding of the PCB layout and function.

3.2: Electrode:

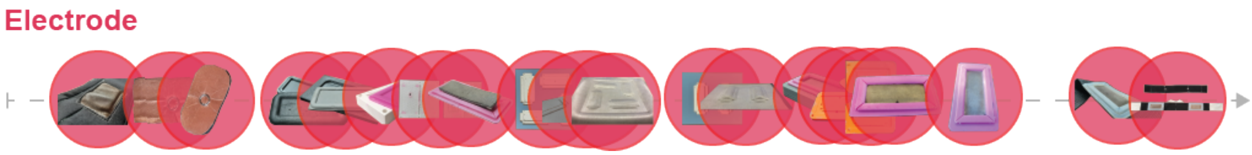

Figure 52

Timeline of Electrode Iterations.

3.2.1: Early Challenges and Concepts

Another core goal of this research was to create designs substituting the standard silver chloride (AgCl) electrodes for e-textile electrodes to make an ECG garment suitable for long term wearability (Figure 52 shows timeline of electrode iterations and developments).

At the time of joining the project, early electrode prototypes were envisioned as having on-electrode processing. This meant that each electrode would have to be backed by a corresponding rigid PCB. The on-electrode circuit board would then feed the acquired signals to a central processing unit, or micro controller, that would in turn algorithmically reconstruct the signal. Figure 53 shows the concept sketches for an embedded electrode and circuit drafts for an onboard sensor layout.

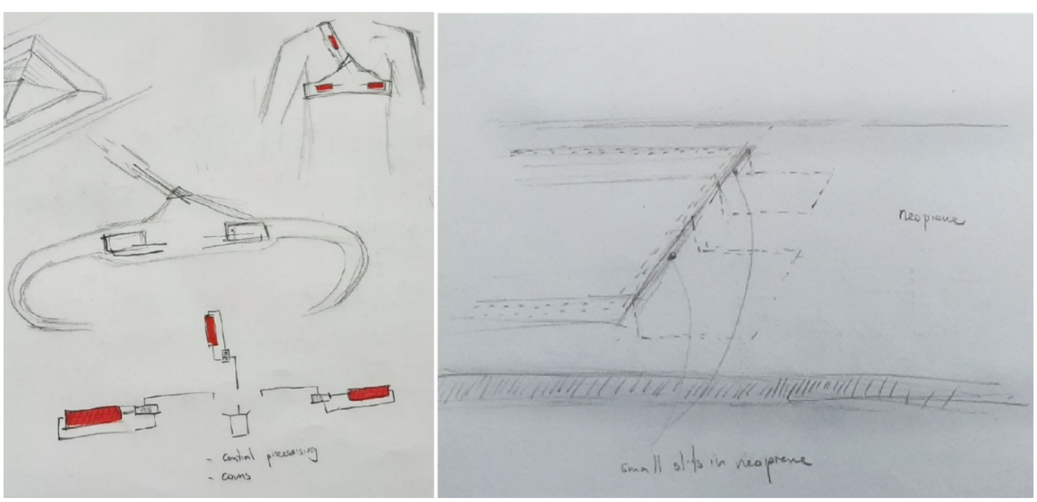

Figure 53

Electrode Concept Sketches.

Previous research around wearability gave the impression that implementing the hardware on the belt in this way would be challenging as the electrodes need to be convex to fit with the sternum. The first clear obstacle to this was having embedded hard components in the soft garment that sit above a natural curved part of the body. Additionally, due to the difficulty of designing electrical hardware around the body, a hard to soft interface is often handled with proprietary connectors, or standard connectors implemented in novel arrangements (Agcayazi et al., 2018, p. 1-5). Any hardware connections or electronics remaining on the garment should be machine washable and any soft circuits or e-textiles should be tarnished, or pre corrosion treated, to be able to survive the repeated exposure to sweat and washing.

Implementing hard PCB-backed electrodes would require that the electrodes be removable, or modular in some way for washing purposes. Earlier work had shown that modularity is often beneficial to wearables and likely worth exploring. Modularity may have offered a platform for the electrode processing, but the engineers made the decision to try to resolve signal reconstruction on the main PCB. However due to the lead engineers already testing with off-the-shelf AgCl electrodes, the current clinical standard, they did not need immediate action on electrode design for that stage of the project. This allowed for time to be invested in parallel developments like the enclosure, belt, and interconnects. It also allowed for experiments with possible electrode designs under less pressure.

3.2.2: First Embedded Electrode

In the first belt, developed in parallel, the electrode was embedded in the garment as shown in Figure 54. This represents the first electrode in the project but was more oriented toward testing mechanical factors. The garment had a window cut out with silver cloth sewn in with a pocket behind so the team could test various hardness foams inserted behind the electrode (see Figure 55). This allowed the engineers to test electrode density and thickness variations, ultimately discerning that having a firmer backing would help maintain physical/electrical connections through pressure.

Figure 54

First Belt with embedded electrode.

Figure 55

Pocket behind electrode allows for varying density

3.2.3: Heat Adhering E-Textiles - Material Exploration

The first individual, or non-integrated prototypes for the electrodes were small squares of ethylene-vinyl acetate (EVA) that had different e-textiles attached using heat activated adhesive (Figure 56). This exploration of heat adhesives with e-textile materials early in the project turned out to be a boon to development. This was due to the ease with which it can be applied to fabrics, and it still allows fabrics to behave naturally after adhesive bonding.

Figure 56

Early Electrode Designs using copper taffeta.

To create the initial electrode prototypes, a few foam inserts were cut in similar dimensions (approximately 35mm by 60mm). Due to the difficulty in attaching conductive materials with sewing or traditional glue, I opted to use a heat activated fabric adhesive that could be applied using an iron. This attachment proved thin, bonded well, and flexed naturally. The e-textile formed a strong bond with the foam and created a firm conductive pad. The pressure and heat applied to the EVA, a thermoplastic, did however reduce the thickness of the foam and increase its rigidity.

The predominant method of attaching electrical connections, or interconnects, to the pad prototypes was to use snap lock buttons/clasp buttons. However, there were two variations in construction that changed its feel vs function. The first being before heat adhering the conductive fabric, the foam had a snap button punched through. After this the conductive material would be applied to the side with the flat ring. This looked the cleanest as the conductive element was not visible, but the heat adhesive is not a good conductor and made the signal unreliable between the conductive cloth and the button snap. The second method was to apply the button snap after heat adhering the e-textile, so the pad surface would have a metal ring present in the fabric, in this way the teeth would actually bite through the material, forcing a connection. Despite being unsightly, this ensured the best connection between the conductive elements and offered a means of penetrating a signal through an EVA layer (Figure 57). This could be resolved with an appropriate conductive adhesive to enable reliable signals using the first bonding methodology that covers the metal ring.

Figure 57

Button snaps for attaching ECG leads to electrode

The key conductive materials used in this phase were a conductive silver cloth (74% silver 16% Nylon core), and copper taffeta. The silver cloth is finely woven and provided several benefits, such as stretch and durability. In comparison the copper taffeta, while also woven, was more rigid, non-stretching and appeared easy to tear. As conductors the silver appeared better suited and more capable as an electrode. With all the benefits to wearability (breathability/antimicrobial) the silver cloth emerged as the choice for electrode material between Figure 58a and Figure 58b.

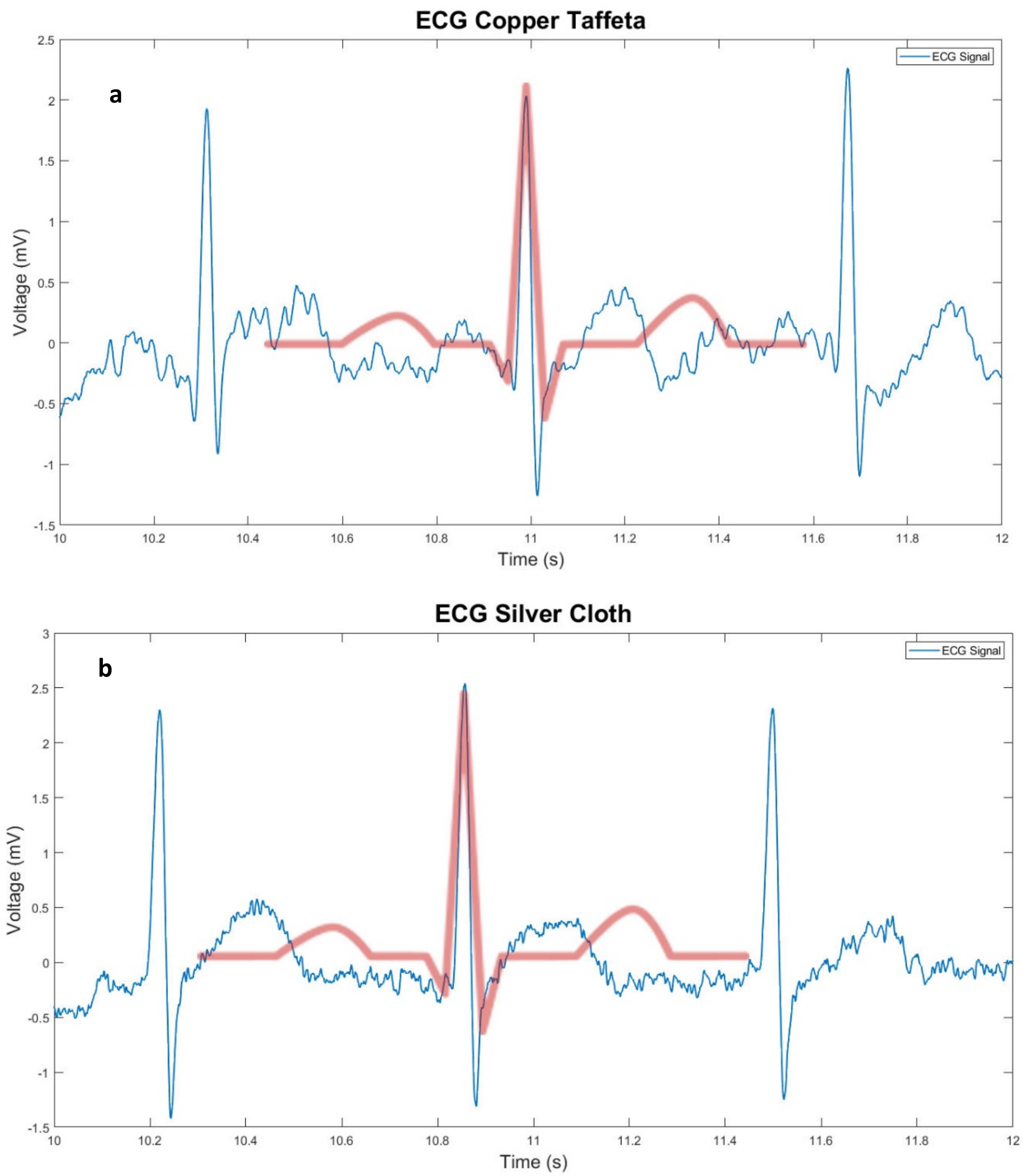

Figure 58*:*

a:ECG signal for copper taffeta EVA electrodes with overlay of 'ideal' ECG in red matched to the middle peak of signal. b: ECG signal Silver E-Textile EVA electrode with overlay of 'ideal' ECG in red matched to the middle peak of signal. The silver cloth shows greater consistency and more defined ECG shape.

3.2.4: Vacuum Forming with E-Textiles

In addition to conductive fabric selection, EVA material properties and fabrication techniques were being investigated. In a parallel, unpublished EEG research project, one concept explored using vacuum forming to manipulate EVA foam into comb-like shapes that could breach the hair line. While the design was not realised for EEG, it provided a novel solution for the ECG space. The theory being that the same materials could be used in an altered process to create 3D forms surfaced with an e-textile. This development, coupled later with silicone injection moulding, was critical in creating the final electrode output for IBTech.

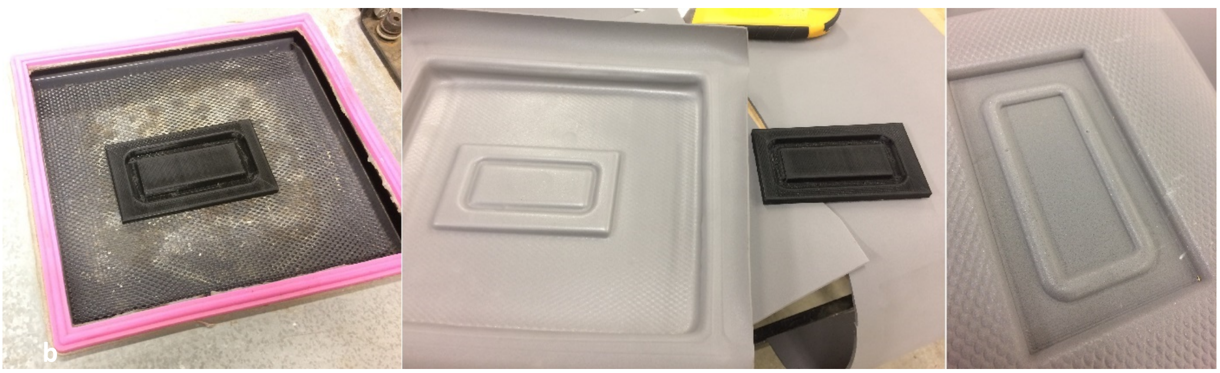

Figure 59

Negative Vacuum Mould plug and resulting mould

Figure 60

Positive Vacuum Mould. Note the difference in fidelity between two given the negative and positive mould plugs are same volume and shape.

