An investigation into the validity of 3D printing as a method to produce upper limb sports prosthesis for specialised sports

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Abstract

Physical activity is important to keep both the mind and body healthy and can reduce the risk of diseases later in life such as type II diabetes and cardiovascular disease. It is therefore important that all individuals have the opportunity to participate in sport and physical activities. Those with limb loss benefit from these activities in the same manner as their able-bodied counterparts, however have less opportunities to participate due to lack of facilities and equipment.

The lack of equipment is more prominent in upper limb than lower limb prosthetics as recreating the many degrees of freedom of the hand is difficult. The issues that come with designing a multi-purpose hand are avoided by creating a different device for each function, especially when it comes to sport. However, there are limited devices available and these are invariably expensive.

This study examined the provision of sports devices for upper limb prosthesis users, and used 3D printing to produce a relatively inexpensive terminal device for use within a minority sport, fencing.

The study employed a mixed methods approach, combining qualitative semi-structured interviews with quantitative motion capture. In the first part, interviews were conducted with professional prosthetists, gathering opinions and experiences with the prescribing and making of sports prosthetic devices.

In the second part of the study, a specialist prosthetic device was made via 3D printing for the sport of fencing. This was then attached to a prosthetic simulator and kinetic data gathered using a Qualisys motion capture system. The motion captured was a basic fencing move, the lunge.

The interviews revealed that most sports prostheses are bespoke and made in clinic workshops. This is a long process each time as there is no standard designs and each user requires slightly different functionality. There are some commercial devices, however they come with high cost and there is little funding available as they are not considered essential items. There may be a place for 3D printing in clinics, however, the issue of safety was brought up by participants.

The 3D printed device conditions produced less compensatory movements than the left-hand condition (when the épée was held in the non-dominant hand) when compared to the gold standard (when the épée was held in the dominant hand). This is despite the rigid nature of the wrist of the device.

Chapter 1 – Introduction

There are numerous benefits to participation in sports and physical activities for people of all ages and abilities [1, 2]. Up until recently there has been limited suitable facilities and access to disability sport. However, with the rise of the Paralympics since 2012, the first Invictus games in 2014 and the generally increased level of visibility for and about disabled people being 'sports active' there has been a gradual change in the wider public perceptions surrounding sports and disability.

Television programs such as the 'last leg' on Channel 4 and paralympians being headlined in mainstream television, such as Jonny Peacock on 'strictly come dancing', has emphasised the fact that barriers to participation are gradually being removed. What is still unclear is whether this publicity, which is focused mainly on lower limb prosthesis users, has been mirrored in those with upper limb absence. Furthermore, it is still debatable as to how much change there has been in terms of opportunities and facilities for those who usually use an upper limb prosthesis.

Retaining or reclaiming independent living for people who have limb absence, congenital or acquired, is a vital component of successful rehabilitation. In the literature there are many examples of studies assessing use of prostheses for activities of daily living (which are usually defined as the activities needed for one to be independent) [3, 4]. However, there is virtually no research on whether individuals use their prosthesis for recreational activities. Whilst a lot of attention is given to daily living, anything that is not considered to be one of these activities, such as participating in sport, is often not reported. To truly retain or reclaim a physically, as well as mentally, healthy and independent lifestyle, the ability to participate in these recreational activities is thus just as important as being able to partake in activities of daily living.

An individual may assess their capabilities and rehabilitation based on a comparison of their ability to perform activities that defined their life prior to amputation, comparing pre and post amputation ability. They may also look at their peers and assess their capability to perform activities against these peers. It is therefore important to recognise that being able to conduct an activity post-operatively, or at a specific stage of life compared to their peers may have both physical and psychosocial impact on the affected individual.

Furthermore, although much of the focus for prosthesis users, especially in the media, has been on the use of running blades, these are not suitable for all physical activities. The choice of sport or activity should be down to the particular wishes of the affected person and not a preconceived stereotype of what a disabled person ‘should’ be undertaking. This is of particular significance for an individual who undertook a sport prior to amputation.

For a person with upper limb absence, especially one who has undergone an amputation, the ability to carry out the same actions and activities they could pre-operatively is very important. However, for an individual who has had an upper limb amputation, often re-training them to use the unaffected arm is more beneficial than providing a prosthesis for the affected side. This is especially so if the prosthesis designs and available components do not match up to the needs of requirements of the specific sport or activity that the affected person wishes to undertake.

The relatively small numbers of individuals with upper limb absence preclude the widespread availability of suitable pre-made devices. Furthermore, the variety of grip types afforded by the biological hand (5, 6] and the variations in grips required for specific sports mean that devices that are available may not be useful for what are considered to be minority sports.

This thesis will investigate what prostheses are available for individuals with upper limb absence who wish to undertake what would normally be termed a minority sport, such as fencing. The aims are as follows:

1- To evaluate the prosthesis provision and clinical prescription options available for people with partial upper limb absence to undertake minority sports and activities.
2- To establish the criteria for prescription, and whether the use of the non-dominant ‘sound side’ may offer a better long-term alternative than using a specialist prosthesis.
3- To investigate whether the use of a bespoke, 3D printed design could offer significant advantages for the prosthesis usage within a minority sport such as fencing.

To begin with, the next chapter will examine the literature to identify the implications of sports participation on both the able-bodied and those with limb absence. It will identify the key aspects of prosthetic treatment and the suitability of current devices for someone who wishes to undertake a sport that wouldn't be considered to be main-stream, such as fencing. Finally, it will also examine whether newer methods of production that do not rely on large quotas to be financially viable, such as 3D printing, offer solutions to the development of sports specific devices by producing cheap, bespoke items in relatively few numbers.

A mixed methods approach will be used, with a qualitative assessment undertaken and detailed within Chapter 3, involving semi-structured interviews with private practising prosthetists. The second part of the investigation, detailed within Chapter 4, will be an evaluation of bespoke devices using a combination of movement and performance analysis. The lead researcher is experienced at the sport of fencing and has a detailed knowledge of the movements involved. This knowledge can be transcribed into a series of relatively simple movements, where sound side right-hand (dominant) movements can be designated as the 'gold standard', and thus used as a baseline from which to compare the movements achieved by the fencer using a prosthesis simulator, or the non-dominant side.

It is anticipated that the combination of both of these methods will provide a greater insight into the provision of sports specific devices. Including what results may be achieved and whether the provision for unliteral prosthesis users is worthwhile, given the fact that the non-dominant side may also be used as a viable alternative for single-handed applications.

Chapter 2 – Literature review

2-1 – Chapter introduction

This chapter aims to give an overview of the literature to provide background knowledge of the themes and processes discussed in this thesis, beginning with the general benefits of sport, highlighting why it is important for all individuals to have the opportunity to participate. Next, the difficulties faced by those with upper limb absence will be explored with a focus on functionality and issues faced when trying to recreate the biological functions of the hand, followed by a look at current prescription options for both every day and sporting scenarios, highlighting the different needs in these scenarios. The chapter then moves on and identifies the movements involved in the chosen specialised sport of fencing in order to identify the actions that need to be recreated. The chapter then discusses the option of re-training the individual to use their naturally non-dominant hand and the possible success or failure of this in the sport of fencing. The specific prosthetic considerations are then explored for the socket and terminal device in relation to the design process of a fencing prosthesis. Finally, an overview of 3D printing is given, covering both current uses for the process and the possibility of using the process to create a bespoke solution.

2-2 – Benefits of sport and physical activities

2-2-1 – General benefits

There is a significant amount of evidence showing that participation in sport is important for both physical and mental wellbeing [7]. Participating in sport is not only a way to keep fit and active, but also a chance to interact with others. Increasing levels of sports participation can help to build social contacts and develop friendships. Conversely, a sedentary lifestyle is linked with increased metabolic risk, increased risk of cardiovascular disease and increased risk of mental disorders [8]. It is widely recognised therefore that keeping the body in shape can also keep the mind healthy and help the individual to achieve both physical and mental wellbeing [9].

In addition, participating in sports can prevent many diseases that are linked to inactivity, such as type II diabetes, cardiovascular insufficiency and anxiety / depression. Given the fact that disease prevention is a key aspect underpinning the delivery of economical modern healthcare in the United Kingdom, the importance of providing and supporting an active lifestyle cannot be underestimated.

The type, intensity and participation rate all affect the benefit of physical activity. Physical benefits such as the prevention of conditions like high blood pressure, type II diabetes, the likelihood of contracting cardiovascular disease and osteoporosis later in life are reliant on an appropriate type, intensity and frequency of physical activity [10]. In the UK, the national health service recommends that an adult (19-64 years old) participates in 150 minutes of moderate aerobic exercise a week in combination with 2 muscle strengthening sessions a week. Alternatively, they suggest 75 minutes of vigorous aerobic exercise a week in combination with the same two muscle strengthening sessions [11].

The social and mental benefits of sport can also be affected by the chosen sport. Individuals, especially disabled individuals, may have a negative view on sports based on school physical education. This could be due to the competitive team nature of most school sports or the lack of adaptability or teaching style. It has been found that adolescent males are more likely to benefit from competitive team sports than females of the same age range. Adolescent females have been found to prefer to participate in more individualistic sports such as swimming, athletics and horse riding [10]. The mental benefits, such as self-image and social inclusion, will differ from individual to individual depending on quality of coaching, teaching style and adaptability of the coaching staff [10,12].

2-2-2 – Benefits for those with limb absence

Participating in sport can offer those people with limb absence the same physical and psychological benefits as their able-bodied counterparts. Indeed, often the need for sports and activities in this particular demographic is far greater, given the propensity for amputations to occur because of the very factors that plague modern sedentary life [13]. However, just as able-bodied people are able to choose from a range of sports to participate in, so an individual with limb absence should ideally also be able to choose from a similarly large range of prospective activities. 73.4% of amputees experience restrictions when trying to participate in sports or physical recreation [14]. If those with limb absence cannot participate alongside their able-bodied peers, whether this is due to lack of equipment to facilitate this or lack of opportunity, a feeling of inadequacy or exclusion may be felt. This is particularly notable when an individual was participating in a particular activity before amputation [15]. Commonly, the most popular sport related by the wider populous to amputees is running, with the lower limb running blade for example now being synonymous with sports provision and amputee activity. However, this device is by no means universal in its application or usefulness and is not functionally beneficial for every sport. Furthermore, it may not actually be wise for some amputees to undertake vigorous exercises such as running [16] and every individual should consult both their GP and their prosthetist or consultant before embarking on any sport or activity that would be deemed to be strenuous, either to them, or to their respective prosthetic device.

Selecting the most appropriate activity can be key to providing the most suitable level of recreation and rehabilitation plan for any affected person, but when the affected individual has participated in a previous activity prior to amputation the need to be able to continue to participate can be very beneficial to both their physical and of course their psychological wellbeing. Adjusting to an amputation can be very challenging; however, if certain activities can be maintained, then these changes can have a lesser effect on the wellbeing of the affected person. Sadly, anxiety and depression are more common in amputees than the able bodied [17], with many prosthesis users feeling excluded [18].

Removing barriers to sports participation for amputees is therefore a key factor in delivering good health and positive rehabilitation. One particular barrier is a lack of social support and training surrounding the perceived loss of mastery (of an activity participated in pre-amputation) after an amputation. When an individual has an amputation, they may lose confidence in their ability to perform a certain activity after this, and this loss of confidence becomes a psychosocial barrier to well-being [19]. This perceived loss of mastery may be overcome by beginning to participate in a new sport but being able to still undertake the same activity after amputation, albeit with some re-training, would be beneficial to the affected person.

Furthermore, evidence also suggests that able-bodied children who have less confidence participating in traditional sporting activities such as football, often find a "level playing field" in sports and physical activities that are more unusual [20]. This could potentially encourage some amputees to undertake sports participation in these sports and, with the right prosthesis; amputees could find this same level playing field, boosting confidence and perceived mastery. There is a significant link between amputee's participation in sport and perceived body image. Those that participate in sport and physical activities have been shown to have a more positive body image, improving mental well-being [21]. However, although the link between body image and sport is clear, the driving factor underpinning this link is not, i.e. is it participation that generates positive body image, or vice versa.

In terms of levels of amputation, it has been shown that those individuals with a more proximal limb absence are more affected by the consequences of amputation than those with more distal absence. In addition, more problems arise post-operatively in those whose amputations are due to a vascular cause. However, the loss of a limb is shown to have a lesser psychological impact on the affected individual than those affected by other disabilities, such as loss of sight or a spinal cord injury [22]. It should also be remembered that upper limb amputation cause varies when compared to lower limb amputation. The leading cause of lower limb absence in the UK is amputation due to vascular disease, whereas the leading reasons for upper limb absence are congenital deficiency and trauma [23]; this difference in cause leads to a very different demographic. Lower limb amputees from vascular disease [24] are usually older individuals with a variety of other health concerns whereas, on average, those with congenital upper limb absence are young, otherwise healthy individuals. Those with limb loss due to trauma are also generally younger (at the time of amputation) and therefore have a higher likelihood of being active individuals after rehabilitation [25].

The rejection rate of upper limb prostheses is high, with at least 30% of adults who have congenital limb absence choosing not to use a prosthesis or assistive device. The rejection rate for upper limb prosthesis ranges from 30%-80%. Furthermore, the rejection rates for individuals with trans-radial absence are far lower than the rejection rates for those with a more proximal absence [26].

New lower limb patient referrals account for 91% of all new prosthetic referrals [26]. Trans-tibial is the most common level of amputation, accounting for nearly half of all amputations, with the most common cause being cardiovascular insufficiency, which accounts for 77% of all amputations, with 42% of amputations linked to diabetes. Furthermore, 60% of individuals referred to a prosthetic clinic following a lower limb amputation are aged 65 or over. Upper limb referrals are, on average considerably younger, with an average of less than 55 years of age. In addition, 61% of upper limb amputations are due to trauma. In 2004/5 there were 95 referrals for upper limb congenital absence in the UK but only 64 for lower limb congenital absence [27].

Those with congenital limb loss or amputation after trauma generally have little or no other underlying health complications. This, combined with the average younger age compared to lower limb amputees, means upper limb amputees are more likely to be able and motivated to participate in physical activities and sport.

The sports most popular with people that have limb absence are swimming, cycling, golf, fishing and fitness [22]. It should be noted that swimming doesn't require a prosthesis for participation. Interestingly, ball and racquet sports are often unfavoured by individuals with limb absence. Indeed, the numbers of individuals partaking in these sports is far lower, percentage wise, than the in the able-bodied population. The reason for this may be a lack of appropriate prosthesis, both upper and lower limb, to facilitate these sports; however, there is a general lack of evidence surrounding provision, particularly in the field of upper limb prosthetics. Aside from jogging and track running, there is also a lack of quantitative evidence for the use of sports prosthetic devices overall, with limited number of papers available. Furthermore, what studies have been conducted are usually based on qualitative data and subjective individual opinions [28].

Evidence also suggests that children's participation in sport is strongly linked to their sports identity, which develops at a young age and is their 'perceived' competence in sport. This is seen to be most greatly influenced at the ages of 12-13 years. Positive experiences with sport at this age are seen to increase sports identity and as a result sport participation. Meanwhile negative experiences tend to decrease sports identity and therefore participation [29]. It has also been suggested that children are less likely to be motivated to participate in sport if competition is involved [30]. These suggestions are compatible, as if a child is unsure of their competence in an activity they will not be inclined to compete against others for fear of embarrassment. Encouraging participation is therefore a primary concern if social development inclusivity is to be achieved. If prosthesis users feel that they cannot compete at an adequate level, then they will simply not participate. Providing users with the tools to be able to compete with their peers is thus clearly beneficial. Furthermore, it has been shown that if an individual is active during their childhood, they far more likely to be active in their adulthood.

There is a variety of role models available for those with lower limb absence; this cannot be said for upper limb prosthetic users. One example, however, of someone determined to be a successful athlete with multiple limb absence is John Willis. John Willis has quadruple congenital limb absence and was determined to raise money for his charity, Power2Inspire. He undertook the task of trying all Olympic and Paralympic sports and succeeded with the help of specially designed prostheses for some of the sports. He believes that everyone should have equal access to sport and the opportunity to try all sports to find out which ones you enjoy. Willis has a positive opinion of the hype that surrounded the 2012 Paralympics, however he is concerned that this may not be enough to influence those that have lower ability levels in joining in for "the fun of sport" [31]. He believes that "If you can create that exhilaration of pushing yourself, it doesn't matter what level you're at." [32]. The example of Willis shows that most sports can be accessible if the correct provision of usable devices is achieved, which can be seen as a good motivator. However, his success provides the illusion that these devices are readily available, when in reality most of the devices he used cannot be acquired commercially. Even if they were available, the cost associated with a device for each activity is significant, which could have the inverse effect than was intended and discourage individuals from pursuing these activities.

2-3 – Issues when recreating the biological hand

The many functions of the biological hand are hard to reproduce with a single prosthetic device. This leads to the need to have a multitude of terminal devices for different jobs. The devices could be as simple as a spoon attachment for eating and as complicated as a bionic hand with myoelectric control. The low functionality of all types of upper limb prosthesis, passive, body powered and myoelectric, can lead to the eventual rejection of the device. This could be due to the fact that many activities of daily living can be performed single handed and therefore the user believes, with current devices available, they are more functional without their prosthesis [33].

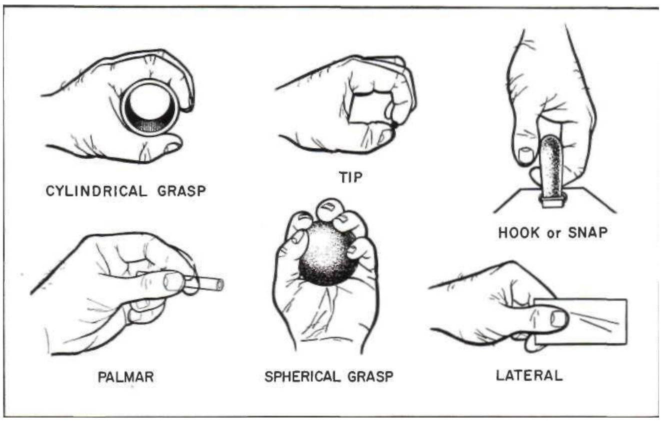


Figure 1 – 6 Grip types [37].