Relatively thin at 3mm thickness, EVA made an ideal candidate for vacuum forming. Early on several positive and negative mould plugs were experimented with to understand the best output for a higher fidelity (See Figures 59, 60). The next challenge in generating this design was whether the process of heat adhering the e-textile to the EVA could be done simultaneously with the vacuum forming process. Due to the way the vacuum former works, the EVA panel is exposed to a high heat to soften it for forming, the heat being also sufficient to melt and bond the heat adhesive. Hypothetically, by applying a vacuum after softening the EVA and melting the heat adhesive, the vacuum would then forcibly bond the e-textile to the EVA through suction.

This proved to not be the case as the vacuum could not generate enough pressure to effectively bond the e-textile to the EVA, additionally the quick cooling effect of the vacuum likely reduced the effectiveness of the heat adhesive. To get around this fabrication constraint, the silver cloth would first be ironed onto the EVA sheets before vacuum forming (Figure 61). The first iteration of this method used a 3D print as a mould plug to create an embossed electrode as seen in Figures 59 and 60. To the knowledge of the researcher this is a novel method of producing 3D e-textile form. This offered an ideal solution for creating formed conductive textiles solutions for electrodes.

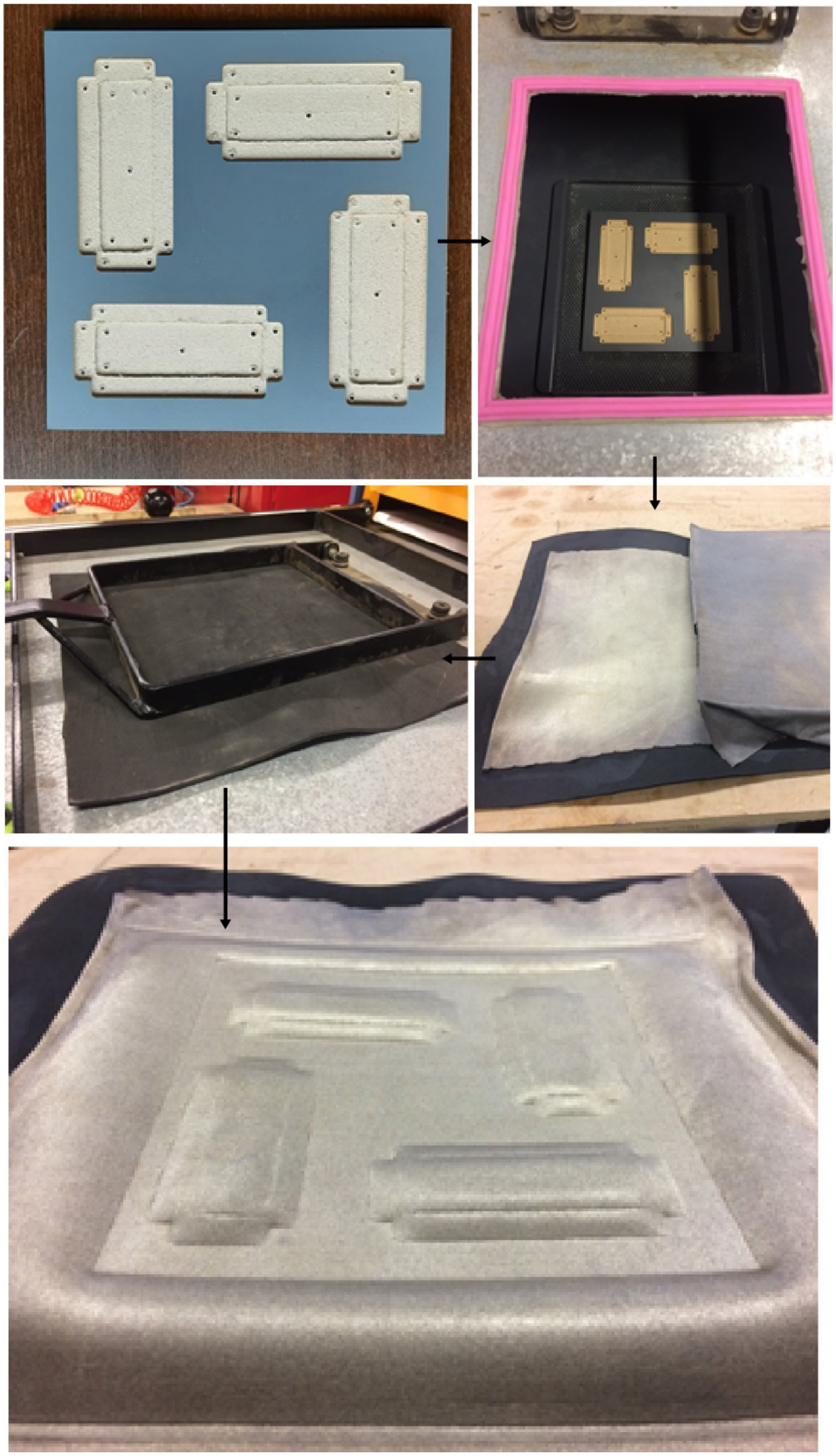

Figure 61

Vacuum forming EVA foam with conductive silver cloth attached to create embossed e-textile electrodes.

3.2.5 Silicone for reducing motion artefacts

A key challenge in acquiring reliable biopotential signals while moving, is reducing motion artefact (Pawar et al., 2007, p. 1). It was established at an early stage that motion artefact was a key hurdle to overcome. It was identified that movement of skin underneath the electrode was a large source of electrical noise, in other studies it had been shown that increasing pressure reduced motion artefact to an extent (Cömert et al., 2013, p. 14). Regardless of the proprietary reconstruction algorithm, any means of reducing noise mechanically prior to ECG signal reconstruction only better serves the outcome. This suggested exploring a means of reducing dermis movement under the electrode, or a way of comfortably securing the site of the electrode to the skin.

The immediate action was to increase the pressure on the electrode by increasing the mechanical pressure behind the electrode, as had previously been explored in the first belt prototype and by Cömert et al. (2013). This thinking appears to come from a particular place, as it is potentially not practical in daily use. From an electrical standpoint, more pressure ensures more robust contact, but also induces greater signal noise when the electrode moves (Cömert et al., 2013, p. 4). From a design perspective it was also impractical. As it was originally requested to be 4cm thick, the resulting electrode would be indiscreet and protrude from the body too much.

A focus point of wearable design is creating something comfortable, low profile and easy to use. This is even more important when designing around health care. Having a bulging pad under the chest region means the garment would be impractical for daily use. A key question that should always be asked of any wearable is, "would you wear it?"

There were clear wearability issues in reducing skin movement with pressure alone. As such the question was reframed as: "How might the skin be pre stretched under the electrode area without adding excessive bulk and material to the design?"

In parallel EEG research, the use of silicones and soft polyurethanes had already been explored as conceptual options. In that instance it was proposed as one solution to breaching the hair line for EEG while reducing hysteresis and instability in conductive threads. Hysteresis refers to something's dependence on its history in how it performs, in this case electrical performance is negatively affected by how the conductive fibres are stretched and loosened over time. The structure would be made by over moulding a section of conductive threads in silicone or polyurethane in a comb-like arrangement. During this time, it was established that silicone was both skin safe and had a strong grip when pressed against the skin.

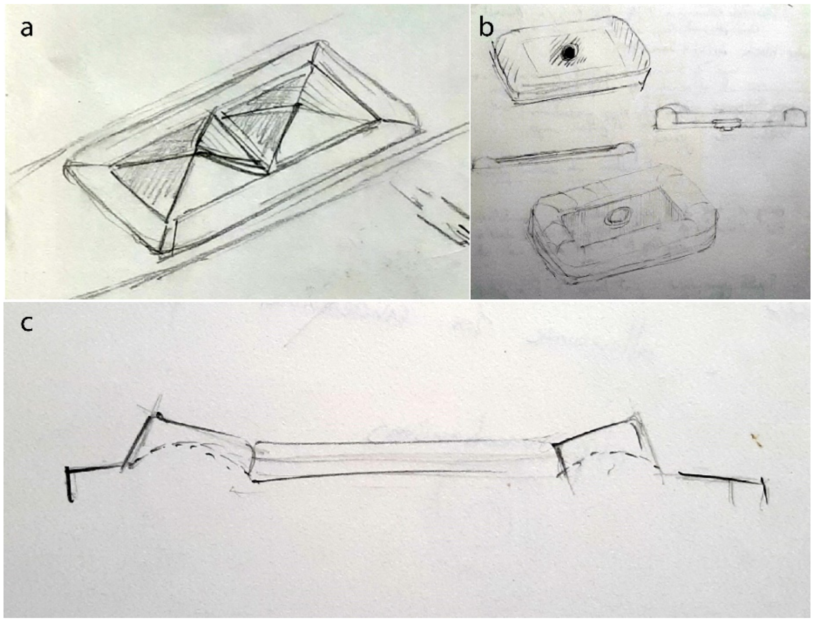

Figure 62

A: Sketches of raised single channel electrode with silicone. *b*: Rough concept duel channel electrode with channels separated as embossed sections. *c*: Cross section of proposed silicone wall structure that surrounds the EVA/e-textile electrode.

For an ECG electrode with silicone, the EVA/e-textile pad would sit atop a four walled silicone bed (Figures 62a, b, and c). The bed of silicone would have raised walls with drafted sides and air gaps in the corners, almost like a plunger. When pressure is applied to the walls, it both stretched the skin and suctioned the site of the electrode. This has multiple functions: the silicone walls sit slightly above the electrode. The walls have break points in the corner, and an inward facing draft angle so that when pressure is applied (see Figure 62c), they correct and then splay outward. Once the belt is tightened the pressure on the walls' inward draft angle, coupled with the skin adhering properties of silicone, would pre-stretch the dermis underneath the electrode and simultaneously fix the electrode in place on the body while also reducing the ability for skin to move underneath it. And finally, the non-permeable but flexible nature of silicone makes it an ideal backing for a textile electrode. Studies have shown that backing the e-textile with a non-breathable membrane encourages sweat and helps keep the fabric wet promoting far greater signal quality (Fleury et al., 2015, p. 4).

To achieve these forms silicone would be injected into 3D printed moulds (see Figure 63). As described in the methods chapter, this process is done by 3D printing a mould block in two parts. The parts seal together with only an opening for the silicone to be pushed through in the top.

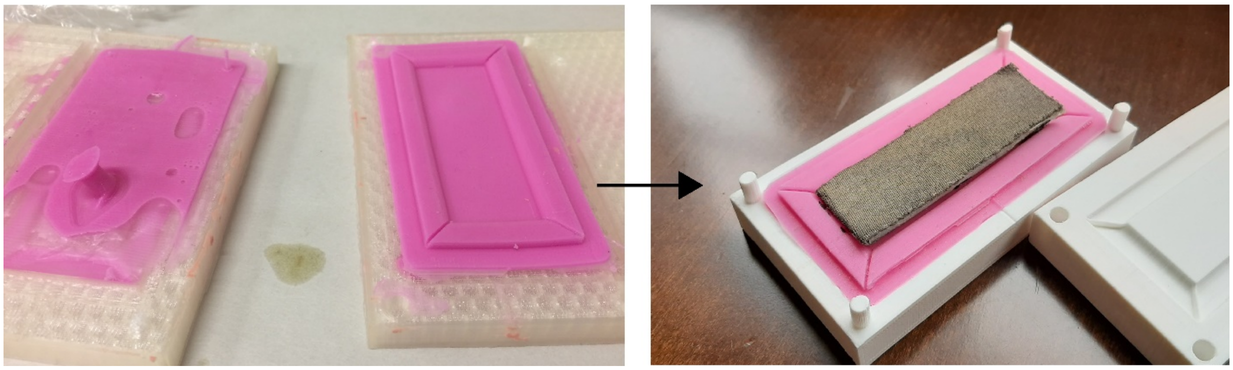

Figure 63

Mould process toward creating first silicone/e-textile Electrode.

3.2.6: 3D Printed Injection Moulds

While the process of fabricating the moulds can be time intensive and iterative (Figure 64), the actual process of casting the moulds happens relatively quickly. The mould is sealed together with any gaps being filled by moulding clay; the cavity is also prepped with mould release spray. Silicone has a short pot life of just six minutes. Once the silicone is mixed, it is pulled into a large syringe and quickly injected into the gate (injection insertion point) and pushed through until the silicone can be seen coming out of the mould in other places. Unfortunately, despite a number of attempts it was not possible to gain access to a viable degassing chamber for prototypes, so the resulting outputs to date all contained bubbles in the silicone.