Due to the 29 bones and 19 Joints that make up the hand, with 34 muscles to power movement [34] the human hand has about 30 degrees of freedom [35]. Attempts to accurately reconstruct this structure and its intricate degrees of freedom robotically have resulted in heavy bulky devices such as the shadow hand [36]. The human hand is capable of many grip configurations. The different configurations can be categorized into power or precision categories. Within these categories, depending on the size and shape of the object to be held and the manipulation desired, different grips are possible. The basic grip types can be grouped into cylindrical, tip, hook or snap, palmer, spherical and lateral (Figure 1) [37].

2-4 – Prosthetic provision for upper limb amputees

2-4-1 – General categories

Upper limb prostheses can be generalised into three categories; passive, body powered and myoelectric [26]. Which category the prosthesis is in depends on the method of control of the terminal device;

1- Passive prostheses, which have no functional movement and come in the shape of cosmetic hands and static tools. For example; cutlery attachments, hammers and dressing sticks.
2- Body powered devices use webbing and harnesses in various configurations to give functional movement to the terminal device, these are often in the form of hooks or articulating hands. The harness is made to fit the user in a figure of eight or p-loop configuration, depending on the method of suspension, and activated by bi-scapular abduction or humeral flexion respectively.

3- Myoelectric prostheses are powered by batteries mounted in the forearm of the prosthesis, resulting in an increase in the weight of the device, and controlled using sensors in the socket that detect the electric signals in the muscles (EMG) of the residual limb. For tans-radial, the muscles usually associated with wrist extension are used to open the terminal device and the muscles usually associated with wrist flexion are used to close the device.

There are hybrids of these prosthesis types when at trans humeral or higher levels of limb loss, this often comprises of a body powered elbow and myoelectric hand. As well as hybrids, specialised prostheses can be made for specific tasks or activities, however each joint will still fall under one of the three categories.

2-4-2 - Suspension

As well as the terminal device, the suspension method must be considered. In upper limb prosthesis this is one of the most important things as, unlike lower limb prosthesis, there will be little/no weightbearing on the prosthesis. Suspension can be achieved by use of a harness, a self-suspending socket or silicon suspension sleeves. For trans-radial level absence these come in the following forms;

1- Suspension harnesses have a figure of eight configuration with most of the weight being taken across the contralateral shoulder and under the contralateral armpit. The harness allows for slightly lower trim lines and can double as functional method for body powered prosthesis. If another suspension method is used with a body powered terminal device, then a figure of eight harness is not necessary, and a p-loop can be used.
2- Self-suspended sockets have higher trim lines than other suspension methods; this is because the socket must encapsulate the bony anatomy. In the case of trans-radial limb absence, the bony anatomy to be encapsulated is the humeral condyles and olecranon. Self-suspension is best suited to long residual limbs however the high trim lines over the olecranon limit extension, so this may not be suitable for all activities.
3- Silicone suspension sleeves provide a layer of padding between the residual limb and the socket, this can be useful when the user is expecting higher impacts due to sport or a manual job. With silicon suspension, lower trim lines can be used,

allowing for greater range of movement. Furthermore, no restrictive harness is necessary. The silicon sleeve attaches to the socket via a pin or lanyard attachment; which attachment is used must be taken into consideration when the sleeve is used for a long residual limb as the pin takes space in the forearm before the wrist unit can be attached. A long sleeve can compensate for a lack of surface area of a short residual limb.

2-4-3 – The socket

The socket itself is generally bespoke, laminated in in-house workshops by qualified technicians. These can be made of fabric layups impregnated with resin to harden and vacuum formed over a plaster model of the user's residual limb. In cases where high impact is anticipated the layups can be layers of carbon fibre instead of fabric. A combination of fabric with carbon fibre reinforcements can also be used. The use of resin with higher or lower amounts of hardener can also be used in different areas of the socket in a two-stage lamination to create a hard socket with a more flexible edge [38]. The shaping of the proximal edge of the socket is determined primarily by the suspension method. The shape of the socket is determined by a plaster cast taken of the user's residual limb. The cast is generally taken with the residual limb in "pre-flexion" to assist with suspension of the prosthesis, this is when the user holds their residual limb in a slightly flexed position during casting.

2-4-4 – Functional control and myoelectrics

The functional use of myoelectric controlled prosthesis is accompanied by a larger amount of training and practice than that of body powered prosthesis. This is often enough to prompt the rejection of the prosthesis or for the user to wear the device but not use it functionally. Carey et al. found that, despite their subject reporting proficient use of both their body powered and myoelectric prosthesis, they preferred using their body powered prosthesis. This could be explained by the reduction of range of motion at the elbow due to the socket design, confidence levels in the ability of the myoelectric devices or lack of feedback from the devices [39]. The lack of proprioceptive feedback may be a factor limiting the use of myoelectric devices, unlike with body-powered prosthesis there is no harness tension to assure the user that the device is gripping correctly. As well as this, the lack of complex actions possible when using a myoelectric device seems to discourage use. The limited degrees of freedom available from myoelectric prosthesis make the movement's achievable look unnatural to onlookers. This is because biological arms and hands move smoothly through multiple degrees of freedom in a single movement whereas a myoelectric prosthesis is only able to be activated on a single degree of freedom at a time. This unnatural movement pattern may also be a reason for disuse [40].

The effective use of myoelectric prostheses relies on the electrodes embedded in the socket to fit over the correct muscle groups every time the prosthesis is donned. The electrodes are subject to shift relative to the residual limb when in use [41]. This is especially relevant when in a sporting environment. When participating in physical activities there is a high chance the prosthesis will experience higher forces than in activities of daily living. This is likely to increase the chance of the socket shifting and therefore the electrodes shifting relative to the skin and underlying muscles, resulting in a lack of control over the prosthesis. Combined with the lack of feedback from the device this may result in failure to complete or maintain the desired movement.

2-5-1 – Current devices available for sports participation

For lower limb amputees, a range of running blades, shock absorbers and torque absorbers are available commercially [28]. Not all of these have children's versions and depending on the size of the child there may not be room to add some of the componentry. The misconception that "sports prosthesis" and "running blade" are interchangeable to the general public is demonstrated by doing a simple google image search of the two terms [42,43] and observing the similarity in the images. Even outside of running blades, in the "sports prosthesis" search there are no upper limb devices in at least the first 50 images.

Currently there are limited specialised sports prostheses for those with upper limb absence, partly because of the low numbers of upper limb prosthesis users when compared to lower limb. Referrals to disablement service centres in the United Kingdom for example in 2012 showed that there were approximately 10 times as many lower limb referrals as upper limb referrals [23]. The small numbers and the low levels of demand from these prosthesis users, particularly for minority sports, has led to a small demand, and a subsequent lack of investment from companies. However, perceptions regarding availability could impact choices and subsequent prescription or selection of devices.

Anecdotal evidence suggests that even when a sports prosthesis is issued, the recipient often finds a “more effective” method to participate than using the device [22], with prosthetists sometimes adapting or creating devices on a case by case basis. This could become a costly exercise if regular changes to the size of the prosthesis are required. The lack of effective, cost efficient prosthesis designed to facilitate sports and physical activities may be a leading cause as to why those with limb absence are less active [22].

A guide to adaptations for upper limb amputees to participate in sport was published in 1979, although this guide mostly illustrates how to adapt sporting equipment to be able to be gripped with a prosthetic split hook terminal device [44]. As the split hook becomes less socially acceptable when compared to other advancing technologies, a change to the approach may be necessary when looking at facilitation to sport for individuals with upper limb absence. The split hook is symptomatic of the clinical stagnation of devices for upper limb usage, given the fact that despite its age, appearance and simplicity, it is still the method of choice for much of the functional work employed by upper limb prosthesis users.

With the lack of specialised sports prosthesis, the prosthesis users and prosthetists that care for them have limited choices. This often means using passive terminal devices for secondary uses or adapting terminal devices to be able to use them for sports. Biddiss, Beaton and Chau [45] found that 30% of upper limb prosthesis users found various sporting activities challenging, including cycling, swimming, and ball sports.

2-5-2 – Control systems for upper limb sports devices

There is limited literature quantitively defining the quality, function and energy efficiency of sport specific prosthesis, with the exception of running blades. A subjective analysis using the views of only one prosthetist is clearly subjective, and potentially unrepresentative [28].

One company that does produce sports devices in numbers for upper limb prosthesis users is TRS, which has some of its products also documented within the literature [27].

Although the feedback from users and documents appear to be positive, the small-scale production of these devices means that the costs are sometimes relatively high. In addition, not all sports are covered, meaning that some users may have to consider abandoning their preferred activity if no suitable device is available.

Most sports specific devices for upper limb are body powered [46]. Most devices are more applicable to sports that are deemed to be more popular, such as swimming, golf, cycling and hockey [47]. Devices more suitable for use with racquet sports, or that require single handed control, do not appear to be so readily available. This may be because users will switch to use their contralateral arm and there are not enough bi-lateral users to justify the costs associated with R&D and small batch production. However, again, there is little or no evidence which clearly defines this.

The availability of sports prosthesis is further limited by the companies that are authorised to prescribe them, funding and prosthetist preference. A user is therefore limited by which clinic they attend.

2-6 – Biomechanics of fencing movements

It has been suggested that the movements performed when fencing are similar to those in karate and are best performed by those around 180cm or more in height with thin musculature. Fencers rely on speed when fighting but must also have explosive power and high aerobic endurance to do well in competition [48].

Fencing can improve flexibility, reflexes, coordination and agility, it can also improve concentration, focus, strategic thinking and decision-making skills. Fencing is often done at local clubs where there is the opportunity to interact with a range of people, both peers and mentors. Fencing is a sport that can be practiced by all ages [49]. In most sports, competitors in high end competition are generally younger individuals, however in 2015 Géza Imre won the men's épée world championships in Moscow at the age of 40 [50], which puts him into the veteran category despite it not being a veteran competition. This shows that fencing is a sport that can be continued throughout life at a high proficiency level.

Fencing is split into three disciplines determined by the type of sword used. The three swords are foil, sabre and épée. Each has slightly different rules in competition.

The tactical aspect of fencing, especially épée, has been nicknamed "physical chess" due to its strategic and psychological tactics [51]. This not only keeps the body active but the mind as well.

Polish fighter pilots stationed in Britain during World War Two requested a fencing master and a place to train as fencing improved their evaluation of their opponent and use of reasoning while under fire which were transferable skills for when in their planes [52]. Fencers generally show a greater cross-sectional area of the dominant forearm, arm, thigh and calf, which shows how asymmetrical the sport is [53]. This heavy asymmetrical training often results in injury [54], some fencers choose to also train with their non-dominant side to attempt to balance this.

It has been observed that the reaction time differs between the dominant and non-dominant side. This is especially important in a sport like fencing where reaction time has been shown to determine proficiency. The difference is more marked in championship competitors, which may be due to their extensive training. Reaction differs to pure speed; the reaction includes recognising the opponent's intentions and reacting to them. No matter how fast the fencer can move their body they are unlikely to score if they have not analysed their opponent first. Between championship level and lower competition level there is little difference in motor time, however higher-level fencers show shorter reaction times, lowering the total time for each action, which is likely due to their higher level of training [54].

2-7-1 – Retraining with non-dominant hand

As most upper limb prosthesis users will be unilateral (i.e. will have one intact hand) there is argument to suggest that they would be better suited re-training with the contralateral side. However, many upper limb amputations are traumatic, and often affect the pre-amputation dominant side. Limb dominance is determined by functional dissimilarities of the hemispheres of the brain. These functional differences result in preferred use of the right or left hand, foot and eye, the preference for each person is not necessarily the same for all three body parts [55,56].

The dominance of the hemispheres of the brain can be linked to hand dominance. Right-handed individuals tend to be uni-dominant for processes such as speech and motor function, and left-handed individuals are more likely to not have hemisphere dominance [57]. The activation of the muscles in the right side of the body are initiated by activations in the left side of the brain and vice versa [58]. The activations in the dominant side of the brain are faster than those in the non-dominant side, therefore control the movement [59]. The motion of the non-dominant side of the body is controlled by the slower activations in the brain thereby causing the activation of the non-dominant side of the body to be slower.

The muscles that make up the body are made up of different types of muscle fibres. The ratio of these fibres is different in the muscles in the dominant and non-dominant sides of the body. The dominant side is shown to be made up of a higher ratio of more favourable, fatigue resistant fibres [60]. The persistent use of one side over the other eventually results in this higher abundance of fatigue resistant muscle fibres [61]. For someone who has undergone upper limb amputation of the dominant limb in adulthood, the contralateral limb will lack this persistent use and build-up of fibres. The difference in muscle composition has been shown to be less significant in those who are left-hand dominant [62], this supports the idea that those who are left-hand dominant are generally less unilateral than those who are right-hand dominant [63].

2-7-2 – Hand dominance in fencing

There is a higher frequency of left-handers in high level confrontational sports, such as tennis, basketball and martial arts, than in the general population. This frequency increases as the interactions between competitors get closer (such as boxing and fencing). It is unclear if this is due to physical or psychological reasons. It has been observed that left handers are, overall, less unilateral than right handers, this could be an advantage in confrontational sports. The high frequency of left handers could also be due to the psychological advantage that comes from the competitors lacking experience competing against left handers. This psychological advantage would explain why the frequency of left handers is only higher than the general population in confrontational sports (such as martial arts and tennis) and not non-confrontational sports (such as cycling, swimming or diving) [63].

In fencing, the fencer is allowed to switch their sword hands between bouts (but not in the middle of the fight), although this is a very rare occurrence. It is not to say that it has never been done; indeed, there are examples of fencers using this technique to gain an advantage. However, for a fencer to be proficient enough with both hands that such a tactic is viable, they must have a very high level of ambidexterity [64].

The winner of the men's individual épée at the London 2012 Olympic games was Ruben Limardo. Limardo originally began to train at a young age in foil with his right hand, this changed at the age of 12 years, when he broke his right arm in a skateboarding accident. After the accident he switched to épée and began using his left hand. At the age of 27 he achieved success at the London Olympics, proving that retraining with your non-dominant hand is possible [65].

This great achievement shows how one person can retrain, but views expressed by other fencers who have attempted to re-train with their non-dominant hand after injury show that it is a very individual experience. Some have little difficulty while others struggle; this could be attributed to length of time training with their dominant hand or natural ambidextrousness. Unfortunately, there is a distinct lack of research in this area [66].

It has been shown in tennis that, due to high levels of asymmetrical training the bone density of the dominant side is significantly higher than that of the non-dominant side. This difference is found to be greater if the individual starts training at a young age [67]. Due to this difference in bone density it would be disadvantageous to switch to using the non-dominant side after many years of training. This is likely to also be true for fencers as this is also an asymmetrical sport.

2-8 – Requirements of a prosthesis for fencing

2-8-1 – Socket considerations

It has been suggested that when constructing an upper limb prosthesis for specific activity the trim lines and angles of the socket may need to be adjusted compared to the accepted normal. The socket may need to be set in extension, favouring freedom of movement, rather than pre-flexion to enhance suspension. The higher trim lines required to maintain suspension lost by the lack of pre-flexion cause a limit to active flexion; however, in a sporting environment this has been shown to be acceptable when compared to the extra extension gained by pre-extension of the socket. The forces expected to pass through the socket during the intended activity must be considered when deciding the amount of pre-flexion or extension built into each socket [68]. This is important to consider in a sport like fencing, especially épée, where reaching your opponent before they reach you is essential to win.

2-8-2 – Terminal device considerations

The terminal device must provide a secure hold on the grip of the sword or replace the grip and be attached directly onto the blade. To ensure a secure hold on an existing épée grip you first have to consider the type of grip used. The two main types of grip are the french grip and the pistol grip. The French grip is a strait handle, often made from plastic or rubber with a metal pommel, this is the grip most fencers learn with and favours reach as it can be held towards the end of the grip (known as pommeling). The pistol grip is an ergonomically shaped handle with various bumps and ridges designed to fit the palm of the hand, it favours strength and dexterity [69]. This grip gets its name from the way it looks and the way it is held, like holding a pistol. There have been various adaptations to both grip types over the years and exact shape of the grip a person uses is down to personal preference [69]. These are not the only grip types but the ones most commonly found, along with the Belgium grip which is a variation on the pistol grip. With so many different grip designs two options arise, design a bespoke terminal device to fit each grip design or replace the grip altogether.

A fencer will usually change their preferred grip over their fencing career in order to find the grip that most suits their style. This can be done simply by removing a single bolt and swapping a new handle to an existing blade. In the same manner, this should be no different to swapping the grip out for a terminal device, which would remove the need to design around the grip. Fencing grips can cost as little as £6 and as much as £45 [70].

The fine movements of the épée are controlled with the tips of the first finger and the thumb. These fine movements will be difficult to reproduce prosthetically as previously discussed in section 2-3. Larger blade manipulations are made by the wrist. The wrist also takes on a shock absorbing role when the blades clash together. Manipulations at elbow level are limited and the shoulder is generally only employed when extending to attack.

Ideally a measure of controlled wrist movement would be built into the terminal device. This is because as the fencer fully extends to attack, the movement includes wrist adduction. This movement changes the sword from a horizontal or upward angled position to a position with the wrist higher than the sword tip. This is to ensure that the sword bends in the correct direction upon impact. If wrist movement is allowed within the prosthesis, it would have to be strictly controlled as when engaging the opponents blade there must be resistance to ensure defence is possible and the sword tip remains in the fighting area.