Figure 64

Development of Vacuum Moulds

Due to the number of moulds printed there were small but important factors learned through iteration. For instance, in the actual process of printing, the wide flat surfaces of the mould would effectively act as a heat sink, cooling the plastic extrusion too quickly and pulling the part from the bed, resulting in several failed prints. For the object being created in the mould there were a number of considerations as listed below:

- Part orientation inside the mould block becomes critical and requires careful thought when considering the desired form and finish of the object.
- Injected moulds usually shrink a certain amount depending on the material being cast. In this case silicone has a very low exotherm so remained a near 1-1 representation of the negative mould cavity, but other materials like urethanes etc. will need to be scaled accordingly.
- Injection moulded parts are usually created with draft angles allowing for easier release of the part from the mould. With silicone, the high pliability means that draft angles were not necessary as it could be easily removed from the mould.
- Silicone has a very short pot life of six minutes and cures in only 30 minutes or so. Longer is required for a full cure.

- The short pot life and high viscosity of the silicone means it becomes easily aerated while mixing its A and B parts. The only viable solution for pulling the air bubbles from the silicone in such a brief time frame is to use a vacuum chamber.
- Mould blocks contain gates, these are the holes in which the casting material is injected. The gate position should be carefully considered as it can dramatically affect the final part. Sometimes multiple gates are necessary.
- Sometimes internal reservoirs and channels are needed to guide the injected material into the part cavity, these channels are called sprues and are vital if there is more than one part in the same mould block.

While going through this digital fabrication process, 3D printing slicing software from Prusa was referenced to better understand how to reduce the number of failures in my prints and acquire better outcomes by simulating prints before printing them. Key takeaways from this revolved around reducing the use of splines or long curves and using chamfers wherever possible and, additionally, developing workflow for quickly recalibrating prints for printers by using better designed parametric models. Parametric CAD (Figure 65) was a skill being developed heuristically throughout this project. I already had a strong base in the software but developed much better practice and habits through the project. In parametric modelling, 3D models are defined by numbers of formulas (parameters). This means if you need to make changes to the model you can adjust the parameters and not the actual model, and if it is designed correctly, the model will adjust accordingly. This can save massive amounts of time and was helpful in creating mould and late-stage enclosures.

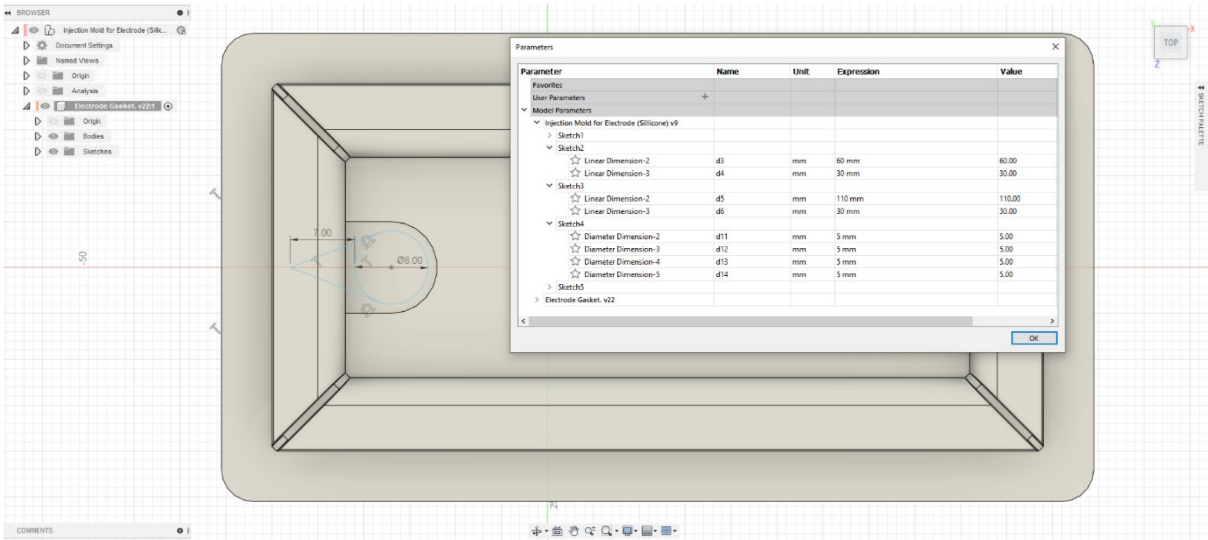

Figure 65

Sketch view with list of model parameters. Careful design allowed objects to scale and change with minimal effort by changing parameters.

3.2.7: Attaching Silicone - Reintegrating Vacuum Formed E-textiles

Several test print mould blocks had been made to reach a suitable mould. The process of injection moulding silicone was guided by a senior technician in the design space using supplied silicone. These proved the viability of the approach, so development proceeded in this direction.

At this point it is important to address a key assumption made during this process and something that was overlooked while researching materials. The key assumption being the ease of bonding or adhering materials to silicone. It had been assumed the silicone bed could be created as a standalone piece and that the e-textile/EVA electrode could be glued into it.

Figure 66

Failed Adhesive Bond from Specialty Glue.

Initial reading around this showed silicone could be glued but this ultimately depended on the nature of the silicone. To date information on suitable adhesives for Pinkicil/Transcil (the silicone product used in this research) have not been found. Despite this, a number of off the shelf and specialty glues had been purchased trying to amend the problem. All attempts failed, ultimately it was discovered that the chosen skin-safe silicone was not suitable for adhering to as shown in Figure 66. With a more nuanced knowledge of chemistry this failing would likely have been avoided. In this instance I should have reached out to our chemical engineer but did not. Had I consulted him through the initial design this exact approach could have been avoided. It did however result in considerable personal learning.

Initially finding the glue would not work was discouraging, given the time invested and the knock-on effect of its failure. This served as a key lesson in being more thorough in testing assumptions at earlier stages and considering consulting other disciplines before executing on design concepts. However, the core idea of the silicone pre-stretching the skin was still presumed to be effective in reducing motion artefact, despite its initial implementation.

Finding the e-textile electrode could no longer be glued meant moving away from glue to find an alternative. A connection was made that vacuum forming allowed for considering using the silicone in a gasket-like arrangement instead of as a bed or base (22).

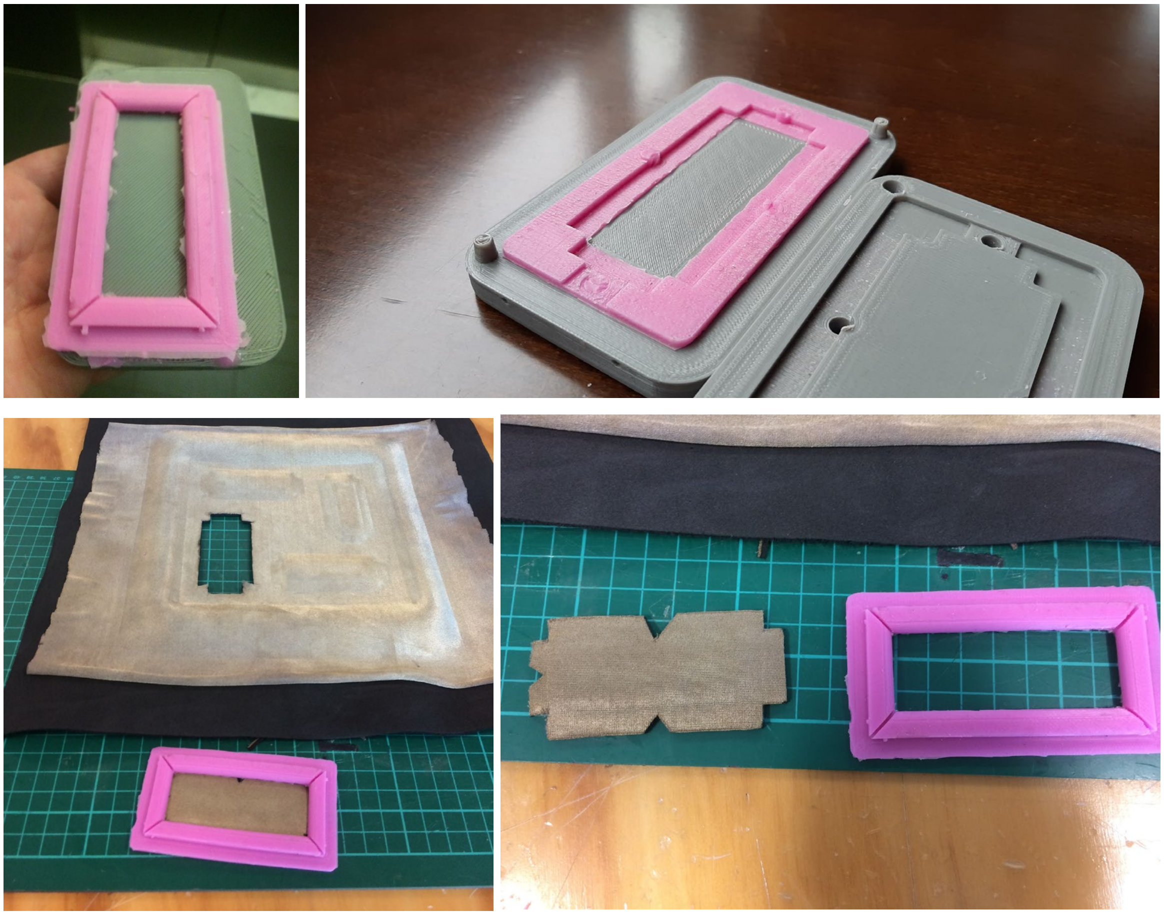

Figure 67

Electrode mould and EVA/e-textile insert interaction (clockwise). The top right shows cavities under silicone walls to locate electrode insert.

In this arrangement the silicone would be sewn to the belt, with cavities under each wall that the EVA pad could slip into once cut to shape (See Figure 67). It was important to establish that sewing silicone of this size would be possible and that we had the facilities to do so. Via expert feedback it was assured that this was an established process and there were specialized tools for sewing silicone available. Correspondingly the electrode process now required a more complex vacuum mould for the EVA as the design now had locating features and multiple height levels and needed greater definition.

The method for creating this form was to use CNC milled plugs for the vacuum forming (see Figure 68). This allowed for implementing locating features and better-defined height levels in the resulting EVA form. The CNC process itself is discussed in more depth in section 2.2.1.

While CNC allows for complex forms, the main concession that needed to be accounted for was the vacuum bed itself. The bed was small and had low suction power. This low vacuum power contributed to the inability to bond the heat adhesive and e-textile while forming the vacuum mould. By halving the number of inserts on each mould plug and spacing them better, the vacuum appeared more effective and had a more defined output as shown in Figure 68.

Figure 68

Improved vacuum mould with more defined result.

3.2.8: Sewing Silicone

Having now produced suitable electrode inserts and the corresponding silicone gasket, they could be attached to the belt. To satisfy the requirement of having a hard backing to the electrode, nylon webbing was chosen to sew the electrodes too. It was judged that at this stage, and given the teams preference for modularity, trying to sew the components directly to the belt would result in major bottlenecks. This meant the nylon webbing approach satisfied the need for modularity, should the engineers decide to test the electrodes in different garment arrangements.

Sewing the silicone from the gasket design required specialty machinery that needed a technician to operate. An industrial sewing technician from the textile programme at AUT was able to operate a heavy-duty industrial sewing machine to sew the silicone. Ideally, we would use a slip coated blind-hem foot to get the ideal finish. Without the specialty foot, the silicone grips the machine and cannot be fed through. The technician was able to circumvent this problem by sewing with a slip of paper between the silicone and the machine. As seen in Figure 70, there was still some skewing of silicone in the result. With multiple attempts the technician reduced the skewing, but it was still present in all the sewn prototypes (See Figure 69).

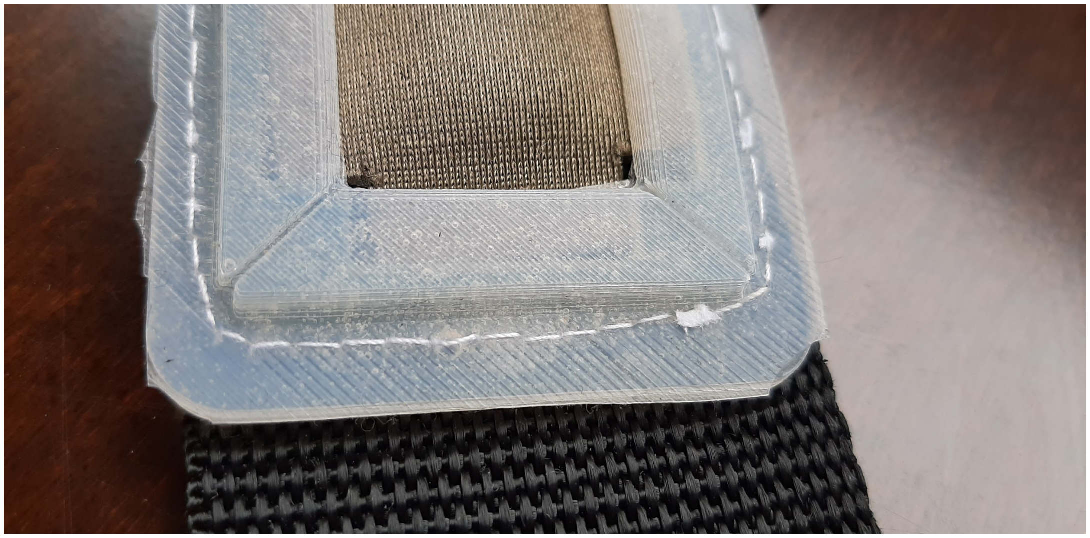

Figure 69

Details on silicone electrode sewn to nylon webbing.