2-9 – 3D printing bespoke solution

2-9-1 – Current uses of 3D printing

The use of 3D printing offers (potentially at least) a low-cost solution for device production, that could be well suited to the provision of low numbers of small, specialist devices needed by upper limb prosthesis users. 3D printing (also known as rapid prototyping or additive manufacturing) is a growing technology that is very adaptable and doesn’t require large scale overheads to be fully operational. This method of manufacture has for example been used within the automobile industry to create unique tools for the instillation of bespoke parts and medical professionals to create skin grafts and faciomaxillary prosthesis from synthetic cultures [71]. 3D printing is currently being used to produce hearing aids, dental implants and joint replacements, manufacturing bespoke devices using scanning technology to ensure fit. As well as the personalisation of these devices ensuring fit, function and comfort there is no stock parts necessary, limiting the storage space needed [72]. All scans and designs can also be stored digitally, providing repeatability if a device needs replacing, furthermore digital records can be kept for comparison of design over time. Through the use of 3D modelling software each item printed can be easily adapted for each individual’s needs. This method of device manufacture could then provide an opportunity to create specialised sports prostheses.

2-9-2 – Materials

There are a range of materials available; the versatility of this method of manufacture is growing. ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid) are the two most commonly printed plastics. PLA has a greater tensile strength than ABS however ABS has a larger impact strength [73,74]. These are not the only options, a flexible material called thermoplastic polyurethane (TPU), commonly known as NinjaFlex, is available as well as a carbon fibre and nylon composite. With the use of these materials and their vastly different properties the adaptability of 3D printed designs increases. The use of a duel extrusion printer increases the possibilities further again as this allows two materials with different properties to be printed in the same design. A duel material design could allow for areas of reinforcement or relief in a socket, it could also allow for strengthening of key areas in a terminal device. These materials are generally more lightweight when compared to lamination and polypropylene used in current prosthetic socket production. Weight is an issue for most prostheses, especially when undertaking sports, as movement needs to be as unburdened as possible in order to achieve the best results possible [33]. The use of lightweight printed plastics could be a solution to this problem. With lower base weight greater focus can go to improving function and comfort.

2-9-3 – Designs and prosthetics

Currently, there are open source ready to print 3D designs available online for upper limb prosthetics at the partial hand and trans-radial levels, functioning from wrist and elbow flexion respectively [75]. These designs are, however, simple and not designed for specific functions. The limited functionality of these devices calls into question whether the manufacturing method is being used to its maximum capabilities. It is important to recognise this method of production as a means to solve a problem, and not a ‘high tech’ gimmick.

Currently there are a couple of companies working on 3D printed prosthetics for everyday use. The first is Open Bionics who focuses on myoelectric controlled trans-radial prosthesis [76]. This company has recently gotten a lot of media attention for their superhero themed prosthesis and have recently gained NHS approval. The second company is a small start-up called Ambionics, which has created a body powered arm for trans-radial users controlled by fluid pressure [77].

2-10 – Chapter Summary

In summary, the participation of an individual in regular physical activities is beneficial to both their physical and mental health. This participation lessens the risk of developing health problems such as type II diabetes, cardiovascular disease and mental health disorders. Those with limb absence share these benefits with their able-bodied counterparts, however the facilities and opportunities for participation are lacking. This may lead to a feeling of inadequacy in the limb absent population, especially when attempting to undertake an activity enjoyed pre-amputation.

The leading cause for upper limb absence is trauma, this generally leads to a lower average age for people with upper limb absence than lower limb absence where the most common cause is disvascularity, often from advanced type II diabetes. Those that have limb absence from trauma or congenital loss generally have no other underlying health conditions and combined with the lower average age are more likely to want to participate in sport than their lower limb counterparts.

There are many difficulties when attempting to reproduce the biological hand. This mainly stems from the many degrees of freedom afforded by the biological hand. It is often more successful to produce prosthesis for a single task than recreating all functions of the hand.

In general, there are three types of upper limb prosthesis, categorised by their control method; passive, body powered and myoelectric. Each have their advantages and drawbacks depending on what the user plans to use the prosthesis for.

There are few upper limb prosthetic devices available for sports participation. The commercial devices available are either passive or body-powered and only some sports are covered.

Fencing is a sport that can improve flexibility, reflexes, coordination and agility. It is a sport suitable for all ages and participants can remain competitive for longer than in many other sports with the épée world champion in 2015 being 40 years old. This could, in part, be due to the tactical aspect of the sport, gaining it the nickname, “physical chess”.

The use of the non-dominant hand is an option for those with unilateral upper limb loss, however the control of the two sides of the body originates in the hemispheric dominance of the brain. This hemispheric dominance of the brain makes it potentially more difficult to achieve the same proficiency with the non-dominant hand than achievable with the naturally dominant hand.

There are many things to consider when designing a fencing prosthesis, such as socket trim lines, the grip of the épée and movement to reproduce with the terminal device.

3D printing is currently being used in the automobile industry as well as medical fields such as faciomaxillary prosthetics and the production of hearing aids. The most common materials used are ABS and PLA however there are many material options with various properties such as flexible plastics as well as carbon fibre and nylon composites. These material options could allow for strengthening and relief in prosthetic sockets. There are a couple of companies currently producing 3D printed upper limb prostheses for everyday use. One focuses on myoelectric prostheses, the other on body powered prostheses.

The next chapter examines the provision of sports specific prosthesis for upper limb prosthesis users, using qualitative semi-structured interviews undertaken with upper limb prosthetists. The aim is to understand what factors determine the provision of devices, if at all, and what outcomes may be achieved. Chapter 4 then explores the feasibility of providing a 3D printed alternative to current devices for a speciality sport and analyses the results of this provision. Since the researcher is a fencing coach with a speciality in épée and, as such, the sport chosen for this study was fencing.

Chapter 3 – Qualitative analysis

3-1 – Chapter introduction

The project was split into two component parts. Firstly, a series of qualitative interviews, followed by quantitative analysis of kinetic data of a 3D printed prosthetic device being used to perform a relevant action to the sport it is designed for. This chapter will cover the methods employed during the interview process, including relevant aims, the interview structure and methods used and the relevant outcomes and recorded data.

The first part of the project was a series of qualitative semi-structured interviews. The interviews were conducted following the interview schedule detailed in Appendix 1. The interviewees were selected as they were HCPC registered private practice prosthetists with at least 5 years' experience, particularly with upper limb prosthesis. The content of the interviews covered;

1- A general overview of the prosthetists professional background.
2- Currently available componentry.
3- Professional opinions on currently available componentry.
4- Sports devices they prescribe.
5- Areas with a noted lack of componentry.
6- Professional opinions on the idea of using 3D printing to create bespoke sports prosthesis.

The lead researcher conducted the interviews both via online video call as well as in person on the University of Salford premises. The interviews were recorded and transcribed following completion. All data was stored on a password protected laptop, allowing access only to the research team directly associated with this project and anonymised before publication. The transcriptions were analysed using thematic analysis [78] using NVivo software [79].

3-2 – Aims and objectives

Semi-structured interviews with private practising prosthetists.

The aim of the semi-structured interviews was to gather qualitative data with regards to sports-specific upper limb prosthesis provided to users in order to facilitate participation in sports and physical activity. The interviews also focused on areas such as available componentry and clinicians' recommendations, availability of components via the NHS or through private clinics and varied opinions from different clinicians. Finally, the willingness to incorporate 3D printing into the manufacture of these sports devices was investigated, gathering opinions and suggestions about the place 3D printing may have in clinics.

3-3-1 – Methods

The participants were selected through purposive sampling [80] and are considered experts in their field. Those selected had a minimum of 5 years of clinical experience in private practice dealing with individuals with upper limb loss. In this time, a sufficient knowledge of current componentry should have been gained.

Interviews took place within the University of Salford or via Skype video calls and were recorded for later transcription. Once collected the transcriptions underwent thematic analysis [78] using NVivo software [79].

3-3-2 – Inclusion criteria:

1- HCPC registered prosthetist.
2- Have at least 5 years of experience working with upper limb prosthesis in private practice.
3- (Or) Have at least 5 years of experience of upper limb prosthesis practice but are no longer practising

3-4 – Results

3-4-1 – Highlighted sports

Sports that where highlighted by all participants as being activities that patients wanted to engage in were cycling, swimming and gym-based activities. Of these, cycling and gym activities require prosthetic provision for those with upper limb absence to fully participate. Swimming can be done without prosthesis; however, some individuals still prefer to swim with one and those that don't sometimes need prosthetic devices for muscle training outside of the pool. Some patients that do not wear a prosthesis day to day request sporting appliances, one participant mentioned one such patient:

"*One guy, and all he wants is a weight lifting arm, he doesn't wear an artificial arm apart from that, when he's in the gym, and that's it. He wears his weightlifting arm and then he takes it off and leaves it in his gym bag until the next time he goes to the gym."*

3-4-2 – Currently available devices

The participants recognised that there are devices available for a range of sports, however, there are not many devices for specialised sports. Furthermore, devices commercially available are costly: this leads to bespoke, one-off devices being made in clinics with designs usually being a collaboration between patient, prosthetist and technician. One example given was:

"They want one like that, also, a press up appliance. I know that sounds silly but it's a popular device. So, all that would be is like a dome on the end of their socket that they could then take off and put on a weight lifting device and use that as well in the gym."

This can produce good results, but there is no standard and as such devices vary from patient to patient and clinic to clinic. One participant said:

"Cycling appliances are all different, some want this, some want that, and it's a pain sometimes but that is a popular one"

One participant provided a PDF [81] which included a range of sporting devices for those with upper limb absence to demonstrate the type of prosthesis being made in clinics. All the devices shown were bespoke and several of the devices for the same activity were designed differently depending on level of limb absence and exact function intended. This shows there is no one size fits all, mass producible option. In addition, good working relationship with the technicians was highlighted, as the better bespoke devices made were designed by an "iterative and collaborative" process between prosthetist, user and technician.

The sports devices available seem to be in line with the sports highlighted by the participants;

"*Swimming is an interesting one because you can get those little paddles you can strap on, but some people like to swim with a complete arm"*

One company that does sell Upper limb sports devices is TRS; One participant commented that it is only recently that devices from this company were allowed to be given in NHS clinics.

"the NHS wouldn't allow us to use the TRS appliances but now they do, they let you use them rather than making bespoke ones"

Before this there was no other option than to make bespoke appliances and even now the cost of the devices limits how many can be prescribed.

3-4-3 - Cost

The cost of current specialist prosthetic components was mentioned by all participants. On this topic one participant commented:

"*Nowadays they buy them from TRS, I think, but one of those appliances probably cost 6 or 7 hundred pounds, which is a lot,"*

This was thought of as excessive when skilled technicians could *"nock them up in the workshop"* for far less money.

The lack of funding was brought up, however there was a sense of optimism that there will be more funding in the future due to government publicity of para-sports. One participant commented:

"Sports prosthesis are considered non-essential therefore there is no funding for them"

3-4-4 – Use of contralateral hand

On the subject of the use of the contralateral hand the interviewees shared their experiences. The general consensus was that those with upper limb absence will default to using their contralateral hand and therefore not use a specialised prosthesis for one handed sport.

One participant said:

"I think if you lose one arm, and it's the dominant arm, the other arm becomes the dominant arm"

And

"…but that's what everyone does. You lose one hand, you use the other, if you lose both then you're in trouble."

This does not agree with the literature that says that hand dominance is due to dominance in the hemispheres of the brain. However, this participant believes that if an individual loses their dominant arm then due to the necessity of using the contralateral arm day to day it becomes as skilled as the naturally dominant arm. This participant mentioned that prosthesis use was, however, important as a supporting arm.

Another participant said:

"Patient's always re-train however if a suitable prosthetic replacement was available [they] would probably go back to natural dominance"

This is a more positive reaction to the use of prosthesis for one handed activities.

3-4-5 – Use of 3D printing

All participants showed a positive interest in 3D printing, however there were some concerns and suggestions about how it could be effectively used.

1- Safety

   There were concerns over safety as there have been test sockets produced in the US that have not held up to the user's weight. These sockets have cracked and as such would not be up to standard to send home with a user.

   "The safety aspects would need to be considered first, 3D printed test sockets have been shown to crack in the US."

   It was acknowledged that this may not be such an issue with upper limb prosthesis as, depending on the intended use, they are generally non weight bearing.

   One participant said:

"3D printing can be a solution if it can be substantial enough and proved safe enough."

2- Prototyping

Making prototypes with 3D printing could allow the iterative process to be sped up, with prototypes being able to be produced overnight and the whole process taking days instead of weeks. The final design could then be sent to a manufacturer as a solid object to be made, negating safety issues.

3- Saving designs

The idea that designs could be saved and produced at the press of a button seemed appealing to participants. Once a general design is saved, slight adjustments could be made to suit any user that desires a device of that type. When talking about reproducing devices for multiple patients wishing to participate in the same sport one participant commented:

"You don't need to design each individual one and you wouldn't want different ones, you might want slight differences, but you could adjust that on your 3D printer"

3-5 – Chapter summary

In summary participants were selected through purposive sampling following a set of inclusion criteria;

1- HCPC registered prosthetist.
2- Have at least 5 years of experience working with upper limb prosthesis in private practice.
3- (Or) Have at least 5 years of experience of upper limb prosthesis practice but are no longer practising

Semi-structured interviews were held between the lead researcher and each participant either via skype video calls or in person on University of Salford premises.

The participants commented on sports their patients chose to participate in and the prosthetic devices they provided to facilitate this. They highlighted that there are few commercially available devices and created bespoke devices more often than providing commercial ones. They also commented on the high price of commercial devices and the marked lack of funding for this area.

The use of the contralateral hand was considered by participants as the obvious option over the use of prosthesis for specialised sports. There was however a split on how strongly this would be true if there was access to better, cheaper sports prosthesis.

All participants reacted positively to the use of 3D printing however there were concerns over the safety of the devices. Using 3D printing to make prototypes for bespoke devices was suggested as a good use of the process. The idea that the designs can be digitally saved and easily adapted was well received and could standardize provision between clinics.

Overall the responses were positive towards the use of 3D printing with suggestions on usage, with comments on cost and safety to consider. The next chapter contrasts the qualitative data achieved in Chapter 3 with quantifiable results based on the use of specialised designs, that aim to mitigate some of the issues raised in this chapter by prosthetists.

Chapter 4 – Movement capture and analysis

4-1 – Chapter introduction

This chapter will describe the process and methodology used to capture relevant performance and movement data from defined fencing actions that were undertaken with a simulator, in conjunction with the relevant terminal devices. The lead researcher is experienced at the sport of fencing and has a detailed knowledge of the movements involved. This knowledge was transcribed into a series of relatively simple movements.

It is important to understand the necessary movements associated with fencing in order to appreciate the unique requirements of the device being tested. For this reason, a methodology describing the movements to be captured will be presented first, followed by an overview of motion capture methodologies. The outcomes to be measured and placement of markers will then be discussed. Finally, the results of the motion capture will be reported.

4-2 – The movements of fencing

The en garde position for a right-handed fencer is defined as standing with heels approximately hip width apart, the right foot pointing towards the target and the left foot at right angles to the right foot. The upper body should be upright with bodyweight evenly distributed, facing the direction of the right foot. Both knees should be flexed to approximately 120°. The right hand should be raised to chest height with the elbow flexed to comfortably enable a 'fist width' between the elbow and torso. The tip of the épée should be pointing roughly where the opponent's heart would be. The left arm should be in a relaxed position behind the line of the torso; traditionally, the left hand should be held up almost at shoulder height. When looking in a mirror the fencer's heels should be in line and the right forearm should be hidden behind the épée's guard.

The basic attack, or primary movement, is called a lunge. This is the movement that will be used within the trial for this study as it forms the basis of all other fencing manoeuvres. The lunge commences from the en garde position (described above); the right arm extends in a smooth movement, lifting the hand to shoulder height but ensuring the tip of the épée remains at chest height. Simultaneously the left arm is thrown back and down as a counter lever. Once the arms are fully extended the right foot is raised, toe first and kicked forwards by the extension of the left leg. The left foot remains flat on the floor. The right foot should then land with the knee vertically over the heel [82]. The right and left heels should still be in line. The final position should be left foot flat, left knee extended, right knee over right heel, right arm extended with hand at shoulder height and sword tip on target, left arm back and down, head and body upright. From this position whether a hit was scored or not (unless a remise (renewal of attack) is attempted) the fencer should recover to the en garde position. When recovering the movement should be the opposite of lunge, with the feet moving before the arms. The fencer should end the movement back in the original starting position [82].

4-3 – Motion Capture Methodology

A Qualisys motion capture system [83] was used, comprising of 3 Oqus 300 and 5 Oqus 700 cameras with a capture rate of 100 Hz. Similar studies investigating the actions of fencing were extremely limited, but similar evaluations relating to baseball pitches and tennis serves were found which correlated broadly to the requirements of this study [84]. For example, data capture for the tennis serve used 10 markers that were placed at the anterior and posterior of the shoulder joint, medial and lateral humeral epicondyles, radial styloid process and ulnar styloid process, 2nd and 5th metacarpal heads, and each side of the racquet at the widest point [85]. For this reason, initial marker positions were based around these, and modified to capture the more specific requirements of fencing in line with the descriptions afforded in section 4-2.

The markers used on the knuckles for the other sports would be covered by the guard of the épée which meant that, as the cameras would be unable to capture them, they could be discounted. For this reason, a slightly more extensive 14-marker set up was used, with markers positioned on either side of the target, the tip of the blade, midway along the blade, the base of the blade, the top of the guard, ulnar styloid process, radial styloid process, a 4-marker cluster on the mid forearm, medial humeral epicondyle and lateral epicondyle. This set up enabled data concerning the position of the blade, relative target, as well as the corresponding anatomical landmarks, to be captured (for more information, see section 4-4-3).

The action performed for analysis was a single fencing lunge; this is a principle action needed to be performed within the sport of fencing (see section 4-2). The starting point of the action ('zero seconds') is determined by the initiation of forward motion and the end point (time taken, seconds) is contact with the target (identified by motion of the target markers). The collected data were then exported into Visual 3D software [86] where start and end points of each data set were identified and converted into a graphical format.

The process was completed for four conditions;

1- The researcher holding the épée in their dominant hand (this is the baseline/gold standard movement).
2- The researcher holding the épée in their left hand.
   The left-handed condition was in response to interview responses (section 3-4-4) that those with upper limb absence will use their contralateral hand. If the user is missing their naturally dominant hand the use of the contralateral hand may not be as effective as the use of a prosthesis due to the neural pathways in the brain (see section 2-7-1). This condition was implemented in order to confirm or deny this.
3- The specially designed 3D printed terminal device attached to a prosthesis simulator with a strong 2-part epoxy glue. (Details regarding the construction of the device can be found in Appendix 2)
   The device was glued to provide a firm hold that would restrict wrist movement.
4- The specially designed 3D printed terminal device attached to a prosthesis simulator using tape.
   The device taped was to simulate how a user may resort to attaching sports equipment when no other option is available.

4-4 – Outcomes and methods of measurement

4-4-1 – Outcomes to be measured

1- The ability to accurately hit the target with the épée held in the selected device.
2- The amount of compensatory movement necessary to achieve this accuracy.
3- Rotation of the epee.
4- Time taken to complete the action (see 4-3).

4-4-2 – Justification of outcomes

1- A participant's competence in the sport of fencing is determined by their ability to hit an opponent in order to score points. In the épée category the target area is the whole body and the first to hit scores a point. This means the most effective way to score points is often to aim for your opponent's wrist as this area is the closest and negates the possible difference in arm length that comes into effect when aiming for the torso, head or legs. To achieve this, a high level of blade control is necessary to be able to accurately hit these small, fast moving targets.
2- When in a match, the opponent will be attempting to score a touch (hit/point) against the fencer before the fencer can score a touch against them. As such when attempting to attack, the fencer must also be able to defend from oncoming attacks. This defensive movement is called a parry and involves using the blade to push the opponent's blade out of the "fencing line" (the line in which the blade tip is pointing down the piste at the opponent (poised for attack); if moving down this line a touch will be scored unless there is a deviation from this path). During this movement it is advantageous to keep the tip of the épée pointing at the opponent (Keeping your fencing line). This is so that a riposte (an attack after a parry) can be facilitated without changing line.

   The en garde position (starting position) is developed to achieve maximum defence (easy to defend from any attack). In order to maintain the ability to

Figure 2 – Tip of broken blade [87].

properly defend it is imperative to maintain the fencing line as an attack is made. Exaggerated compensatory movements will leave gaps in the fencer's defence and therefore give the opponent opportunities to attack. Any compensatory movements needed to make contact with the target mean that the participant had to deviate from the fencing line. If there are purposeful deviations (always follow the same pattern between trials) to achieve a satisfactory level of accuracy, then defence is compromised, and this is not acceptable during a fencing match. If there are random deviations, then there is a lack of control and this is also not acceptable during a fencing match.

3- Rotation of the épée is important to note as the épée is designed to bend only one way. If the épée is bent the wrong way it is more likely to splinter and break (figure 2) than if it is bent the correct way. As such, attacks in fencing are designed to allow the épée to bend in the correct way (figure 3). If the épée rotates it will be more likely to bend in the wrong direction and consequently become weakened or break. If the épée is allowed to rotate due to lack of control, then the blade may be damaged and as a result become dangerous.

The blade is not only more likely to break when it is bent the wrong way but if it is repeatedly bent the wrong way a weakness is developed and makes the blade

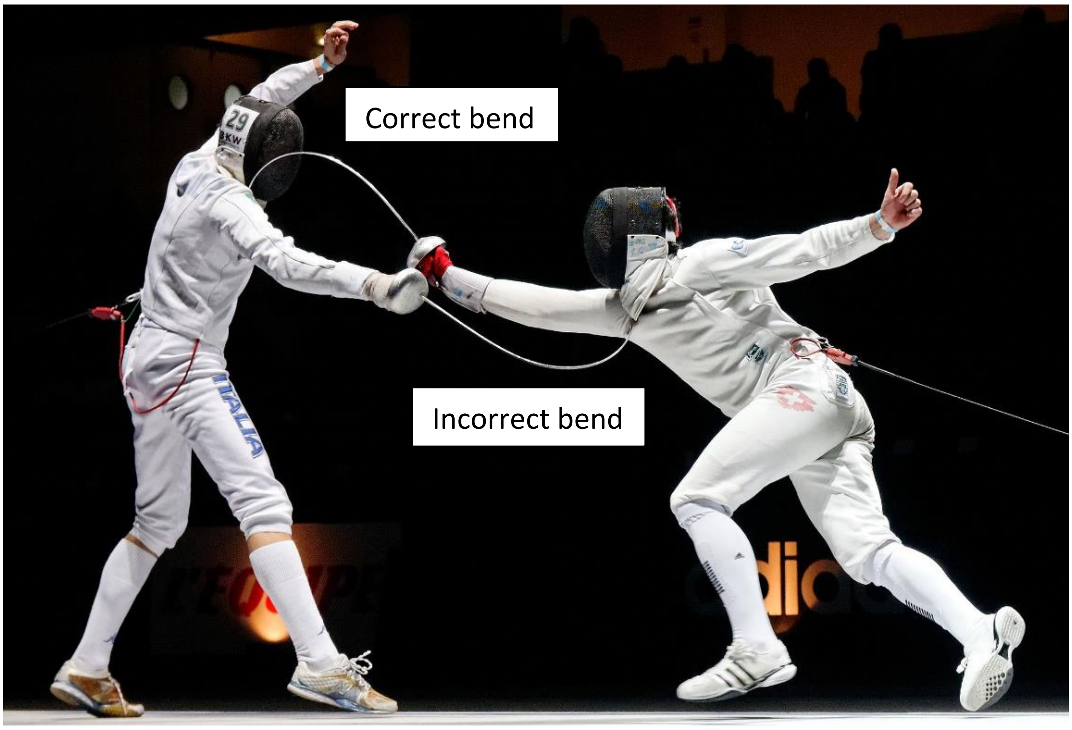


Figure 3 – Demonstration of correct and incorrect bend of blades [88].

more likely to break even when bent in the correct direction. Therefore, rotation of the blade is important to monitor.

4- The beginning of the action is defined by the initiation of forward movement of the forearm; the end of the action is defined by contact between the tip of the épée and the target. The time elapsed between these two defined points will be the time to complete the action. The difference between a clean (single) point and a double (both sides gain a point) is 40ms [89] as such if the fencer and the opponent initiate action at the same time any hit that would result in a double will be considered a success.

4-4-3 – Marker placement

1- A target was set up in the lab. Two markers were attached to the sides of the target (Figure 5). When the Y coordinate (forward-backward) is the same for the marker at the end of the épée and the markers at the edges of the target then the X (left-right) and Z (up-down) coordinates depict the accuracy of the touch. The closer to the midpoint (X axis) between the two target markers and similarity of Z coordinates, the more accurate.

Figure 4 – Marker positions along épée [90].

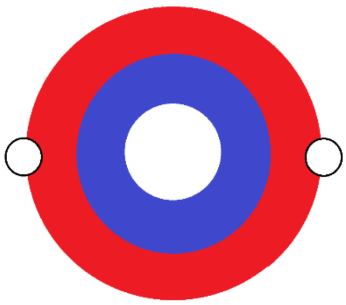


Figure 5 – Marker positions on target.

2- The starting position was the same for all trials, this was determined by assuming the end of lunge position with the tip of the épée touching the target, from this position the researcher returned to the en garde position (starting position). This determines the distance needed to hit the target: as the back foot does not move during a lunge, the starting position should not move between trials. The baseline trial provides an ideal trajectory described in all 3 planes with angles between the forearm and épée, around the wrist joint, and the angles between the forearm and the stationary origin point of the lab. The forearm is identified by 8 markers. One on each humeral epicondyle, showing the proximal end of the segment, one on the radial styloid process and one on the ulnar styloid process to show the distal end of the segment (figure 6). A 4-marker cluster was also attached mid forearm to identify the body of the segment with one of the cluster markers on a stalk to allow the identification of segmental rotation. The combination of forearm-lab angles describing the position in the lab and the sword-forearm angles will describe the overall compensatory movements and deviations from the fencing line.

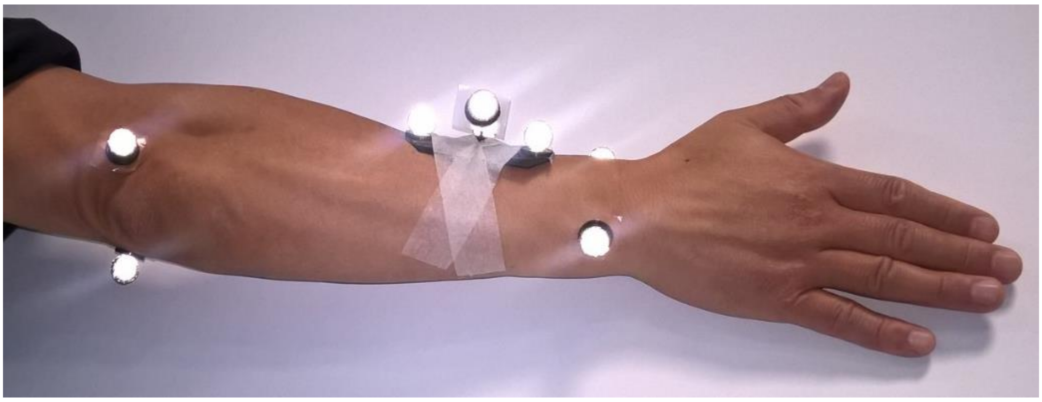


Figure 6 – Forearm marker placement

3- The offset marker on the guard will show the rotation of the épée (figure 4). If the épée rotates in relation to the forearm a lack of grip is present (even if the angle is constant). The marker on the guard is needed in addition to the three markers showing the length of the blade. This is because the markers along the blade are unable to show rotation. The offset of the marker on the guard will allow the rotation to be recorded.

4-4-4 – Determining success

Since the researcher is an experienced fencer, use of the épée with the right, dominant hand (normal use) was considered the 'gold standard' in terms of target accuracy and movement. All trials using the left hand, or prosthesis simulator with device with the right hand, will therefore be compared to this 'gold standard'. Use of this term will be maintained to avoid any confusion with the use of the right hand, with the prosthesis simulator.

For example, the action times for each trial will be compared to the gold standard, taking into consideration the time allowance for double hits (see 5-4-2). Any time score that would allow the opponent to gain a clean hit when initiating action at the same instance (assuming the opponent falls within the gold standard) is considered a failure.

Accuracy for the non-dominant hand trials and the device trials were compared to the gold standard in terms of spread of hits across the target with consideration to the possible target areas when participating in the sport. Rate of successful hits, (that is, the ratio of hits on the target compared to the attempted hits that failed to reach the target) was also recorded as this shows both control and distance judgment.

4-6 – Results

4-6-1 – Action times

	Average (mean) action time (s)	Standard deviation (s)	Difference between average and gold standard (GS) average (s)	Difference between slowest and GS slowest (s)	Difference between fastest and GS fastest (s)	Difference between slowest and GS fastest (s)	Difference between fastest and slowest (s)
Right hand	0.673	+/- 0.075	-	-	-	-	-
Left hand	0.704	+/- 0.106	0.031	0.62 *	0	0.212*	-0.150**
Glued device	0.652	+/- 0.063	-0.08	-0.033	-0.009	0.117*	-0.259**
Taped device	0.676	+/- 0.092	0.003	0.020	-0.014	0.170*	0.1640**

Table 1 – Action times (identifies single hit against condition, ** identifies single hit against GS).*

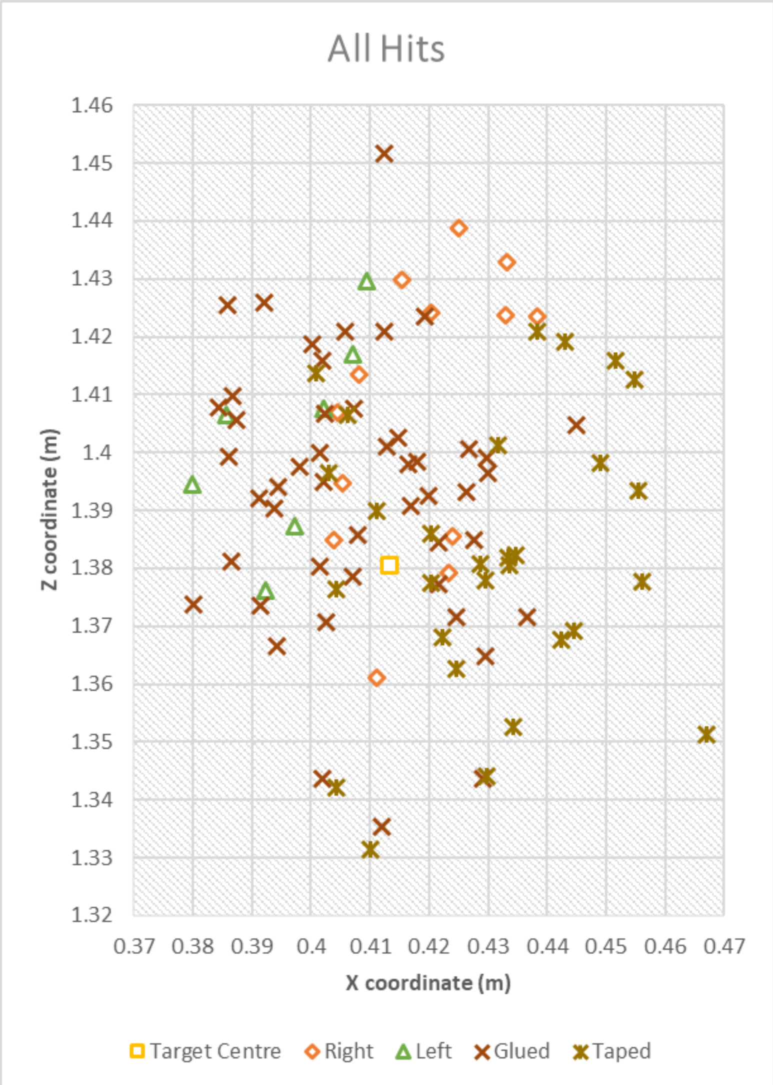
4-6-2 – Hit accuracy

Graph 1-1 shows the hit co-ordinates for all hits for all conditions normalised around the centre of the target. This shows that all hits were within an 8cm radius from the target centre.

The target centre is depicted by the yellow square. Hits made by the gold standard are orange diamonds, hits by the left hand are green triangles, hits by the glued device are red crosses and hits by the taped device are brown struck through crosses.

Graph 1-2 shows the plots from graph 1-1 in relation to the target.

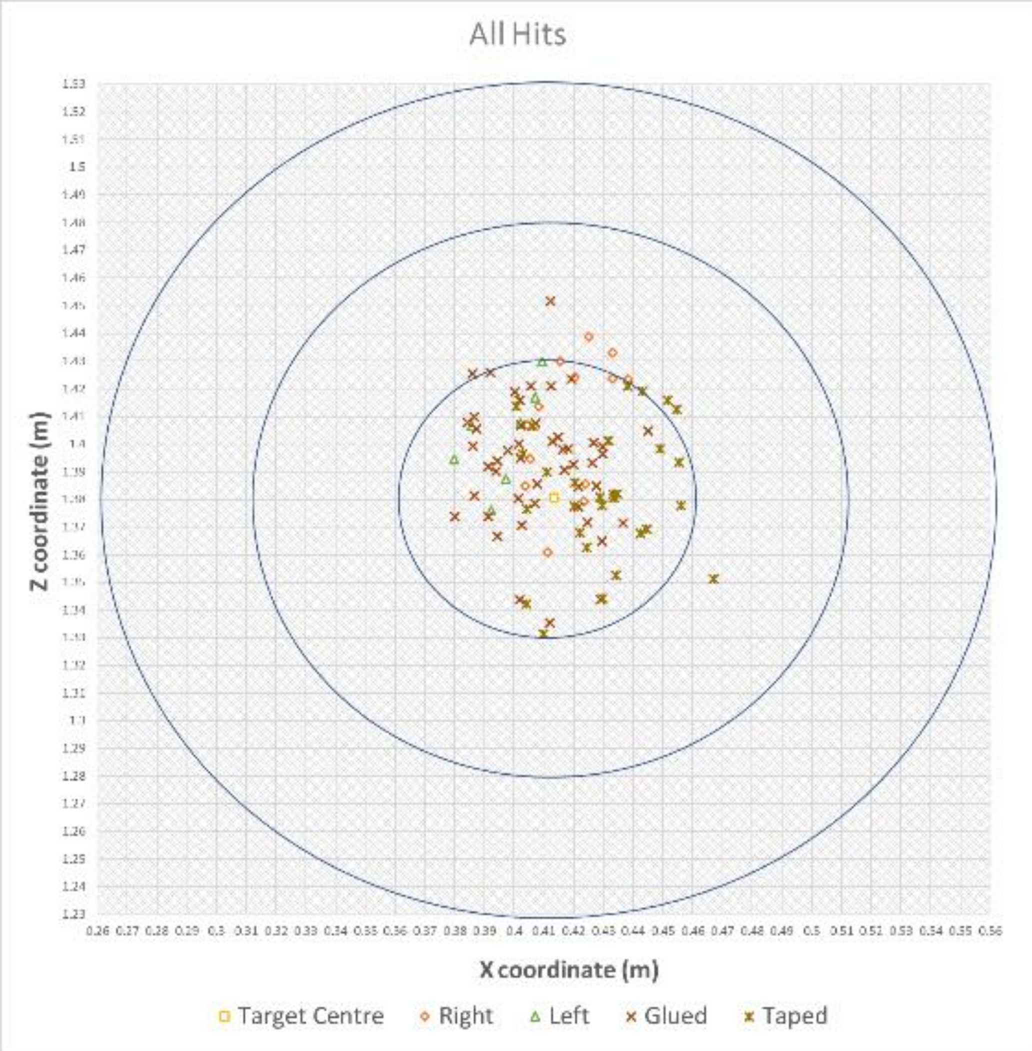
Table 2 shows the average (mean) distances to the target centre for successful hits from each condition. It also shows the distance of the successful hit for each condition that was furthest and closest to the target centre.