Additionally, the nylon backing, now coupled with the silicone and the glued EVA made the overall flexibility appear too rigid. Despite this the lead engineers appeared pleased with the design and took it for testing. Due to the research carrying on beyond my involvement in the project I fabricated multiples of the electrodes and kept them in a modular format to give the engineering team options. This would mark the final electrode output for the IBTech team portion of the making.

3.3: Belt:

Garment

Figure 70

Timeline of Garment Iterations.

3.3.1: Concepts and Challenges

At an early stage in the project while creating the initial enclosures, an opportunity was taken to explore how the housing attaches to the garment and what that sort of hard to soft interface might entail. Several concepts were explored but were too complex to action without significant investment, resulting in simplification of designs. Additionally, changes in hardware components made early concepts like the buckle/rail design unfeasible to carry forward at the time. This was primarily due to difficulty in iterating the design effectively while it steadily increased in size. Retrospectively this could have been better managed with a better knowledge of proper parametric modelling. Unfortunately, this was not learned until after the IBTech research.

The first belt was envisioned to be interfaced with a hard chest piece containing slots to attach to the belt (Figure 71). The details of this design are first discussed in the enclosure section. This was designed in parallel with the first enclosure as can be seen in Figures 33 and 70. The chest piece in these slot designs allowed an ability to manage the interconnect between hardware and garment by protecting the interconnects both mechanically and electrically (see Figures 71 and 72).

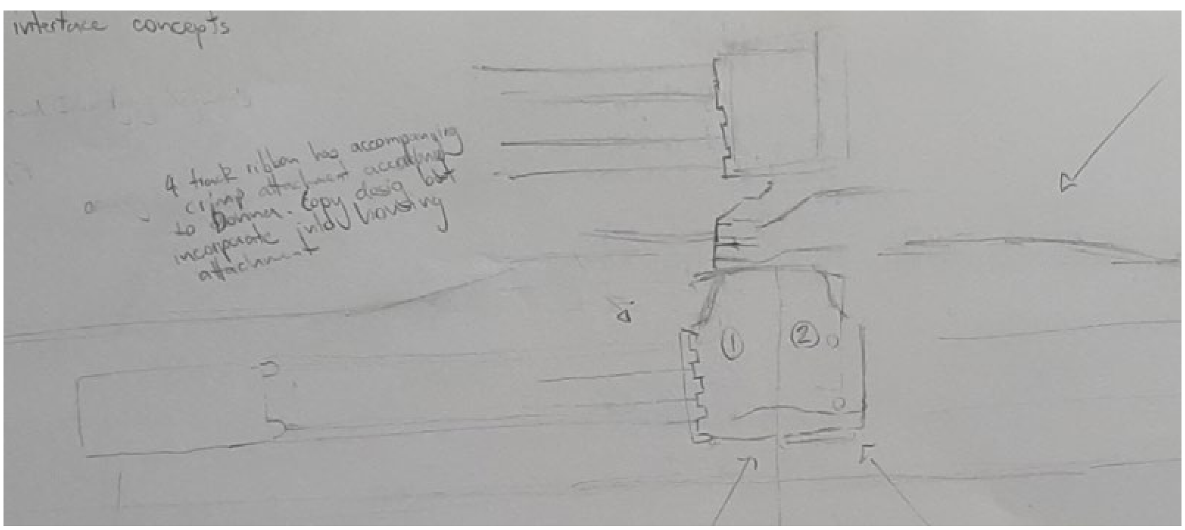

Figure 71

Concept sketch for early belt/enclosure interaction.

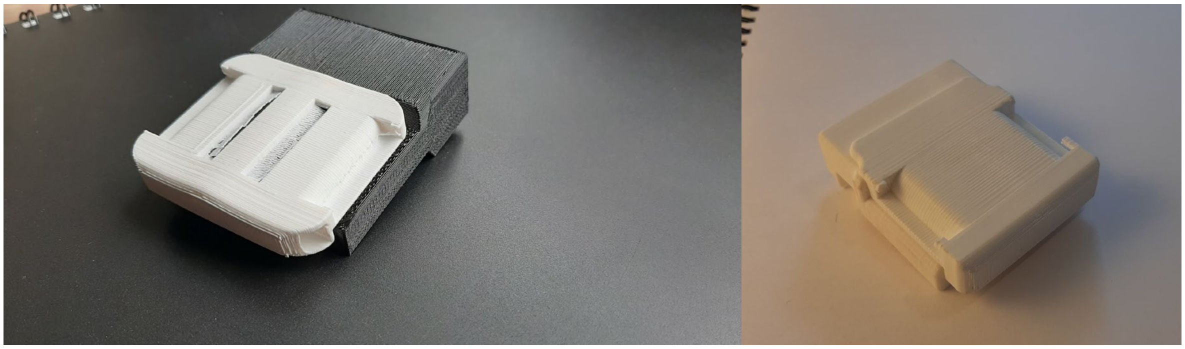

Figure 72

Early enclosure prototypes focused on resolving the enclosure to body interconnect by using a buck connected to the garment with a rail system.

This focus on parallel, integrated design was eventually abandoned to focus on responding to team needs as they arose. A compromise would be reached where any belt prototype would contain a central pocket where the engineers could place development hardware (Figure 73). Unfortunately, an imbalance in fabrication distribution meant frequent bottlenecks. This can be seen in the design timeline, Figure 33, as there is an early attempt at integrated development. After the move away from the early integrated belt, the engineers opted to leave the hardware-garment interconnect unresolved. After producing the first belt prototype for the engineering team the belt was not revisited until later in the project.

3.3.2: First Belt Prototype

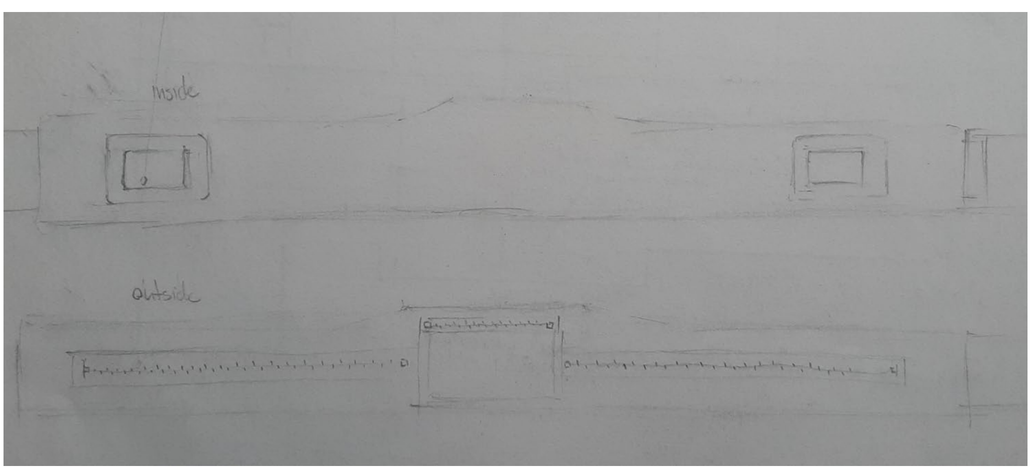

Figure 73

Concept sketch for belt with central pouch and embedded electrodes.

Figure 74

a: Window of conductive cloth with foam placed behind it. b: First belt prototype.

Having decided that the enclosure-garment interconnect was not a priority, it was determined a rudimentary belt would be acceptable for this stage of prototyping, as shown in Figure 74. The first functional belt consisted of a long length of stretch cloth, folded, and sewn into a tube. Before folding the cloth, small windows were cut in the cloth and pockets were sewn behind the openings (see Figure 74). Conductive silver cloth was then placed over the window and attached to the using heat activated fabric adhesive. The cloth was then sewn back together at the fold line, leaving two small slips to access the pockets behind the conductive fabric (see Figure 75). This was done so the engineers could try varying thicknesses of foam behind the electrodes to apply more pressure on the electrical contacts.

Figure 75

Hidden pocket behind e-textile electrode, allows for altering rigidity/firmness of electrode site.

Mechanical pressure had been identified as a key concern in the design by the engineers who were interested in investigating varying pressures and the effects on the reconstructed signal. Despite the earlier effort to establish an integrated hard-to-soft system, the lead engineers decided they would generate their own solution in the short term while still working with development versions of the hardware.

The project would continue to explore electrodes in more depth and got closer to settling on components for the enclosure. After the electrode and enclosure were more resolved, the belt was revisited to explore the best means of integrating these components.

3.3.3: Machine Knitted Belt

After returning to the belt design, focus shifted toward marrying the more developed components. This meant there had to be a shift from the modularity that had underpinned the earlier approach for the sake of testing and utility. To do this, machine knitting was used as an ideal option as it allowed for creating bespoke full garments with custom yarn blends and mechanical knit structures. Additionally, advanced yarns could be incorporated in the process to create functional e-textiles. While some forms of conductive knit, like stainless steel yarns, allow for limited biosensing (Paradiso & Pacelli, 2011, p. 4), the project focused on incorporating the electrodes already developed using EVA.

While previously work with this technology mostly involved incorporating conductive threads into knit to create soft circuitry and soft sensing (seen in Figure 9), in this instance, it relied on a non-conductive technical fibre.

Permatex is a thermoplastic yarn that shrinks and forms semi-solid structures when subject to an industrial steam process after the knitting process (see figure 76). When steamed flat with a paddle this creates a strong rigid pad from the textile, but without pressure or a form to mould around, the yarn will set in unpredictable shapes. For this project, the yarn offered the ability to vary the fit and feel of the belt by creating hard and soft structures throughout the garment in addition to creating novel attachment opportunities.

Figure 76

Machine knitted belt after steaming.

Permatex affords the ability to create more complex hard forms within a soft garment, in this instance a knitted pocket in the centre of the chest piece to house the electronics as shown in Figure 77. To create the hard pocket, during the steaming process a 3D print of the enclosure was placed inside the pocket to form around. Due to the steam the 3D print could only handle being steamed a few times before deforming heavily. This process could potentially be resolved by using CNC fabricated materials that could handle the steam, such as bamboo. The CNC process could also be used to 'steam moulds' that would hold the fabric in set positions while it is steamed and set in place.

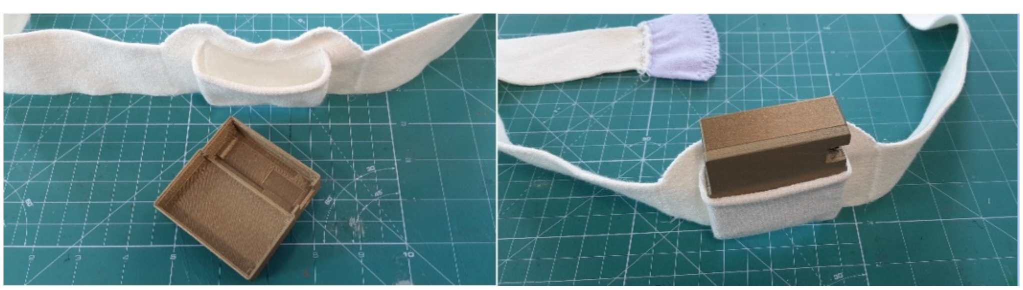

Figure 77

Hard pocket in centre of garment for enclosure attachment.

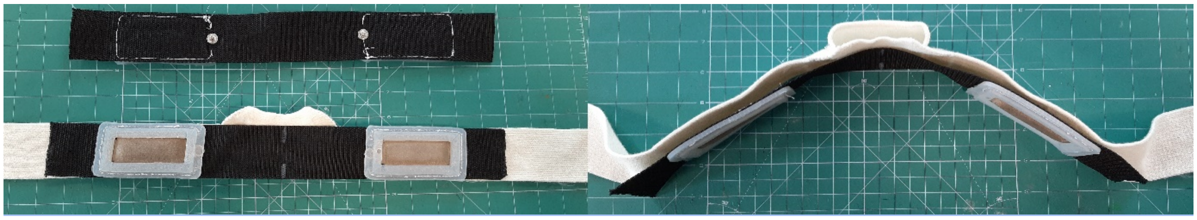

Figure 78

Modular nylon backed electrode section

The final belt outcome was successful in showing that using heat moulded yarns in this way offered a novel solution to housing hard electronics on the body. Additionally, the knit offered a viable means of housing the enclosure and electrodes. With more time and earlier focus, the knitted garment could have likely incorporated even more aspects of the design. This would be the final design submitted to the IBTech team (see Figure 78), after which they would continue their research and I would continue resolving elements of the design for my own research. The electrode section was left detached in case the engineers wanted to use it in a different arrangement, but instructions were provided on attaching the nylon. It was agreed the testing of the silicone gasket electrode around reducing dermis movement and motion artifact would be handled by the engineers as it related to their larger work. In later retrieving the wearable for further documentation, test data around its mechanical or electrical efficacy could not be provided. Subsequent testing found that the double stiff backing of the nylon and Permatex flexed awkwardly, and the silicone did not conform naturally to the body. Efforts to amend these shortcomings are detailed in Chapter 4.

3.4: Interconnects:

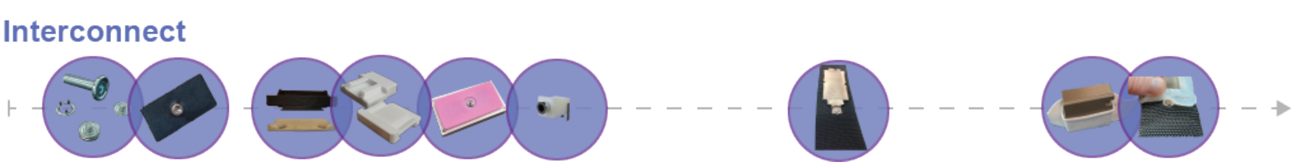

Figure 79

Timeline of Interconnect Iterations and Developments.

3.4.1: Interconnect Design Considerations

Past familiarity with wearables development and literature research showed facilitating interconnects is a primary challenge in wearables development (Agcayazi et al., 2018, p. 1-3). Its criticality to successful outputs is further evident in the design timeline (see Figures 33 and 79), as they join all the functional components of the design. While distinguished as its own component, interconnects are inherently dependant on the other components in the design. Some interconnects were carried through iterations and used together with new developments.

The type and implementation of interconnects often dictates what is technically possible for the garment, how much data can be transferred, how hard components are attached to soft, where on the body they are attached (Gemperle et al., 1998), and how these attachment points are protected and made intuitive to use (Agcayazi et al., 2018, p. 2).

3.4.2: Establishing Enclosure-Garment Interface

A fork in design outcomes was forced by how many circuit paths would be needed per electrode, two, or four. Simply put, the less channels of data that need to be interconnected, the easier it is to facilitate the chain of transmission (see Figure 80). This point would be circled often as various early aspects of the design were explored. The constant motion of the body requires thoughtful positioning and orientation of connections.

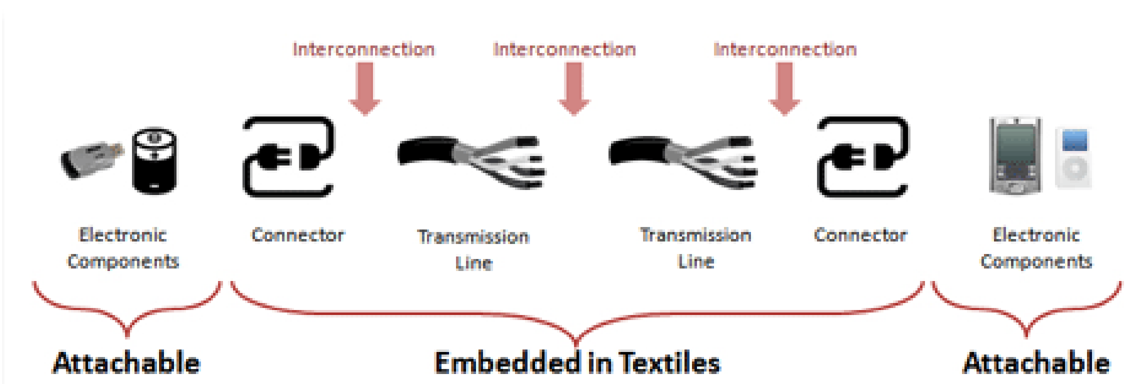

Figure 80

The role of interconnects in wearable design.

Research has identified areas/zones on the body to handle hard components and interconnects (Ferraro & Ugur, 2011). Some of the products researched for this design placed enclosures in areas suggested in the research (see Figures 81, 82, and 83). Some used an array of clasp buttons to attach the hardware to the body. The button acts as the conductive connection between the garment and enclosure, carrying the signals from the internal track in the garment to the enclosure. The clasps also secure the enclosure in place (see Figure 83). Clasp buttons also have the benefit of being readily available and easy to apply while providing a mechanically secure electrical connection. This was discussed early in the project as a potential solution but was initially left unsettled while other aspects of the design were focused on.

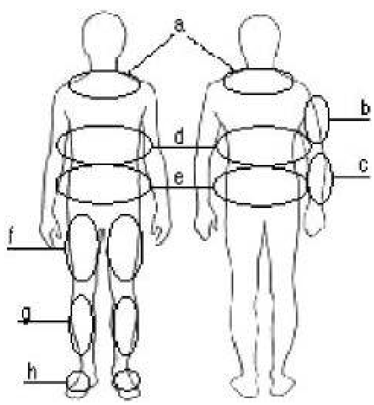

Figure 83

Areas of low obstruction.

Figure 83

Example of firm forms attached to areas of low obtrusiveness.

Figure 83

ECG enclosure attached in area of low obtrusiveness.

A stumbling point for snap lock buttons is they are limited to one channel of data per button, as each male/female button pair is a single conductive path. This introduces a significant challenge as garment-based sensors become more complex and more signal paths are required. This shows the increasing difficulty of adding more channels of data. Additionally, arranging snap buttons in this way can quickly take up an impractical amount of room on the garment. Due to this limitation several advanced connectors were explored early on, these alternatives could handle larger data streams and accounted for body movement, but the most promising wearable oriented candidates were not available for purchase.

Figure 84

Product example with hard plastic pocket fused to garment.

Detailed in both the enclosure section and the belt section, early prototypes created a rail system for attaching the electronics housing to the garment. This was inspired by a hard pocket that appeared to be overmoulded or ultrasonically welded to an industry product (see Figure 84). In this product they used a hard pocket to house the enclosure, as well as to protect both the enclosure and the connection between the enclosure and garment. The pocket also made interfacing the enclosure intuitive and reduced the likelihood of user error. These were all thoughtful design considerations which informed the approach in this practice. Intuitive use and guiding user interaction could be achieved by using the affordance of the rail design as a signifier for user interaction (shown in figures 85, 86).

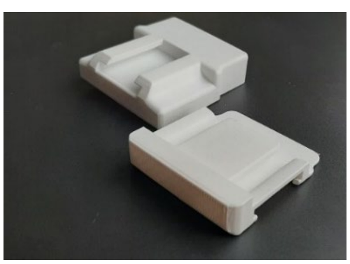

Figure 85

Electrode enclosure and chest piece

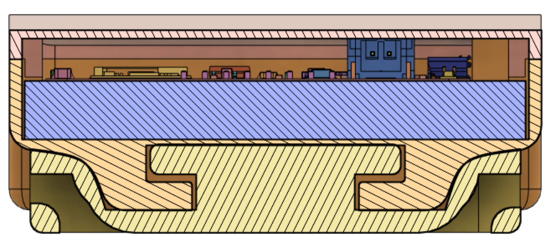

Figure 86

Enclosure to garment rail design interface. CAD cross section of mechanism.

This enclosure interfaced with a hard chest piece with belt loops on the garment side (Figure 85). The rails would serve to guide the enclosure onto the garment. The concept envisioned an interconnect at the centre base of the chest piece that would interface with the enclosure, as well as protect the garment side interconnects. The rails afford attachment and securing of the enclosure and connection while also signifying to the user how it will be attached (see Figures 85, 86). This approach was initially desirable as I did not have manufacturing means such as industrial injection moulding to create hard pockets.

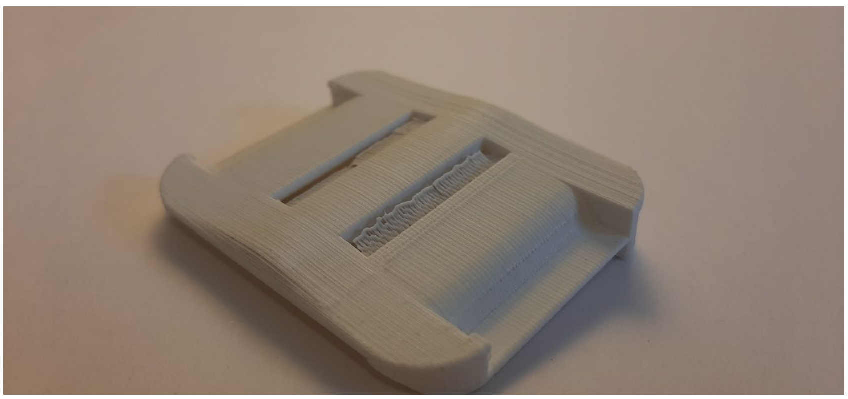

Figure 87

Chest Piece with Curvature to sit more naturally in the sternum.

At this stage, the garment piece had advanced to have a more humanistic form in line with the suggestions from the literature review (see Figure 87). 3D printing initially proved too thin on the belt loops and they easily broke off. Despite the initial time investment, the engineers opted to facilitate their own interconnects for enclosure-garment interfacing while research continued in other areas. One contributing factor towards not wanting to continue in this direction was a lack of correspondence from the providers approached about advanced interconnect options. In lieu of these products, simpler methods like crocodile clips were used to manage electrical interconnects while testing.

3.4.3: Snap Locks and Auxiliary Jacks

While researching materials for the electrodes, it was found that the electrode hook-up for hospital grade silver chloride electrodes was a standardized 6mm clasp button, similar to those found at sewing stores. Having established their viability given widespread commercial use, these buttons were used on all electrode outputs moving forward. This meant the team could quickly integrate new electrodes into testing as this interconnect already interfaced with their existing testing equipment.

Figure 88

Different garment and electrode iterations using snap lock buttons as interconnects.

In addition to an easy integration with testing apparatus, the manner in which a button bunch binds the button can join material layers and carry charge through otherwise nonconductive materials; A toothed ring on one side, biting through to the base of the button on the other side is shown in Figure 88.

The snap locks were ideal for the electrode to garment interface, but they did not facilitate the garment to enclosure connections as intuitively. Additionally, PCB selection determined the means of connection. Turnaround times in designing proprietary connectors also made the engineers reluctant to engage with less proven methods.

While relying on snap locks as a placeholder solution, the engineers had simplified the electrical design in that they claimed they could achieve similar results with single channel electrodes as opposed to two channel electrodes. This effectively meant that the garment-enclosure interconnect only needed to facilitate three connections in total from both electrodes to the enclosure. Two hot signals from each electrode and a combined ground. This reduced complexity allowed for using off the shelf options and made it a viable approach within the time allowed in the project.

At this point the enclosure interconnect was resolved to a 2.5mm three channel auxiliary jack, similar to those used in headphones. It easily combined three channels, offered some electrical shielding and was relatively intuitive to use given its ubiquitous use in electronics.

With these elements settled, the development proceeded in integrating the components. Designing around these interconnects involved considerations like:

- Accounting for button snap heights in injection moulds
- Devising ways of applying button snaps to the EVA/-textile electrodes
- Designing the electrode modularity around a snap lock interconnect
- Devising trace/cable routing from the belt to the enclosure

While it may not exactly fit the definition of an interconnect, I would argue the steam moulded belt should also be considered an interconnect; the ability to create targeted areas of varying rigidity in the material structure of the belt afforded a number of novel approaches and allowed for creating a semi-hard pocket for a hard-soft interface that would have previously only been possible with access to industrial injection moulding and overmoulding facilities.

As evident in the enclosure section, a micro USB port was maintained from the second iteration of the enclosure onward. This was so the engineering team could quickly access the micro controller for debugging, serial monitoring, and programming.

The concepts and designs discussed in this section were presented to IBTech at the end of the team project. From this point forward designs were left with IBTech for use/testing.

Chapter 4: Independent Continuation

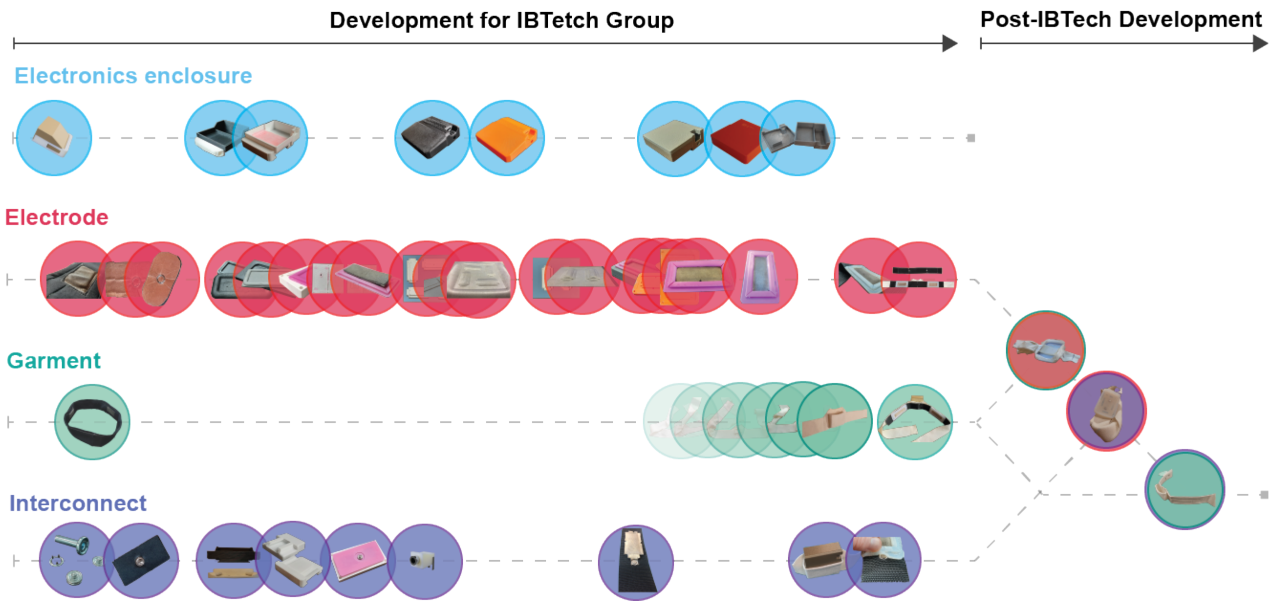

Figure 89

Timeline of IBTech and Independent development. The post IBTech development on the right ceased enclosure work and integrated the aspects created in the earlier phase of research.