Graph 1-1 – Co-ordinates of all condition hits.

Condition	Average (mean) distance from target centre	Furthest point from target centre	Closest point from target centre
Right-hand (gold standard)	0.035m	0.060m	0.010m
Left (non-dominant) hand	0.030m	0.050m	0.017m
Glued device	0.027m	0.072m	0.0006m
Taped device	0.031m	0.067m	0.0008m

Table 2 – Distances from target centre for successful hits of each condition.



Graph 1-2 – Hit co-ordinates in relation to 30cm target.

Table 2 shows the average (mean) distances from the centre of the target for successful hits of all conditions. Table 2 also shows the distances from the centre of the target for the successful hits that were the furthest and closest to the centre of the target for each condition. On average, the 3D printed device glued to the prosthesis simulator achieved hits closest to the target's centre. However, this same condition also achieved the furthest hit from the target centre, showing the least consistency. The average hit distances for all conditions were within 8mm of each other.

Table 3 shows the successful hit rate for each condition. This refers to the percentage of attempted hits reached the target. Attempted hits that did not reach the target may have been due to misjudged distance or a lack of control.

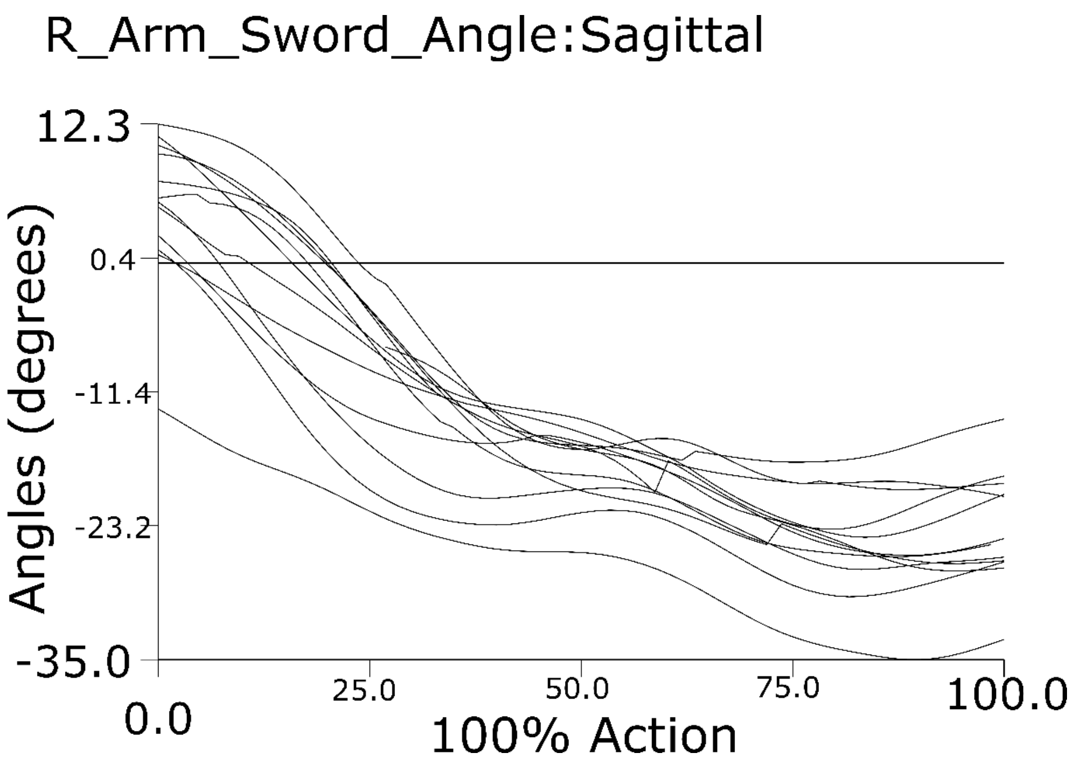
Condition	Successful hit rate
Right-hand (gold standard)	79%
Left (non-dominant) hand	41.5%
3D printed device glued to simulator	94%
3D printed device taped to simulator	80.5%

Table 3 – Successful hit rate for each condition.

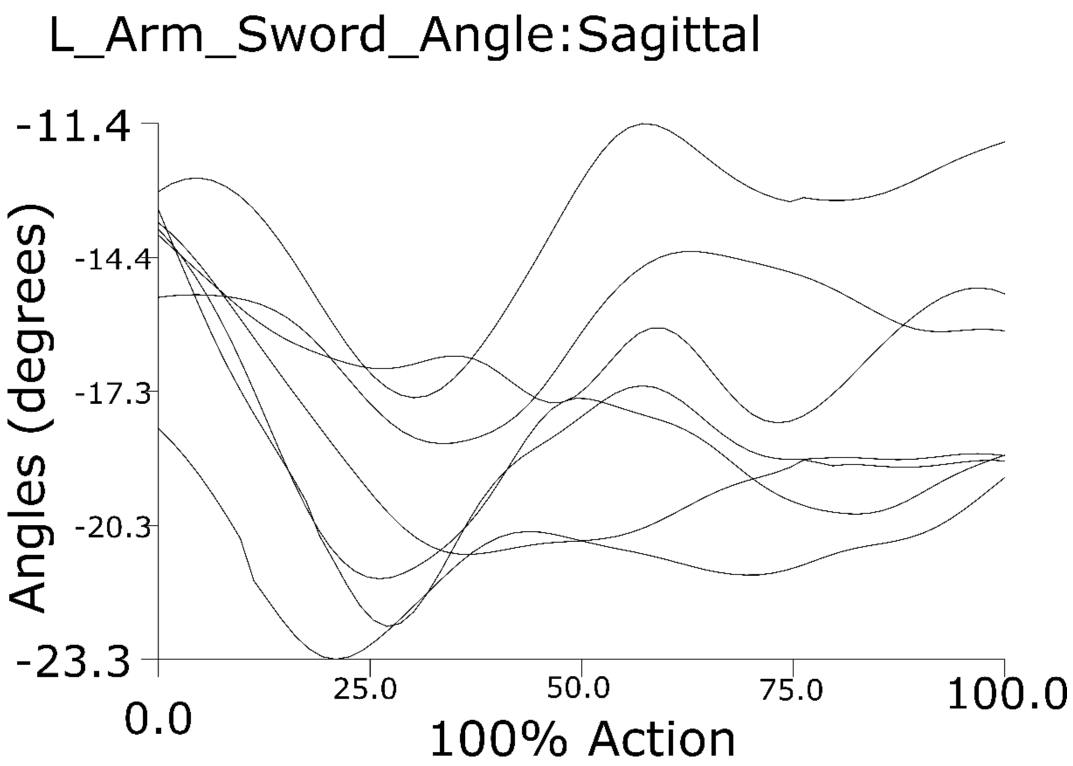
Table 3 shows that both the 3D printed device conditions had a higher hit rate than the gold standard. It also shows that the left (non-dominant) hand condition hit the target in less than half of all attempts.

4-6-3 – Arm-Sword Angles (wrist movement)

Graphs 2-1 and 2-2 highlight the differences in wrist movement between the use of the gold standard and the use of the non- dominant left hand during the fencing lunge.

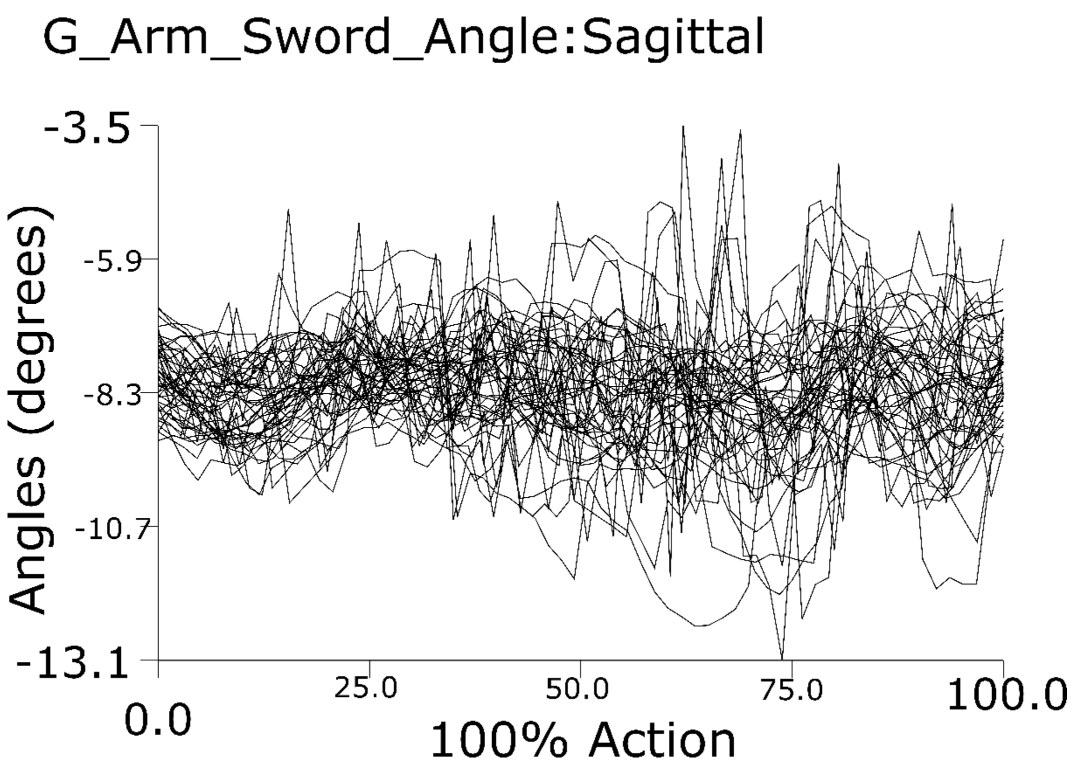


Graph 2-1 – Movement of the épée markers in the sagittal plane using the right hand (gold standard).

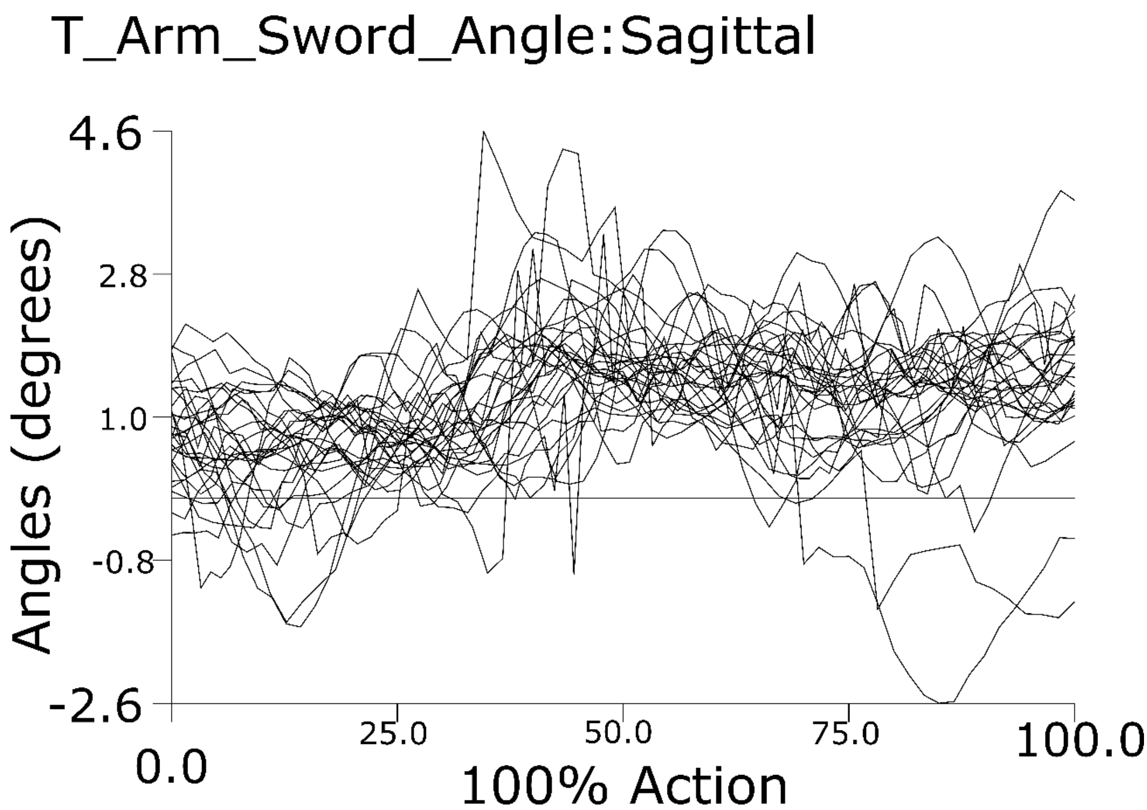


Graph 2-2 – Movement of the épée markers in the sagittal plane using the left (non-dominant) hand.

Graphs 2-3 and 2-4 highlight the differences in wrist movement between the gold standard and the use of the prosthesis simulator in conjunction with a 3D printed device during the fencing lunge. Graph 2-3 shows a simulator with a 3D printed device that is glued to the distal end; in graph 2-4, the device is taped to the distal end.



Graph 2-3 – Movement of the épée markers in the sagittal plane using the prosthesis simulator in tandem with the 3D printed device glued to the end of the simulator.

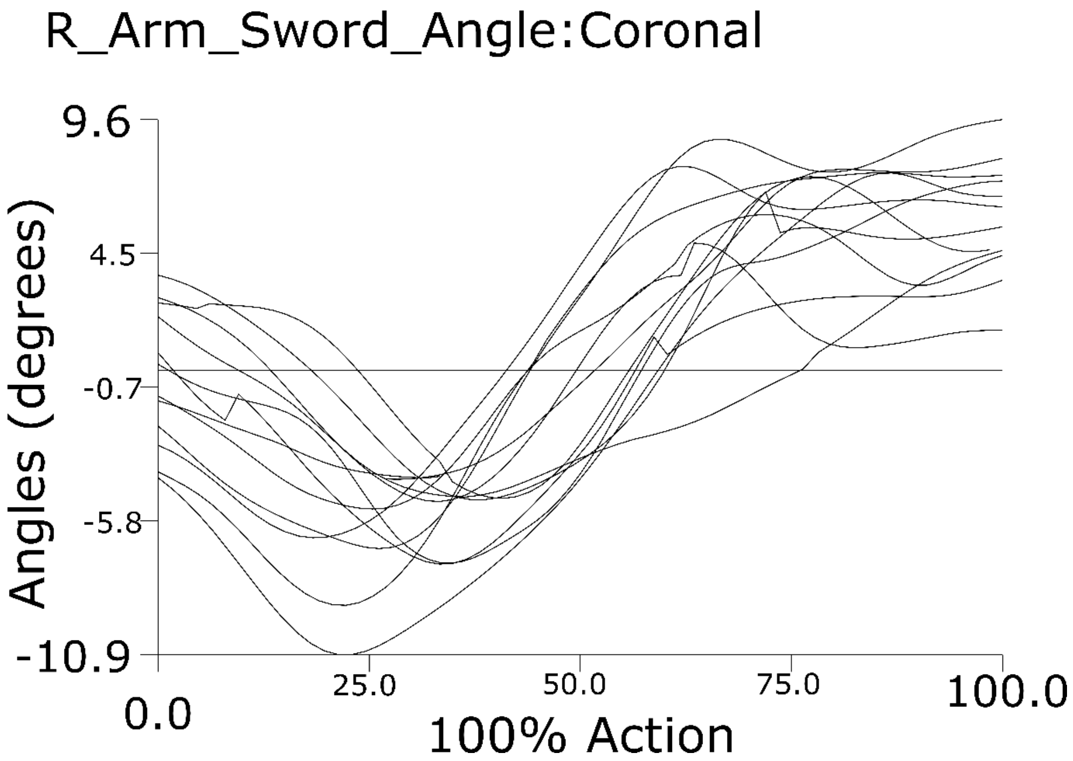


Graph 2-4 – Movement of the épée markers in the sagittal plane using the prosthesis simulator in tandem with the 3D printed device taped to the end of the simulator.