This section discusses the research and making that occurred after the team project to address core design challenges previously encountered with the aim of creating a more integrated outcome. This is reflected in the Figure 89, as it shows the components being merged. The fundamental conceptual and practical developments that occurred during the IBTech team project were inherently carried into the individual stage. However, the additional time and freedom allowed me to improve upon and integrate the components further.

Moving on from the IBTech project meant I was no longer involved with the continuing developments around the hardware or software. From this point forward the last enclosure fabricated was used as a default in ongoing making. Additionally, establishing there would not be access to the hardware meant leaving those aspects of the garment to enclosure interconnects unresolved. This meant focus could be shifted entirely to integrating the soft and composite elements of the design. Specifically resolving the shortcomings of the silicone/e-textile electrode. Bypassing one of the former key aspects of the development meant that freed up the time necessary to focus on further developing the knitted garment to support more embedded components. It was also important to understand the current behaviours of the design to improve upon it.

The final prototype and silicone gasket design had not been tested and the proof of concept for the silicone/e-textile electrode was not yet validated. Testing done after finishing the IBTech phase of the project revealed the belt did not perform as intended in a few areas, specifically the mechanical behaviour of the electrode and electrical performance appeared poor (Figure 90).

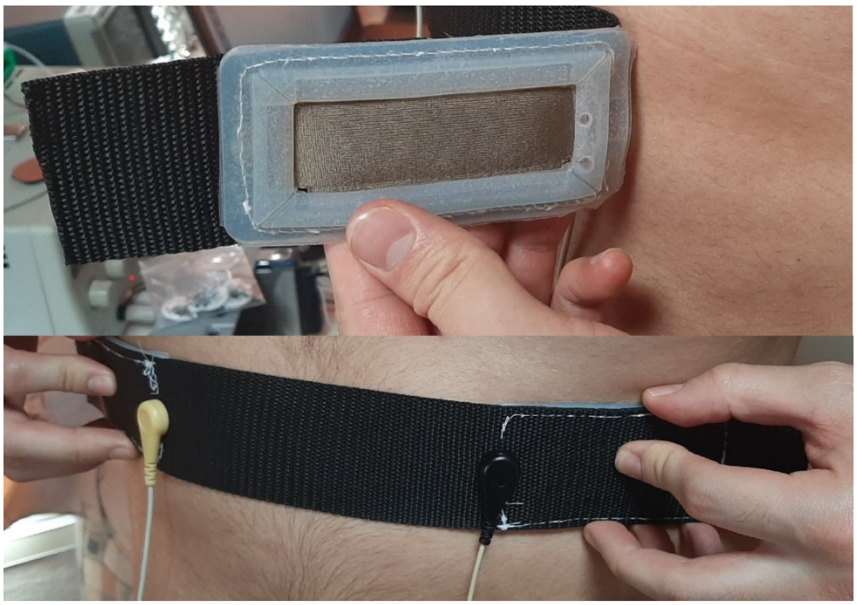

Figure 90

EVA/e-textile electrodes with silicone gasket with leads attached.

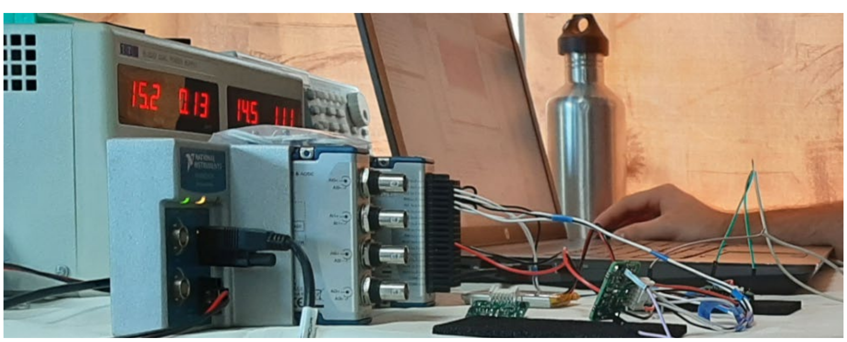

Figure 91

Data Acquisition Module (DAQ) for testing electrodes.

The tests were run through the proprietary hardware developed by IBTech for the ECG data acquisition and processed by the project electrical engineer (Figure 91). The heart signal from the body itself must be algorithmically reconstructed with a delay to accurately reduce artefacts from motion and standard 50/60 Hz electrical noise.

The code running algorithmic signal processing was not run through an on-garment PCB, but rather ran through a laptop using MATLAB and more advanced electrical testing apparatus. Therefore, the code is simulating the software rather than running natively on a chip. This means alterations in code were needed to amend certain differences in testing implementation for different prototypes. This required a considerable amount of time and tweaking, meaning much of the testing was spent troubleshooting. Additionally, with no historical data available for the prototypes and no established test protocols available, further time had to be spent devising testing protocols.

An additional challenge was that some earlier prototypes had been made and left with the team for testing but were never assembled and the interconnects that were presumed resolved, were in fact not. This required attaching the electrodes to the body with a cloth wrap and circumventing any comfort and mechanical fit aspects of the belt design (Figure 92). Unfortunately testing in this way negated many of the functions of the design.

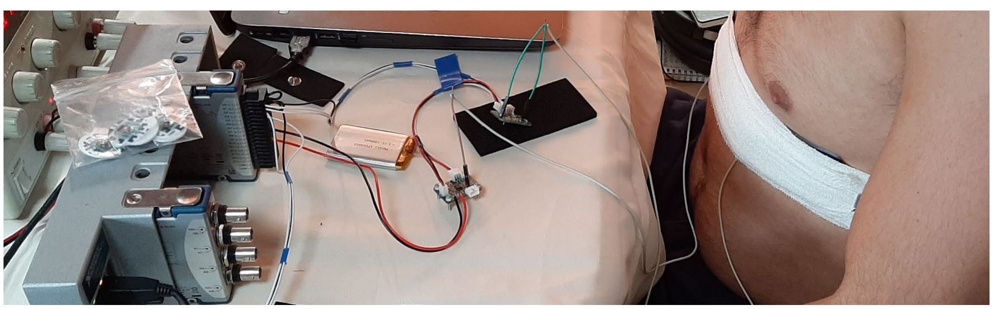

Figure 92

Silicone Gasket Electrode Secured by wrapping the nylon blet section in place

Through imperfect fit, and poor electrical results, it was shown that the silicone gasket was not performing as desired. This was likely due to the hard backing of the nylon combined with the double thick thermoplastic yarn in the knitted belt made the electrode too stiff to properly conform to the body. With amending this in mind, the electrical considerations for the actual e-textile became secondary, as the vacuum forming e-textile process had proven successful enough that re-applying a different e-textile would not be considered a problem. The main challenge in addressing the design limitations would be reducing the stiff backing of the electrodes and letting the belt flex naturally.

To do this overmoulding would be explored as a means of integrating the silicone gasket element directly onto the machine knitted belt. The process was initially tested using the same silicone without an injection mould by casting directly onto the knitted belt suspended in a container (see Figure 93). This would allow for assuring the viability of the approach by testing how the silicone and knit would bond.

Figure 93

Overmoulded belt section with embedded neodymium magnets.

Initial experiments showed a very strong bond and natural flex. The overmoulded section of belt is knitted with thermoplastic yarn that has been steamed flat. This makes the belt firm, not allowing stretch along the yarn, but also remains flexible enough to fit comfortably on the body (Figure 93). Second experiments aimed at improving the feel and flex removed material from a belt in strategic sections to act as anchor points for the silicone on either side of the belt in addition to re-orienting the overmould tray to get a better more representative shape (Figure 94).

Figure 94

Left to right descending, the process of overmoulding silicone to knit with embedded magnets. Material removed from knit to improve mechanical behaviour.

Space was left on the belt to explore a new design concept that would use conductive knit elements embedded in the garment to facilitate an interconnect. This could be completely integrated in the overmould, the second prototype also used small neodymium magnets underneath of where the conductive pads would be (Figure 94). In this configuration, knitted conductive traces would run from the conductive patches to the centre chest pocket (Figures 95 and 96). The belt to enclosure connection was not addressed due to time constraints and loss of access to the relevant electronics.

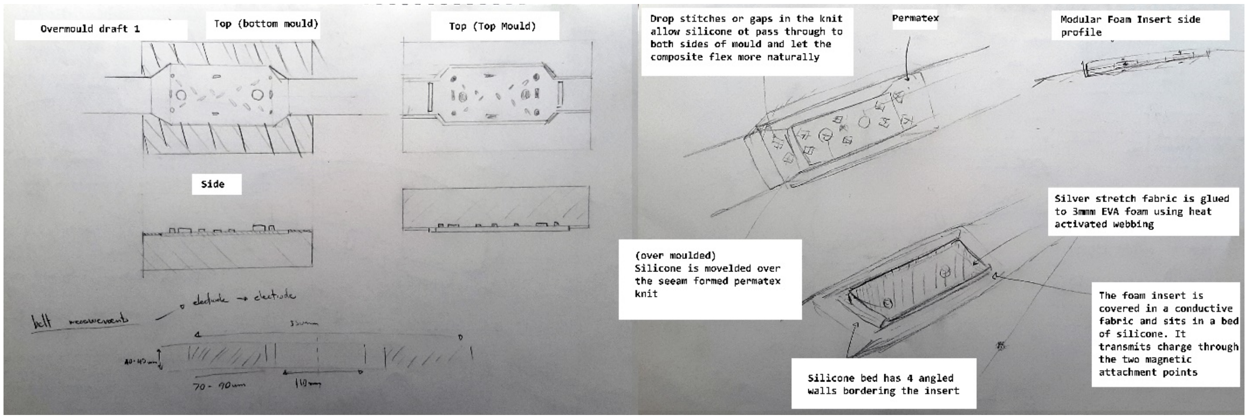

Figure 95

Concept sketches of overmould section.

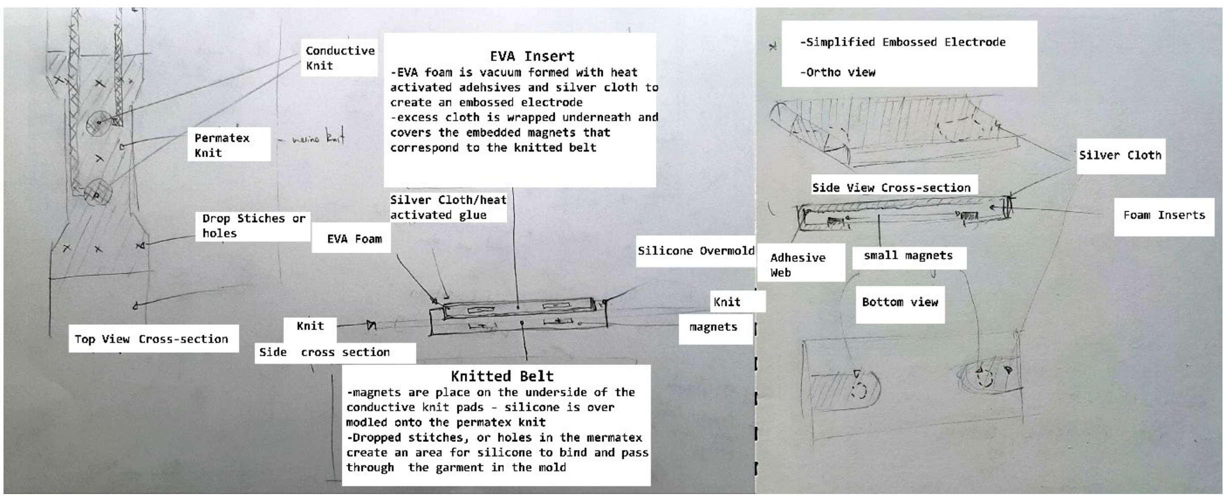

Figure 96

Concept sketches of overmould section.