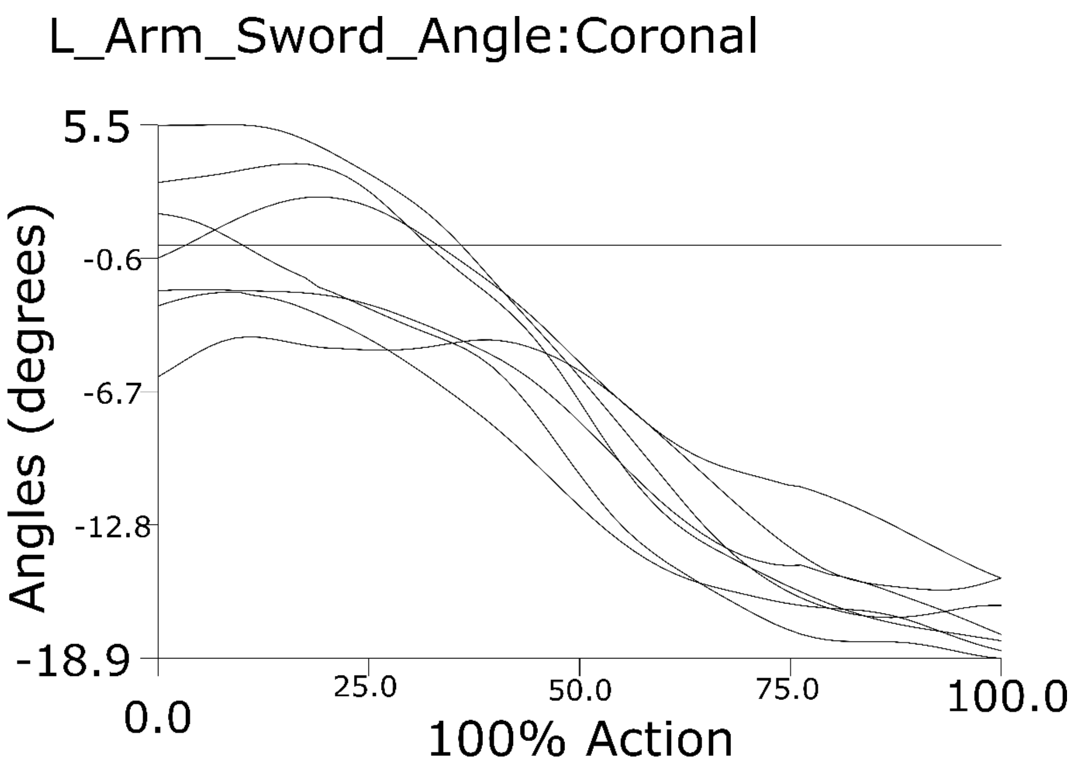
The use of the left arm shows greater variation during each lunge than the same use of the gold standard. The gold standard also shows a distinct pattern of movement and progressive ulnar deviation as the action advances. By contrast, the left arm shows a reduced range of movement, and a less distinct pattern.

The use of a prosthesis simulator with no effective wrist means that angle ranges in the sagittal plane are limited, although not completely removed. The smaller movements using the taped device could correspond to the user being more careful with the lunge when using this method of attachment, knowing that the device may not be so secure.

Graph 3-1 shows the rotation of the épée during the lunge for the gold standard and 3-2 shows the rotation of the épée in the non-dominant left hand during the lunge in the coronal plane.



Graph 3-1 – Rotation of the épée in the right hand (gold standard) during the lunge in the coronal plane.



Graph 3-2 – Rotation of the épée held in the left (non-dominant) hand during the lunge in the coronal plane.

Graphs 3-3 and 3-4 highlight the differences in the rotation of the prosthesis simulator when compared to the gold standard. Graph 3-3 shows the rotation of the épée when the 3D printed device is glued to the end of the simulator; in graph 3-4 the device is taped to the simulator.

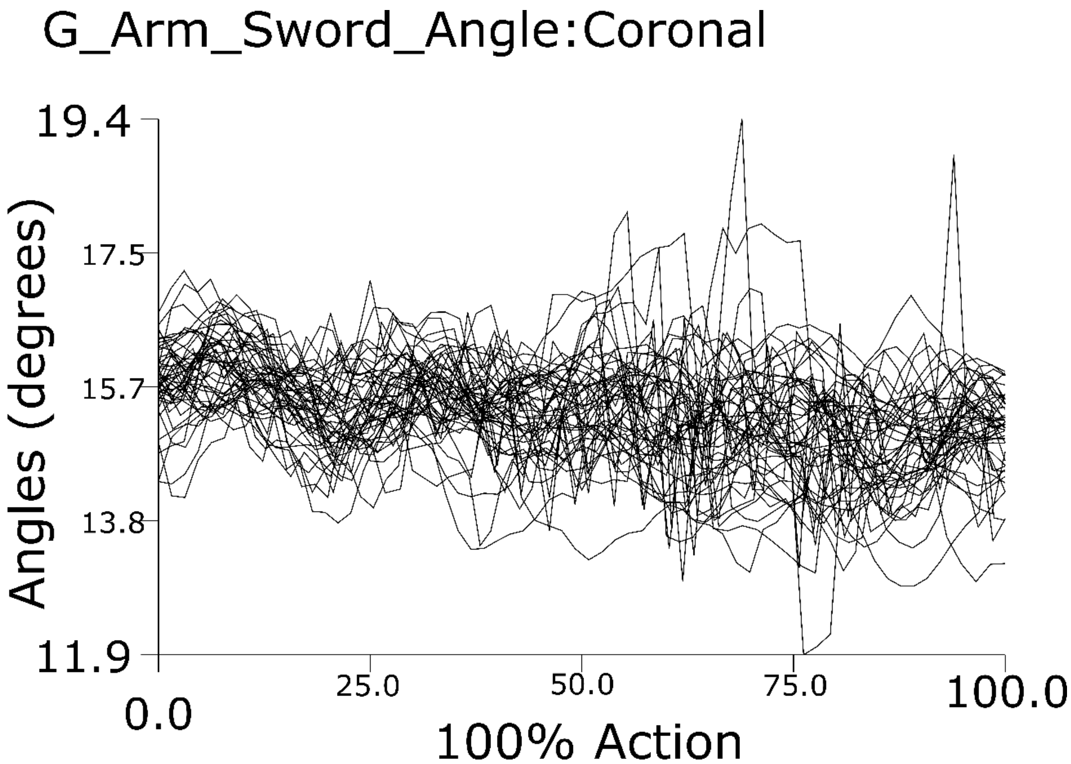


Figure 3-3 – The rotation of the épée in the coronal plane with the 3D printed device glued to the simulator.

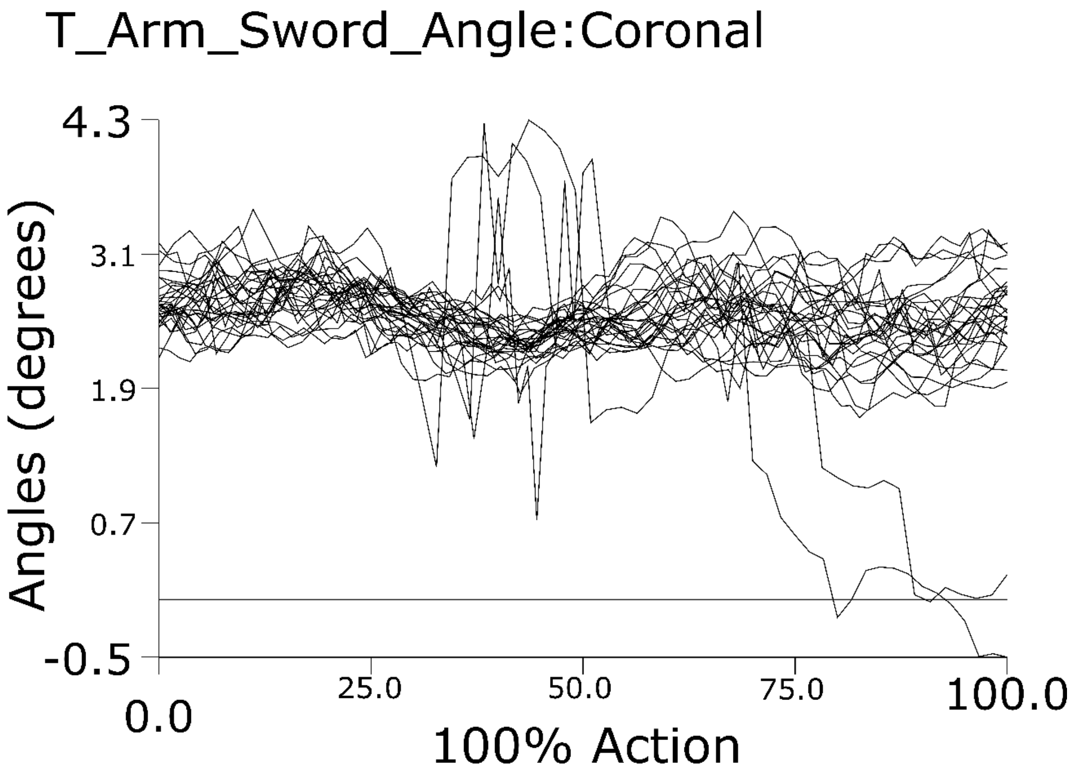


Figure 3-4 – The rotation of the épée in the coronal plane when the 3D printed device is taped to the simulator.

The gold standard shows internal rotation of the épée in relation to the forearm, followed by external rotation of the épée with the end position being only slightly more internally rotated than the starting position. Both the arms show distinct patterns; however, the left is dampened in comparison to the gold standard.

As with the sagittal plane, there is little movement in the prosthesis simulator. The rotation that has been recorded is minor and has no distinct pattern.

Graph 4-1 shows the movements of the gold standard (natural right hand) and graph 4-2 shows the movements of the épée held in the left (non-dominant) hand in the transverse plane during the lunge. Graph 4-3 and graph 4-4 show the movement of the épée when held in the device glued to the simulator and the épée held by the device when taped to the simulator respectively in the transverse plane.

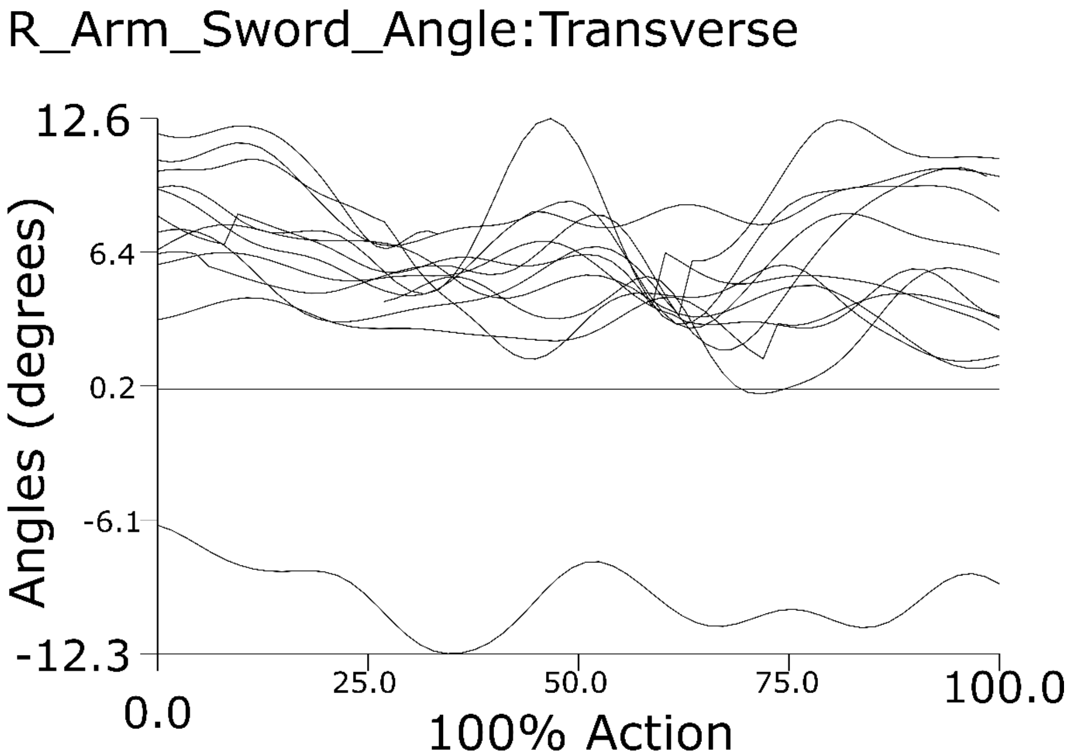


Figure 4-1 – Movement of the épée in the transverse plane when held in the right hand (gold standard).

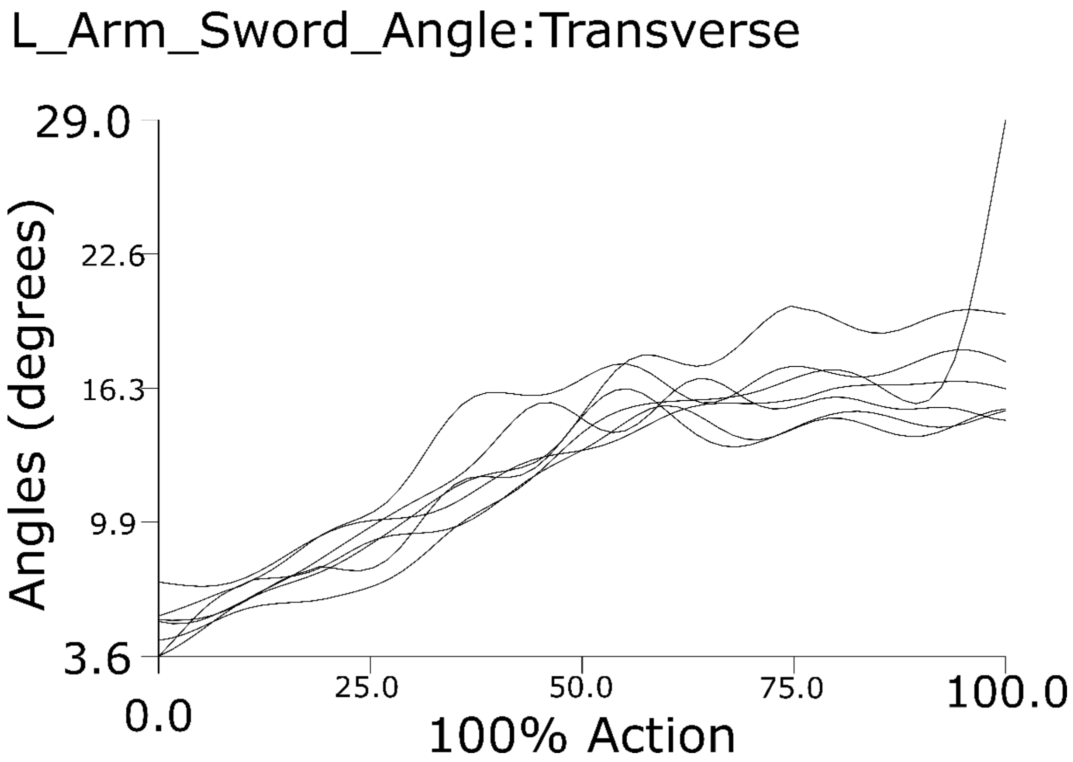


Figure 4-4 – Movement of the épée in the transverse plane when held in the left (non-dominant) hand.

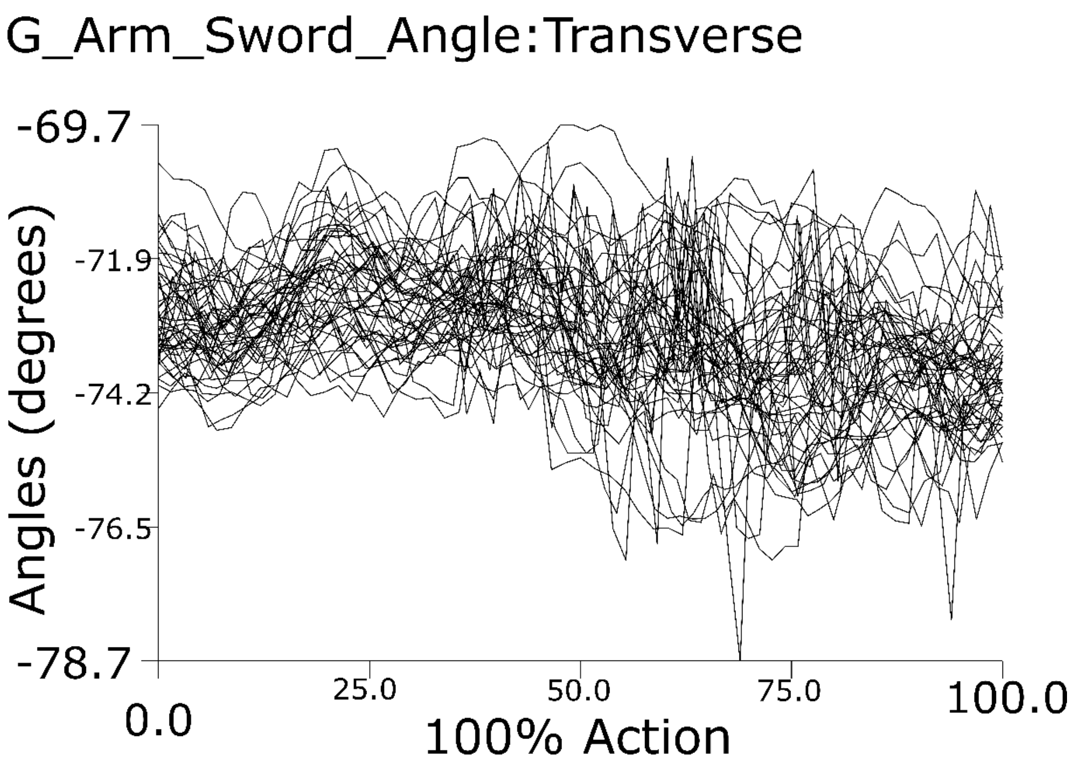


Figure 4-3 – Movement of the épée in the transverse plane when held in the 3D printed device when glued to the prosthesis simulator.