In an overmoulded configuration (Figures 94, 95 and 97), the silicone element is smaller, flexes more naturally and offers protection for the knitted conductive elements. The mechanical behaviour of the joined knit and silicone has proven to be far more natural than the previous designs. This concept also still used an e-textile EVA pad that interfaces with the silicone section (see Figure 96). This aspect could not be completed in time, but if completed would contain magnetic elements that correspond to the ones embedded in the belt, forcing the conductive paths together and interconnecting the components as shown in Figure 96.

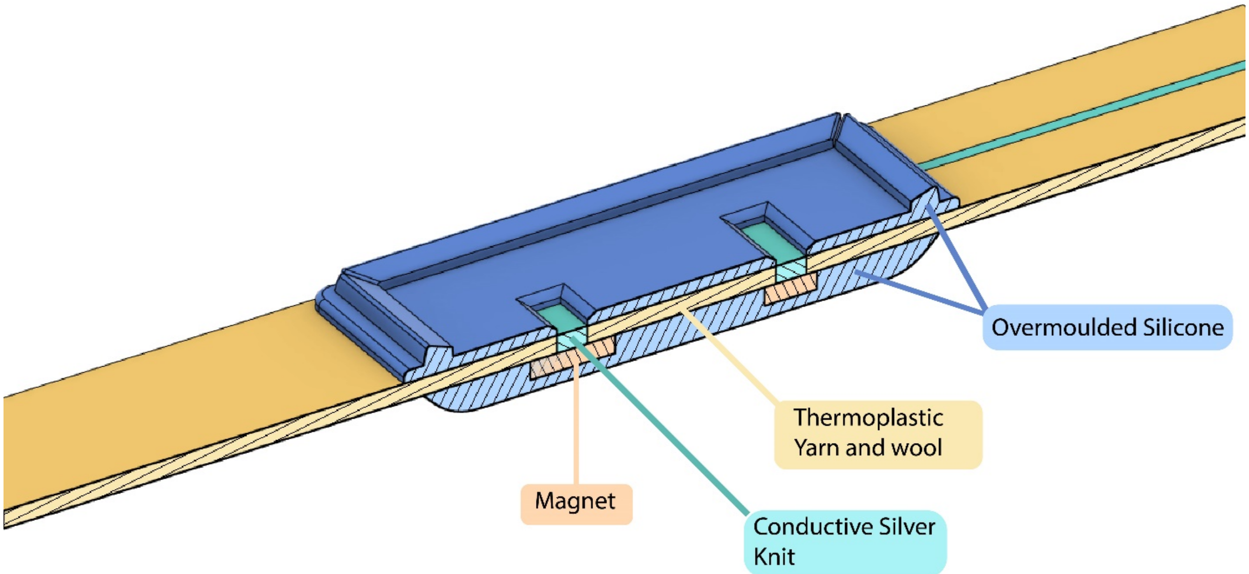

Figure 97

CAD concept of electrode overmould. Isometric cross section shows magnets embedded in silicone overmould sitting below

Integrating the belt in this way would also allow for electrode processing onboard each individual electrode. It also reduces the complexity and steps involved in producing a silicone gasket and attaching it to the belt. To create a 3D form on top of the belt (Figure 97), another injection mould is needed. In this instance a mould was 3D printed to clamp onto the belt section, sealing off the belt and creating internal cavities on either side of the knit that would be filled with silicone. Injecting silicone into this creates the raised walls needed for the design, but it also allows for pinching the magnets in place against the conductive sections on the electrode pad interconnecting the electrode. This means the correct conductive connection is exposed after the mould is removed.

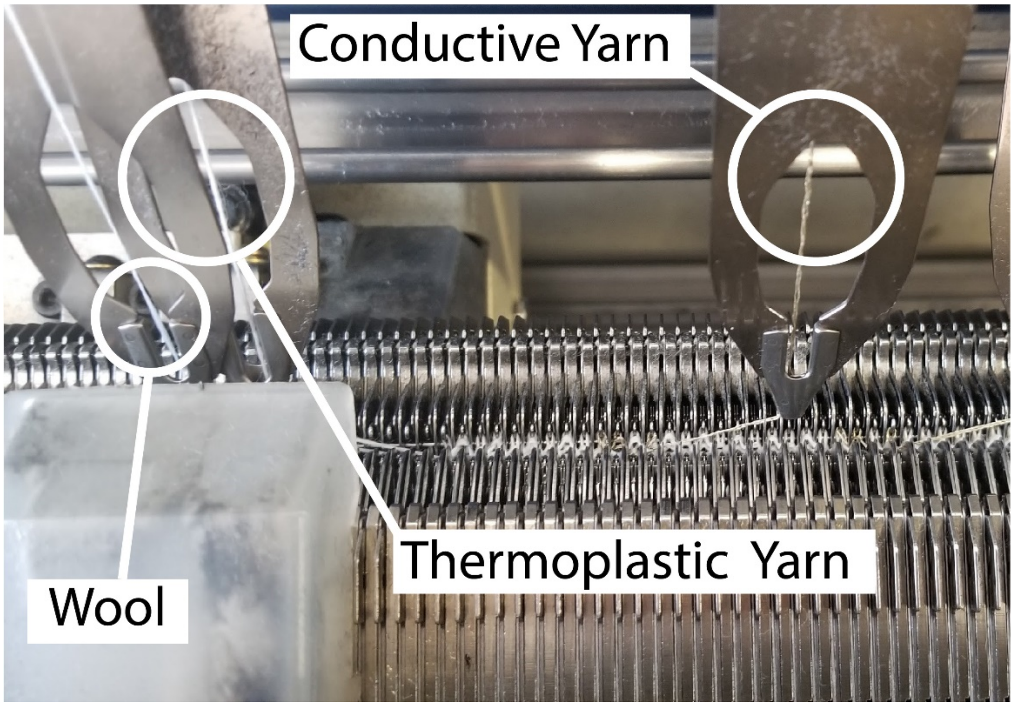

Figure 98

Needle Bed for Shima Seki knit machine showing the creation of the belt.

Figure 99

Belt with embedded soft circuit being knitted off.

A critical aspect to this revision is shifting some of the mechanical and electrical elements to the machine knitted garment (Figures 98 and 99). To achieve this, I worked with the machine knitting technicians at Textile Design Lab (TDL). This used a combination of conductive and technical yarns in a single knit (Figure 98). In this iteration, the belt would forgo interconnects like snap locks from design in favour of pads and tracers of conductive yarn knitted into the garment as seen in Figures 99, 100 and 101. This was a more technically demanding knit than the IBTech phase belt that used Permatex. It required several iterations and refinements, as the belt shrinks dramatically after knitting (Figure 100). This is especially relevant for overmoulding, as the mould needs to be located exactly about the knit. This would typically be more difficult but parametric modelling skills developed over the project allowed for prebuilding the model and then making quick and easy adjustments to accommodate the resulting knit.

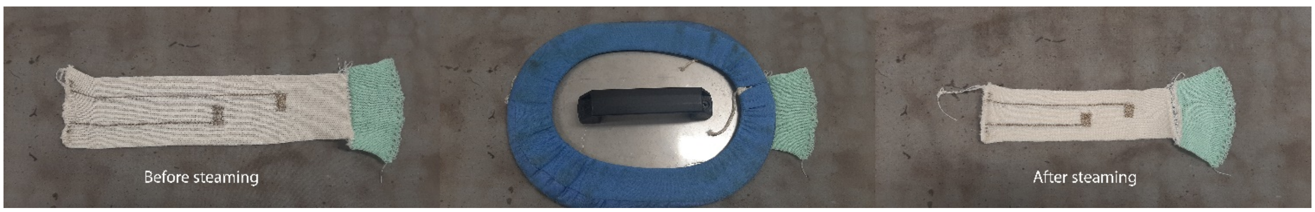

Figure 100

Left to right, shows the process of steaming a knitted piece and the resulting shrinkage.

Initially the conductive yarn was knitted into test swatches to test spacing, size and knit structure. After several revisions we arrived at a design that did not leave the back of the conductive pad area exposed. Once this was achieved the technician transplanted the design into the original Permatex belt knit. After knitting, the belt was prepared for steaming by stuffing the chest pocket to hold it out (Figure 101). The electrode sections were held flat with a steam paddle (Figure 100). After this the garment was steamed to form and almost ready to be over moulded. There would need to be some sections removed from the belt to help the mould process. Ideally this would be done by a punch tool in a pneumatic press, this would allow for precise placement and should be considered if this type of development is pursued in the future.

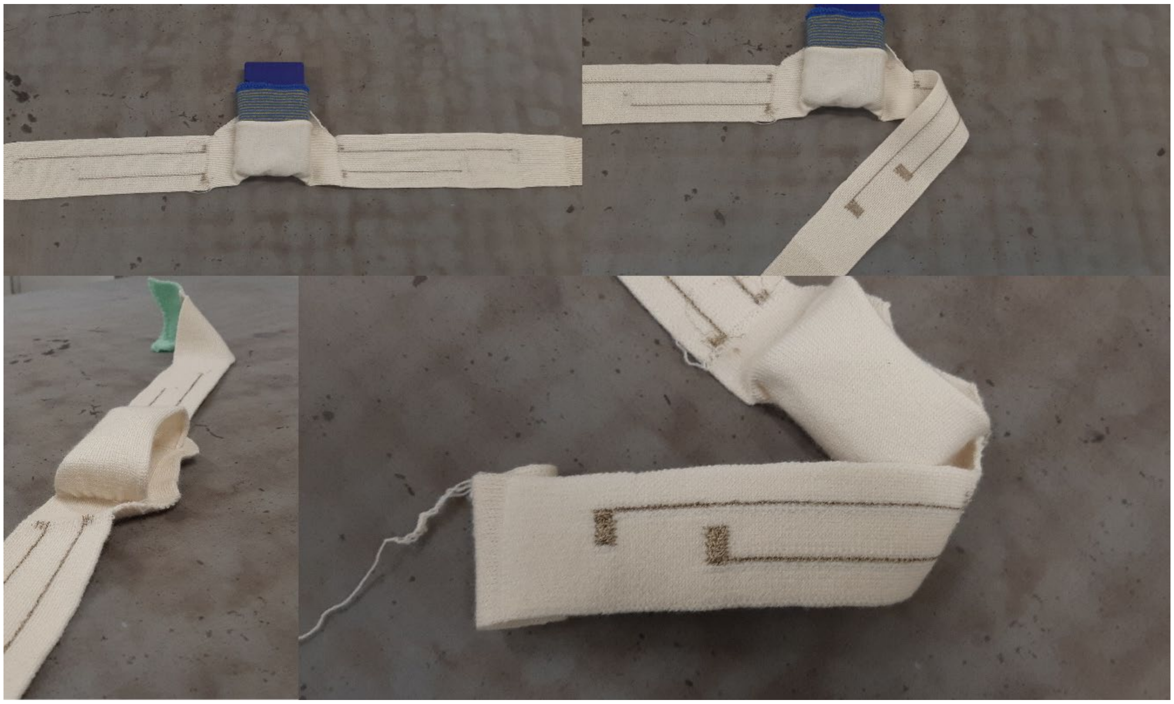

Figure 101

Process of steaming the entire belt. The pocket is packed out so that it has a form to steam around.

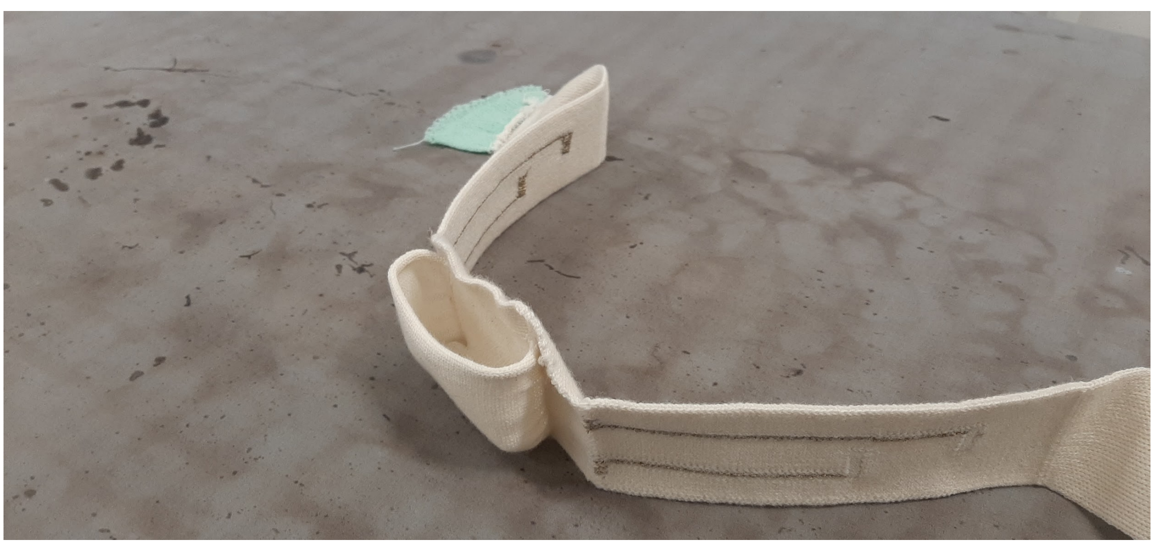

Figure 102

Steamed belt, with hardened enclosure pocket and electrode sections. Embedded high conductivity silver yarns provide soft circuit and electrode interconnect.

The overmould sections would be modelled to let the brim of the silicone sit on top and flush with the edge of the belt as shown in Figure 97. This would be cast atop the hardened sections of the belt strap and orientated around the conductive pads shown in the belt in Figures 101 and 102. The mould would be orientated and cast upside down with the complex geometries being at the lowest point (See Figure 103). This allows the silicone to fill the form and set more accurately. The conductive pad sections are held by pillars in the mould block that hold it suspended between the two mould blocks (see Figure 104). The opposing side has a located magnet that will be pinched against the conductive pad and moulded over as shown in Figures 103, 104 and 105.

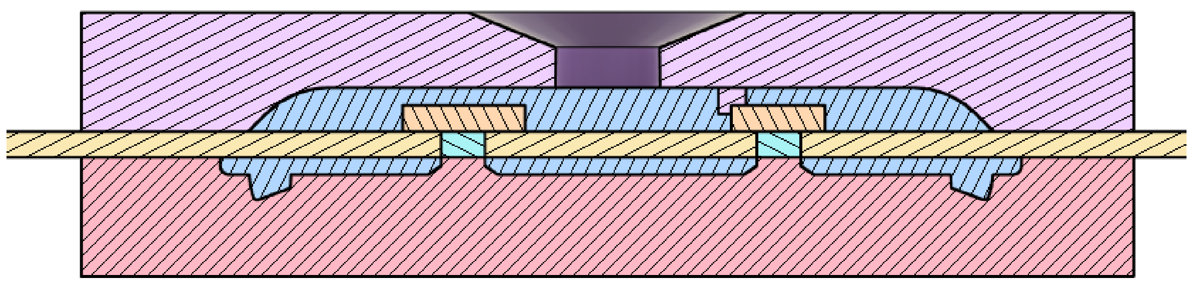

Figure 103:

Mould oriented correctly for casting. Cut outs in the fabric allow the silicone to pass through and fill the other side.

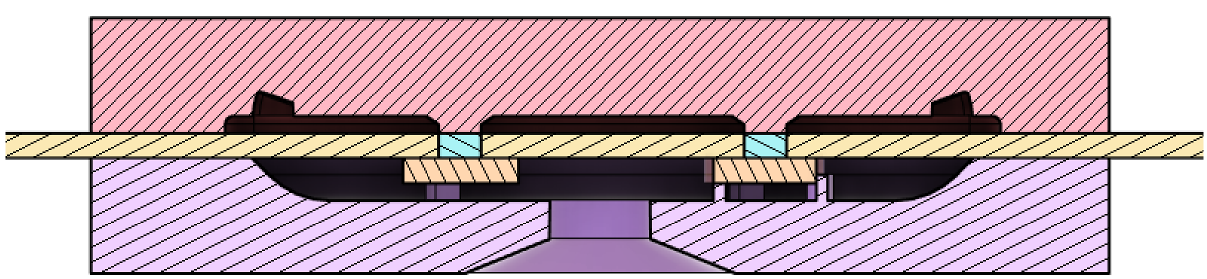

Figure 104

Feet for holding magnets visible in mould negative cross section.

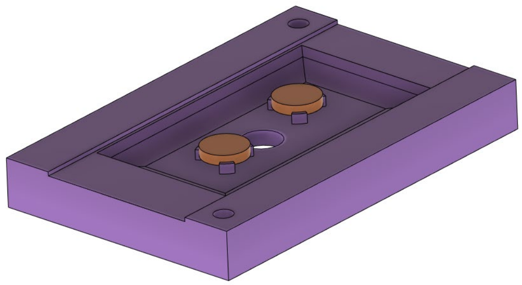

Figure 105

CAD of the lower mould with magnets sitting on feet.

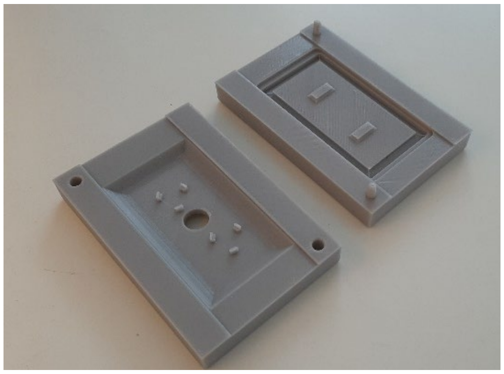

Figure 106

3D print of injection mould block.

Unfortunately, there was not enough time to test the 3D printed overmould block. Despite this, this process had shown a good synergy between the manufacturing methods, materials and how the resulting forms might complement each other. If developments were able to continue forward it would likely seek to resolve the electrode interconnect and reapproach the e-textile material space for material better suited for biopotential monitoring. In a future health wearable project these designs could offer an integrated, skin-safe, comfortable garment output. These conclusions, along with those related to the challenges and concepts discussed in the literature review and methodology are discussed further in Chapter 5.

Chapter 5: Conclusion

This research was successful in producing several original, functional e-textile electrode designs for monitoring ECG biopotentials, aided by the use of materials like thermoplastic yarns and silicone moulds/overmoulds. These designs addressed challenges presented in the introduction of this research and framed in the literature around designing for the body, integrating components and specific challenges around ambulatory ECG monitoring, like motion artifact, e-textile electrodes drying out and electrode slippage.

Despite not being fully integrated into a complete system, the components designed and documented in this research offer potential solutions to current problems in long term, everyday ECG monitoring. Later efforts beyond the group phase of the project, offered further solutions to integration by incorporating the electrical interconnects in the garment itself via a combination of manufacturing processes developed through the research.

One of the general challenges in creating a wearable discussed throughout the research is designing for the body. Accordingly, enclosures were placed and oriented in areas of the body that would be unobtrusive. Further development of an enclosure on the body should focus on reducing hard edges and giving the enclosure a more organic form that will contour better to the body. This would only be possible once the hardware aspects of the design were settled. The garment addressed comfort and fit concerns by using thermoplastic yarns to create areas of rigidity, creating breakpoints on the garment to control where pressure is applied on the body. Thermoplastic yarn in the knitted belt was also used to create a semi-rigid pocket for the enclosure, effectively securing the enclosure to belt connection. The structural strength of the thermoplastic yarn also allowed for created firm back pads for the electrode area, allowing the electrode to apply a uniform pressure on the skin. Machine knitting could be used to further integrate components by replacing electrical elements like snap lock buttons with knitted conductive yarns and removing the need for wires to and from the electrode. Any means of addressing interconnection issues should be covered as early as possible. This was an area of the research that was reasonably addressed, but could be advanced much further with more development.

Issues of comfort and wearability should also be considered throughout development to create the most successful outcome. Challenges outlined in the introduction of this research around e-textiles were addressed in both literature and practice. Novel methods were developed aimed at solving issues around tension between fit/comfort and efficiency. This research established a viable method for creating highly compliant e-textile electrodes by combining e-textile cloth and EVA foam with heat activated adhesives, and then vacuum forming the composite into the desired shape. This allowed for complex semi-rigid conductive forms that hold their shape against the body, providing the necessary firmness and pressure for acquiring ECG, but also easily conforming when pressed against the body. Additionally, the mouldable nature of it affords making specific surfaces to match the body. The denser EVA foam also offers a helpful means of acquiring biopotential signals in lieu of electrolyte gel, a particular issue to e-textiles. The foam promotes sweat at the electrode site, helping to embed the e-textile with sweat. This has been shown to greatly increase signal fidelity in visual comparisons (Paradiso & Pacelli, 2011, p. 3).

The primary concern of the IBTech group for the wearable was motion artefact, an ongoing and currently unsolved challenge in ambulatory ECG monitoring. Silicone was explored as a way of securing the electrode site while pre-stretching the skin. An additional benefit of the silicone backing is further promoting and retaining sweat at the site of the electrode. The engineering team identified the movement of skin underneath the electrode as a primary source of electrical interference. In the earlier design, the silicone walls surrounding the e-textile bind the skin and press outward due to the draft angle of the walls. This would pre-stretch the skin while significantly reducing slippage of the garment, another problem area in ambulatory monitoring. However, the initial nylon backing used to attach the silicone proved too rigid to be worn comfortably and appeared to negatively affect electrical results due to being non-conforming and more subject to motion/breathing artifacts. To address this, the component was developed further by integrating the silicone directly onto the knit using overmoulding. This significantly improved mechanical behaviour and fit, while reducing the overall weight and obtrusiveness of the garment.

These outputs show considerable promise and with development in this direction, could produce a fully integrated, functional ECG system. The components designed in this research also afford opportunities in other areas of wearable healthcare devices, specifically the use of integrated thermoplastics to vary mechanical fabric behaviour, e-textiles secured via silicone to reduce slippage in dry sensing electrodes, 3D formed e-textiles via vacuum forming and overmoulded e-textiles. The research to date suggests these as viable wearable design solutions to problems like motion artefact, electrode slippage and some elements of e-textile electrode performance.

Beyond the physical outputs of the research, interdisciplinary issues and collaborative frameworks were discussed, and ongoing attempts to work better in this space were characterised (in the methodology section). These discussions were critical to my understanding of the research goals and challenges, and while the questions posited may not have been conclusively answered, they did broaden my understanding of engineering considerations for the project. The concepts discussed were often aspirational in the sense that all parties would be involved and there would be a shared understanding. In practice this was naive to the realities of larger interdisciplinary team projects, with their specific timeframes and institutional drivers. Addressing the interdisciplinary concerns outlined in the literature, such projects can only be fully realised if design considerations are incorporated into the project framework from the beginning, rather than as an addition to the technical development. From the work done in this research I would suggest that many of the interdisciplinary challenges identified in the literature likely stem from the maturity of the hardware before designers or wearable developers are brought into the project. This issue needs to be considered when planning wearable projects with a model like that presented by Tenuta and Testa (2018, p. 11). The model provided by Tenuta and Testa merges scientific method and the creative process to present a more complete view of a wearable design process. One that considers wearable specific challenges by incorporating end users in the design and development process. This model could be further developed to account for the level at which the technology is being integrated. This would help developers be aware of the challenges specific to the level of integration and plan accordingly.

An additional component of the interdisciplinary research was the conceptual lens model, developed from writing by Crouch and Pearce. This aimed at promoting better workflow between disciplines and bringing awareness to each other's challenges. Conclusions around this can only be offered from a personal perspective, as others in the project were not concerned with this element of the research. As discussed in the methodology section (2.1.4, pages 43,44), it became apparent that the concept of applying a disciplinary lens proactively was fundamentally flawed. But used retrospectively it offered a means of reflecting on practice or concepts with the added input of a specialist. Incorporating others' views in this way would allow them to test assumptions around certain aspects of design and get valuable feedback for creating design outputs that would better interface with the hardware being developed. In this respect, I would reposition the lens concept from a broad multi-person tool, to an additional reflective tool, as it is essentially expert feedback on designs and processes. The awareness of disciplinary challenges and collaborative aspects was fostered by separate phases of development. This allowed for comparison of the differences between individual practice, interdisciplinary work and the larger team effort.

The practice and concepts described in this research involved two distinct periods of development, the first and longest being the ECG development that occurred as part of the sponsored IBTech group project, and the second being amendments made personally after the group project. While not originally the intent of the research, this offered an opportunity to compare differences between the two phases in relation to wearable design and fabrication, but also to contribute to the wider interdisciplinary discussion.

The first and most obvious advantage in continuing development beyond the group stage was having total creative control over the direction of the development. Decoupling from a predominantly technical mandate allowed me to be explorative in how the previously developed components were integrated. Not having to react to new changes in hardware and requirements meant planning and design were easier. Conversely, removing access to technical expertise of the team cut off input from a group of different engineering specializations that could have added valuable input. It is difficult to come to any conclusions around the different phases, as the considerations of the IBTech research group did not include my research around the interdisciplinary challenges of wearable design and there was a fundamental difference in expectations around this issue. One key variable that affected the outcome was the stage of development for the IBTech hardware. In my time with the project the PCB and components to be used were constantly in flux, this made planning around how to integrate certain aspects difficult. Resolving the enclosure in the independent phase allowed for much clearer focus on integration and resulted in better planning in the individual phases of the research.

In conclusion, it is possible to produce an integrated e-textile wearable for acquiring ECG in everyday monitoring. Functional components were developed in this research that may present solutions for future research in the smart garment, wearable healthcare space. Beyond the physical outputs of this research, it is worth considering that the focus of the team, and stage of hardware development has a dramatic effect on design and how hardware is integrated in the wearable. Wearables development should establish the level of technological integration desired as early as possible to better plan toward that outcome. Following this, it becomes easier to understand how hard and soft systems might integrate, and how to design those systems around the body. The interdisciplinary challenges in the wearable development space, particularly as it relates to e-textiles, will likely continue until e-textiles develop further and are less subject to the electrical variations created by the complex mechanical strains of textiles. Difficulties in development might be mitigated by accounting for these challenges in the planning phase either via exploring new interdisciplinary design models developed in research or incorporating designers and end users earlier in the project.

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