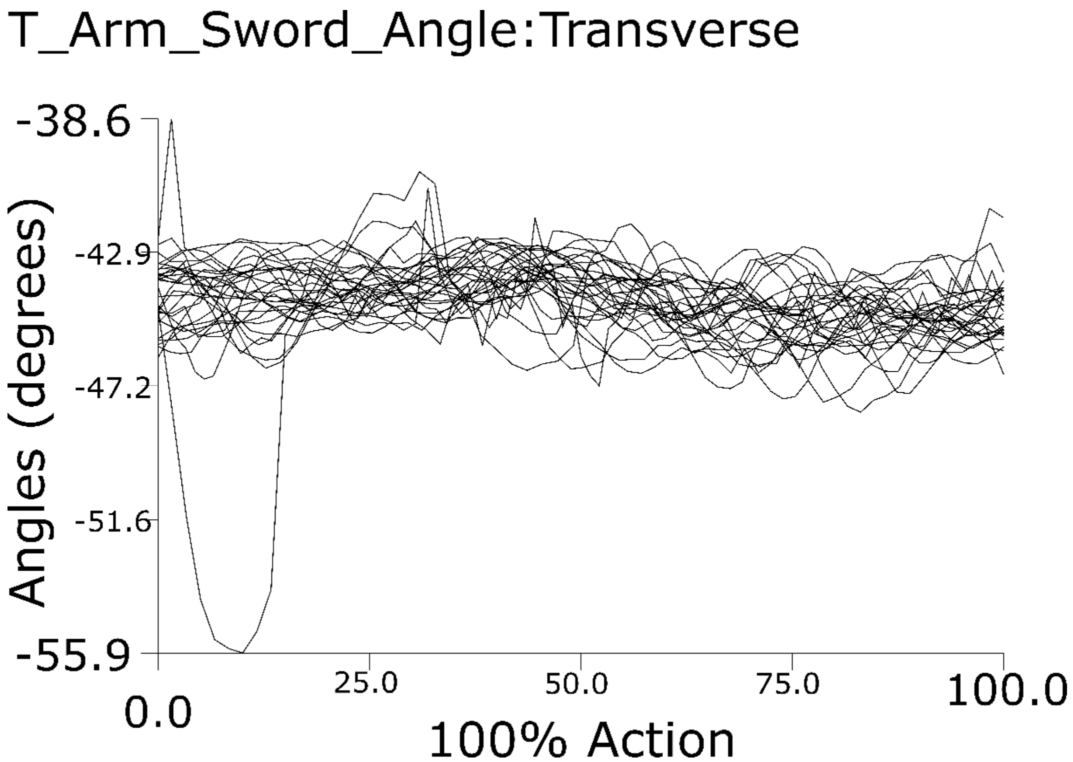


Figure 4-4 – Movement of the épée in the transverse plane when held in the 3D printed device when taped to the prosthesis simulator.

The gold standard does not seem to follow a distinct pattern; however, all trials seem to oscillate around the same angle. The left (non-dominant) does follow a pattern, the tip of the épée moves from lateral to medial in relation to the forearm.

Both prosthesis conditions show little movement, the condition where the device was glued to the simulator seems to produce a larger range of movement than the device taped to the simulator in this plane.

4-6-4 – Lab-Arm-Angles (orientation within the lab)

The following graphs show the positioning of the forearm in space via angles between the forearm segment and the origin axis in the lab. This is to assess the compensatory movements within the space that may not appear when looking at wrist angles alone. This is important as large compensatory movements may provide the opponent an opportunity to score in a match.

Graph 5-1 depicts the gold standard angles of the forearm in the sagittal plane when holding the épée. Graph 5-2 shows the angles of the forearm when holding the épée in the left (non-dominant) hand in the sagittal plane.

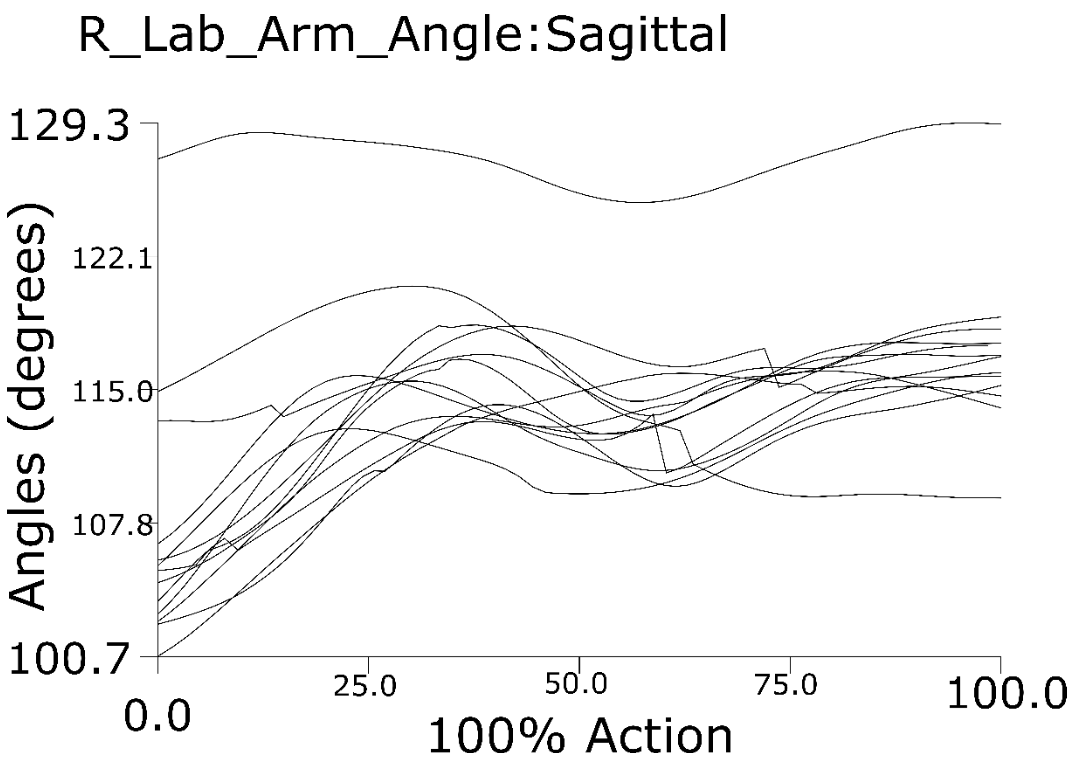


Figure 5-1 – Movement of the forearm within the lab when the épée Is held in the right hand in the sagittal plane (gold standard).

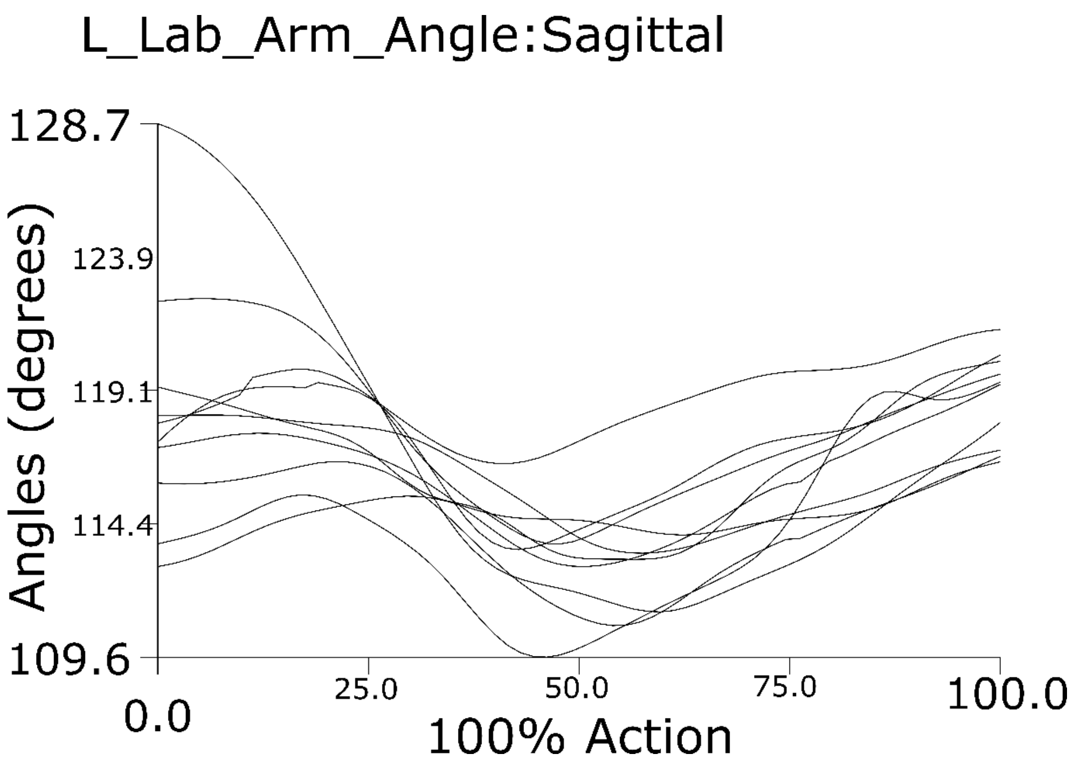


Figure 5-2 – Movement of the forearm in the lab when the épée is held in the left (non-dominant) hand in the sagittal plane.

Graph 5-3 shows the movement of the forearm in the lab when the épée is held by the 3D printed device glued to the prosthesis simulator in the sagittal plane. Graph 5-4 depicts the movement of the forearm in the lab when the épée is held by the 3D printed device taped to the simulator.

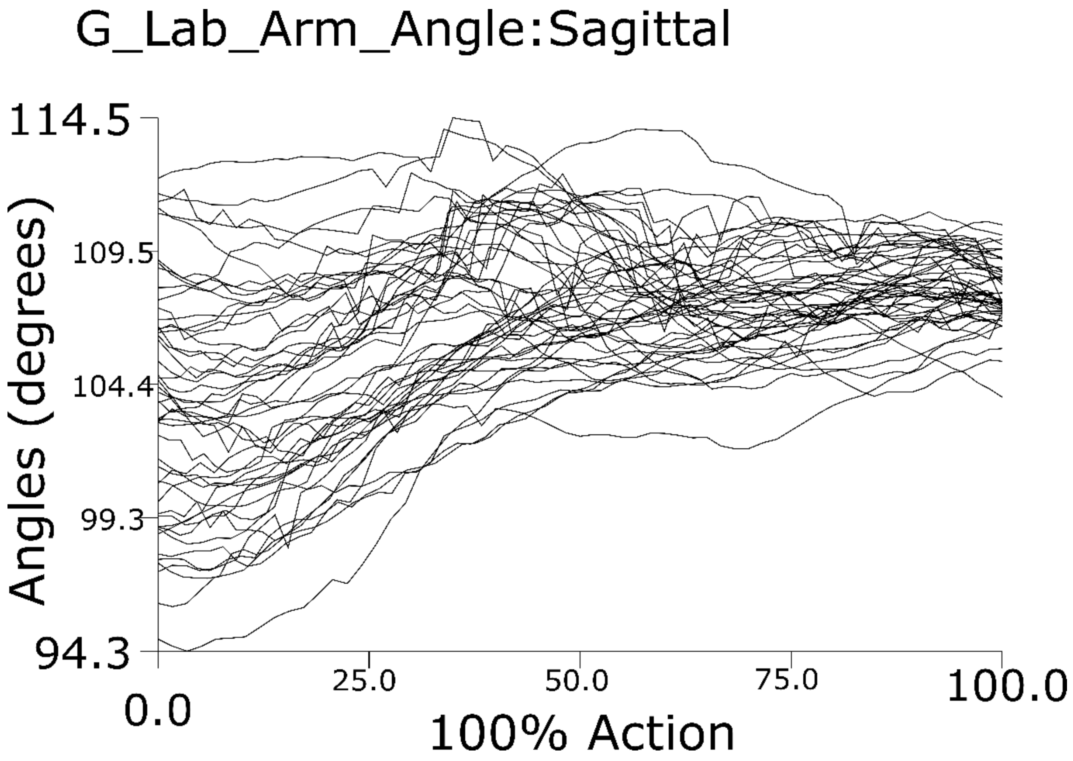


Figure 5-3 – Movement of the forearm in the lab when the épée is held in the 3D printed device glued to the prosthesis simulator in the sagittal plane.

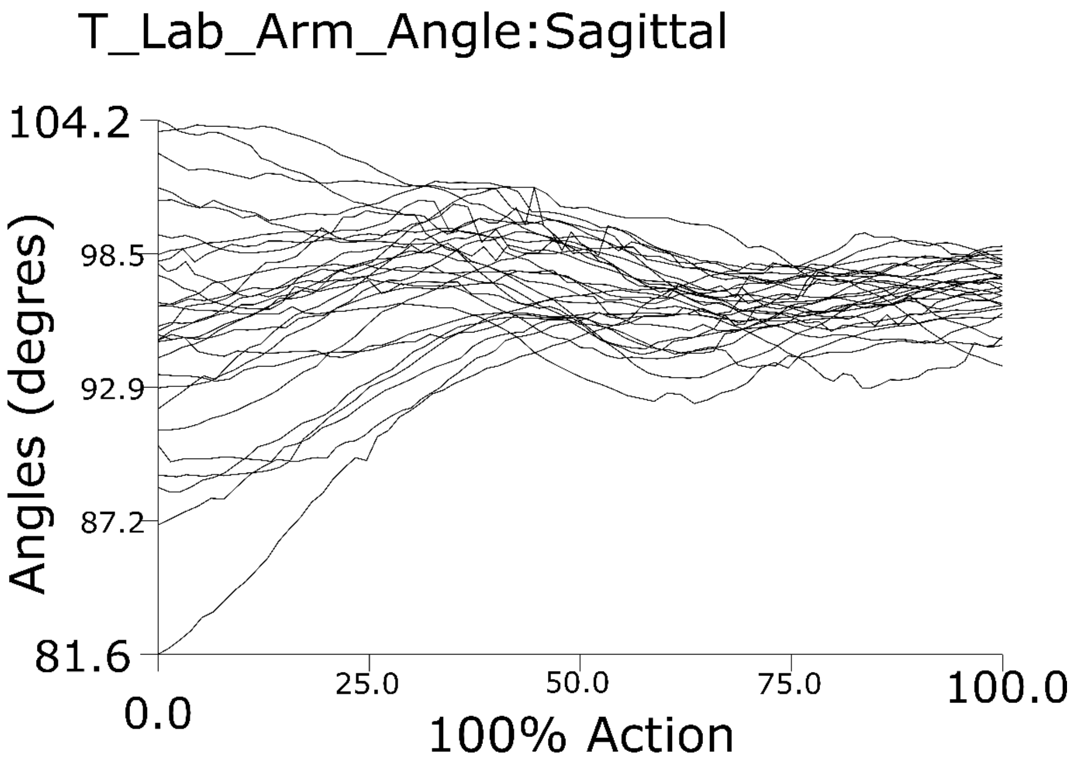


Figure 5-4 – Movement of the forearm in the lab when the épée is held in the 3D printed device taped to the prosthesis simulator in the sagittal plane.

The gold standard trajectory shows elbow flection when lifting the épée and elbow extension when approaching the target. The left-hand trials show an initially more flexed position, extension when approaching the target then flexion when about to contact the target. This variation from the gold standard could be linked to the arm-sword angles (graph 2-2).

Both the glued and taped conditions show the same basic pattern as the gold standard, however, there is a larger range of starting angles and small adjustments, likely linked to the lack of wrist motion.

Graph 6-1 depicts the rotation of the right forearm (gold standard) in the lab in the coronal plane. Graph 6-2 shows the left (non-dominant) forearm rotation in the lab in the coronal plane.

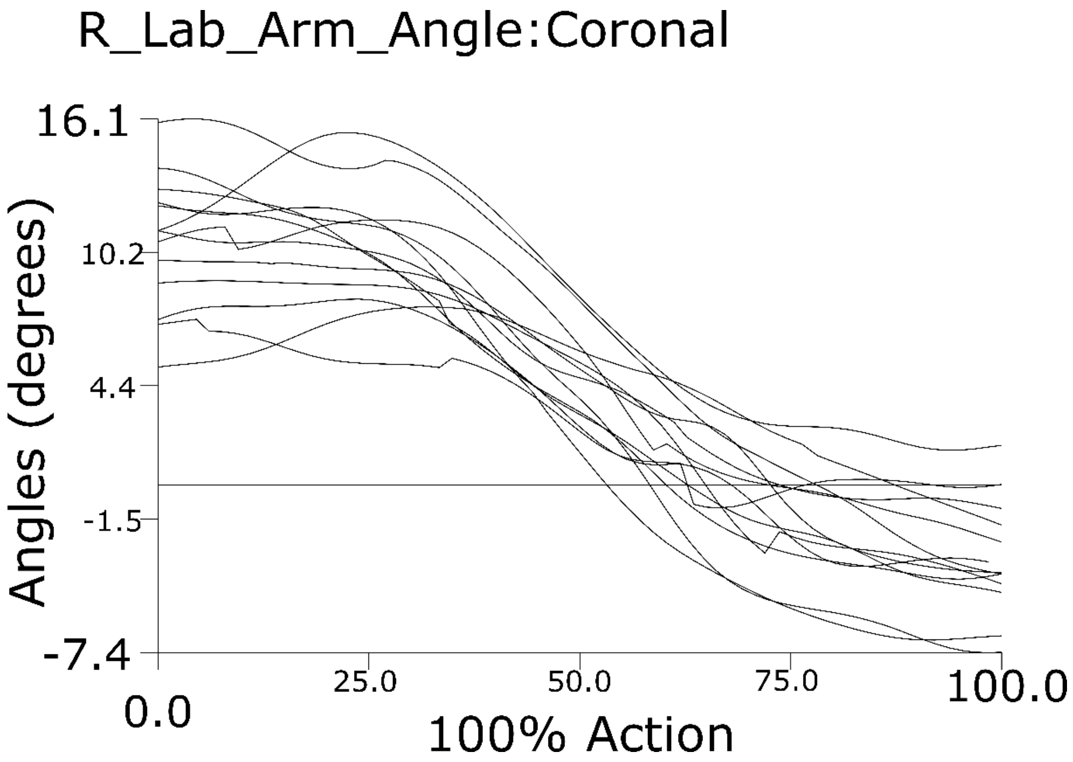


Figure 6-1 – Rotation of the forearm in the lab when holding the épée in the right hand (gold standard) in the coronal plane.

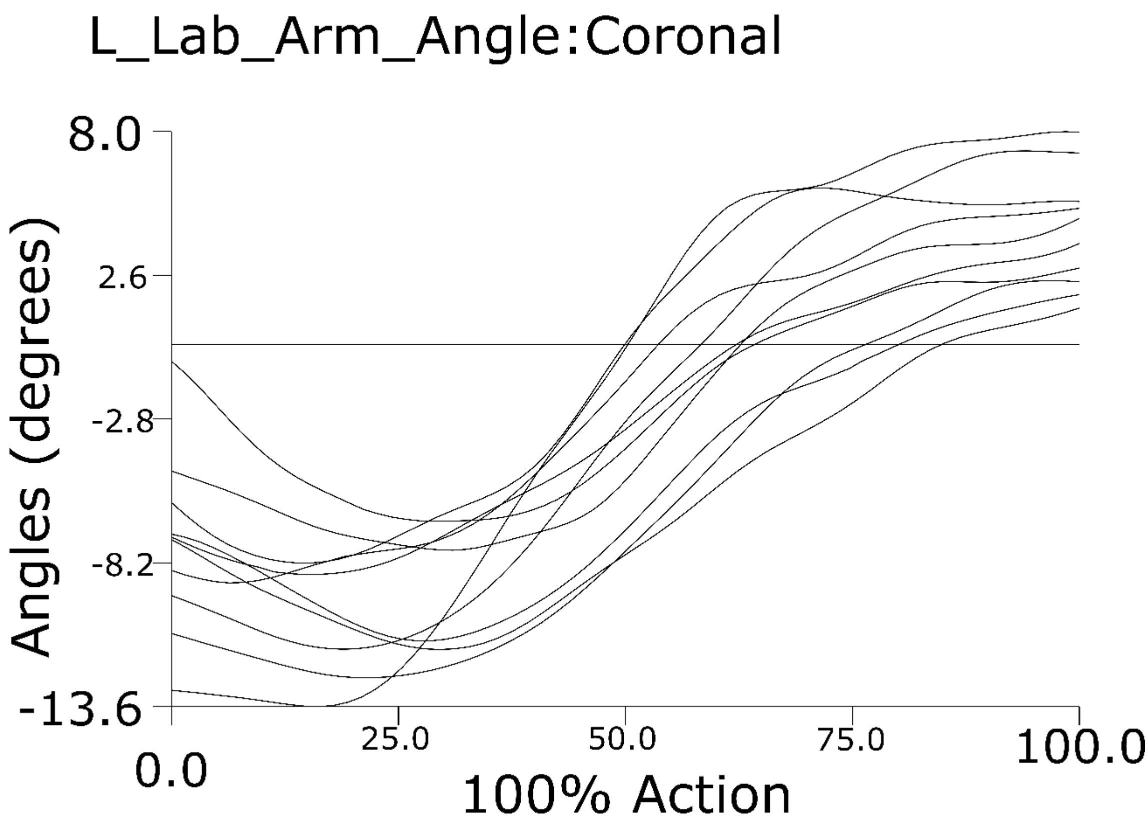


Figure 6-2 – Rotation of the forearm in the lab when holding the épée in the left (non-dominant) hand in the coronal plane.

Graph 6-3 shows the rotation of the forearm when holding the épée in with the 3D printed device glued to the simulator. Graph 6-4 shows the rotation of the forearm in the lab when the épée is held in the 3D printed device taped to the simulator.

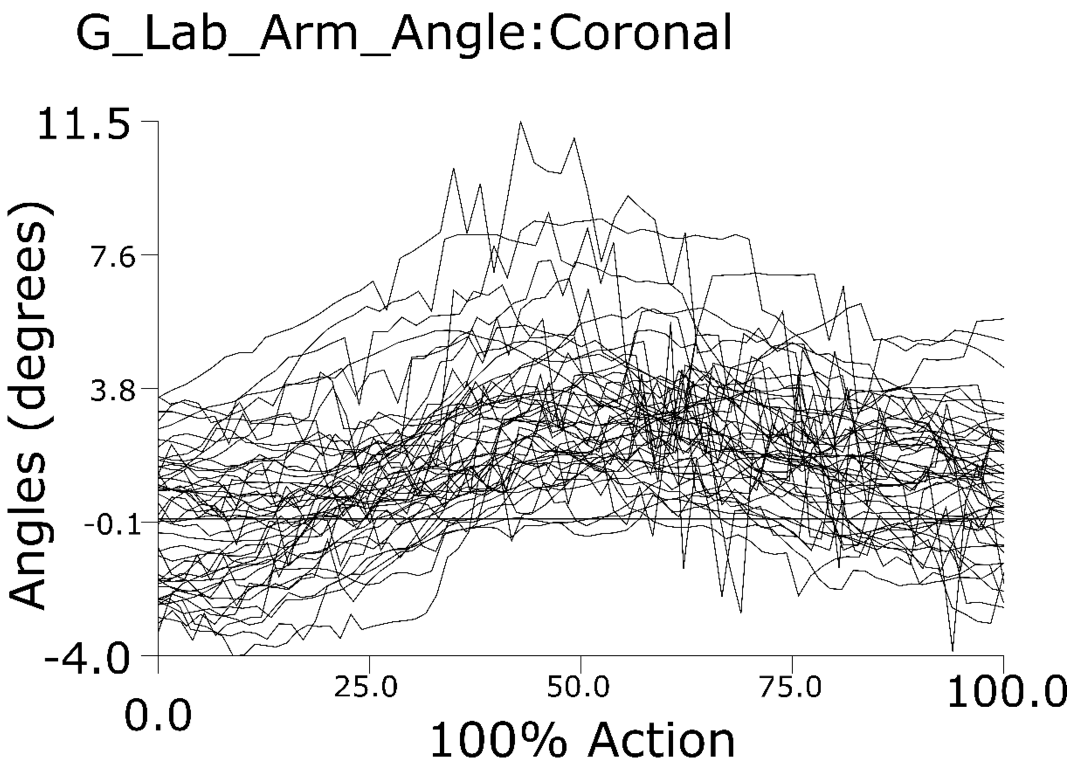


Figure 6-3 – Rotation of the forearm in the lab when holding the épée in the 3D printed device when glued to the prosthesis simulator in the coronal plane.

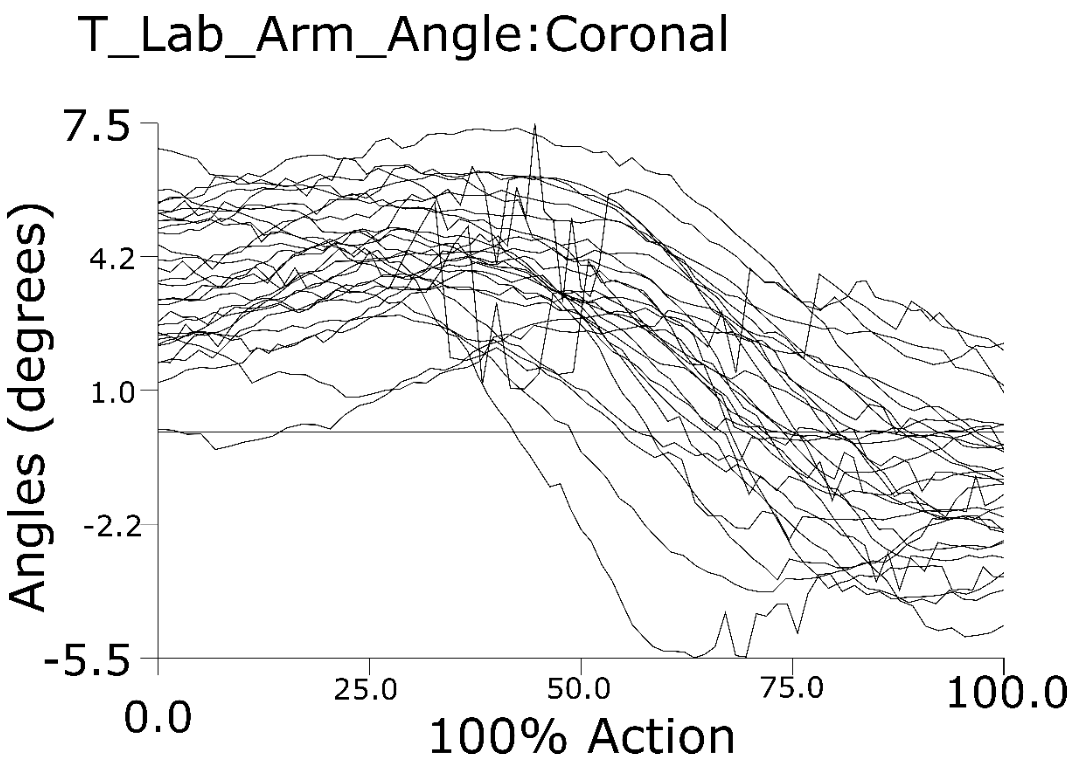


Figure 6-4 – Rotation of the forearm in the lab when holding the épée in the 3D printed device when taped to the prosthesis simulator in the coronal plane.

The gold standard shows internal rotation of the forearm through most of the action, the trajectory could correspond to the wrist movement in the same plane (graph 3-1). The left (non-dominant) hand and the taped device show similar patterns to the gold standard. The 3D printed device when glued to the simulator shows a different pattern, however its pattern is consistent between trials.

Graph 7-1 depicts the movement of the forearm in the lab of the right-hand (gold standard) in the transverse plane. Graph 7-2 shows the movement of the left (non-dominant) hand forearm in the lab in the transverse plane.

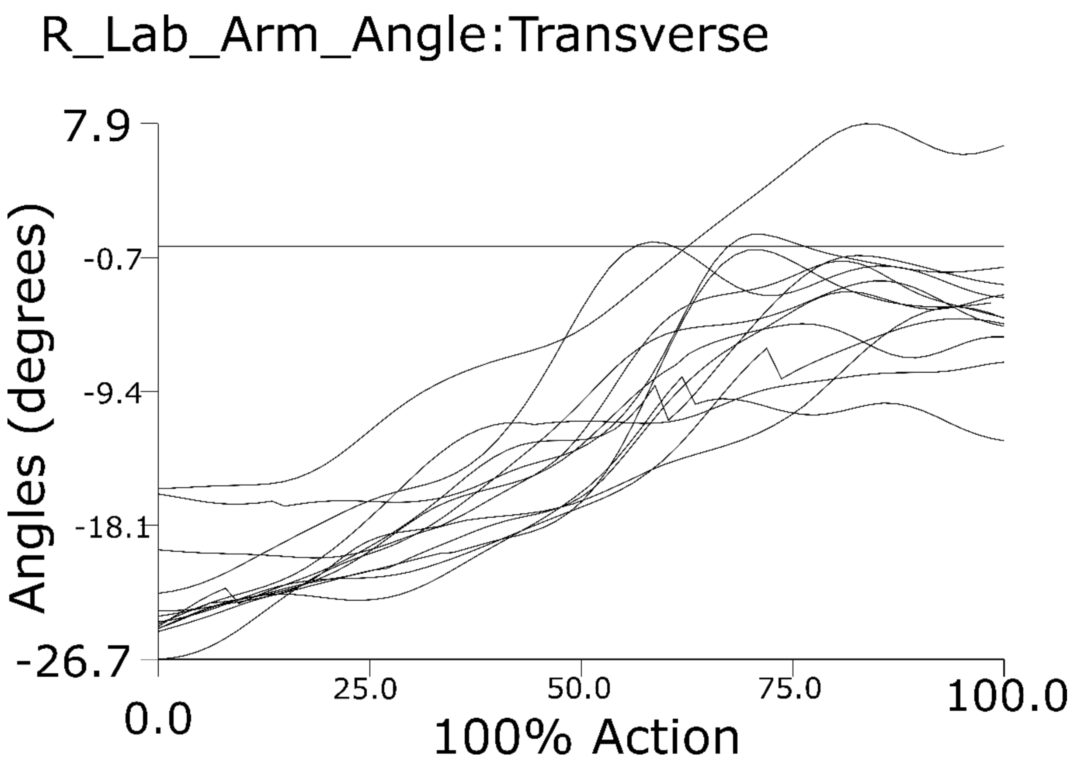


Figure 7-1 – Movement of the forearm in the lab when the épée is held in the right had (gold standard) in the transverse plane.

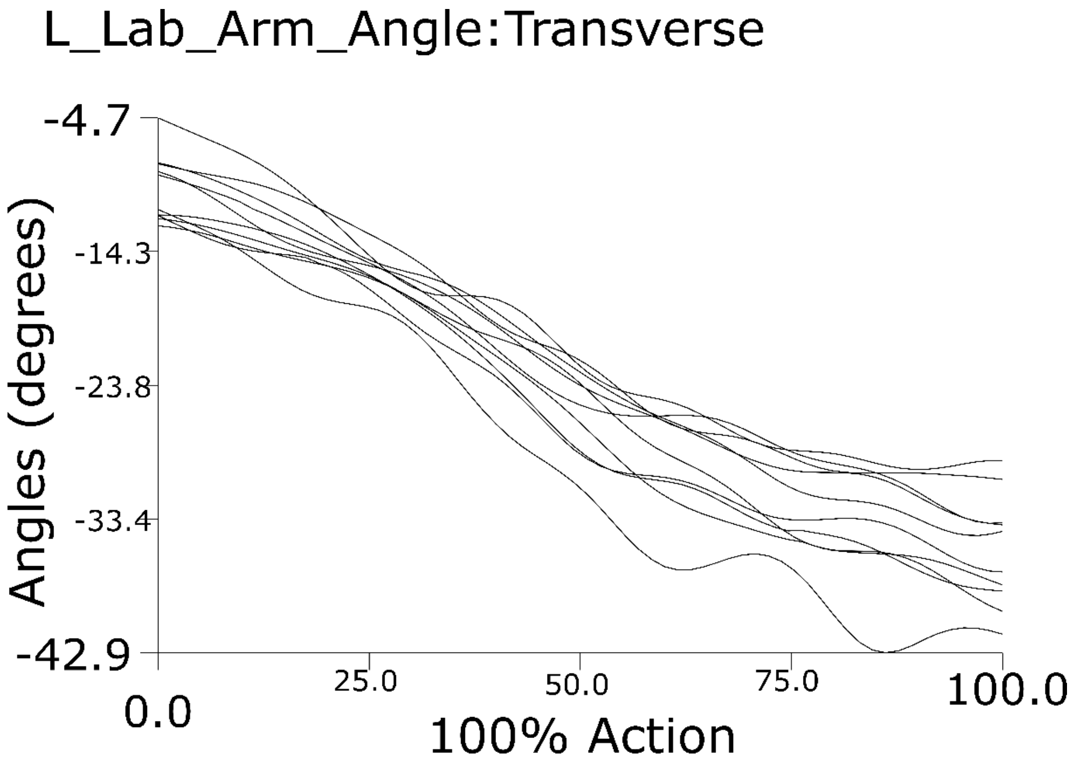


Figure 7-2 – Movement of the forearm in the lab when the épée is held in the left (non-dominant) hand in the transverse plane.

Graph 7-3 depicts movement of the forearm in the lab when the épée is held in the 3D printed device glued to the simulator and graph 7-4 when the device is taped to the simulator in the transverse plane.

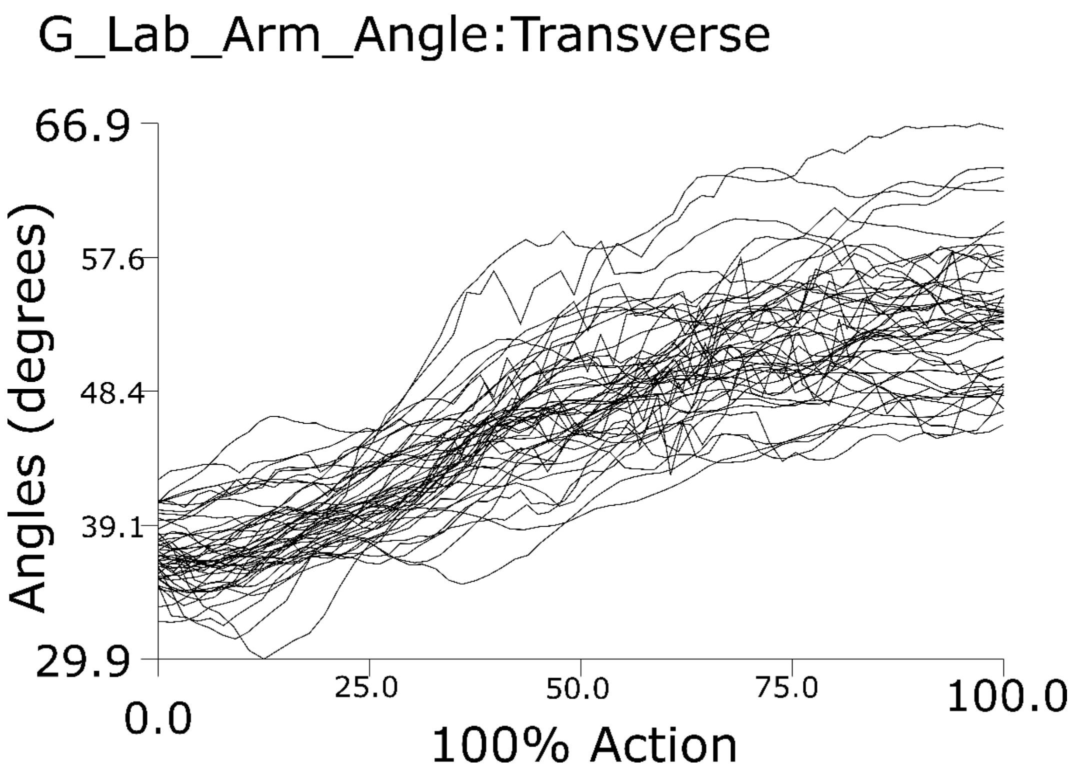


Figure 7-3 – Movement of the forearm in the transverse plane when the épée is held by the 3D printed device glued to the prosthesis simulator.

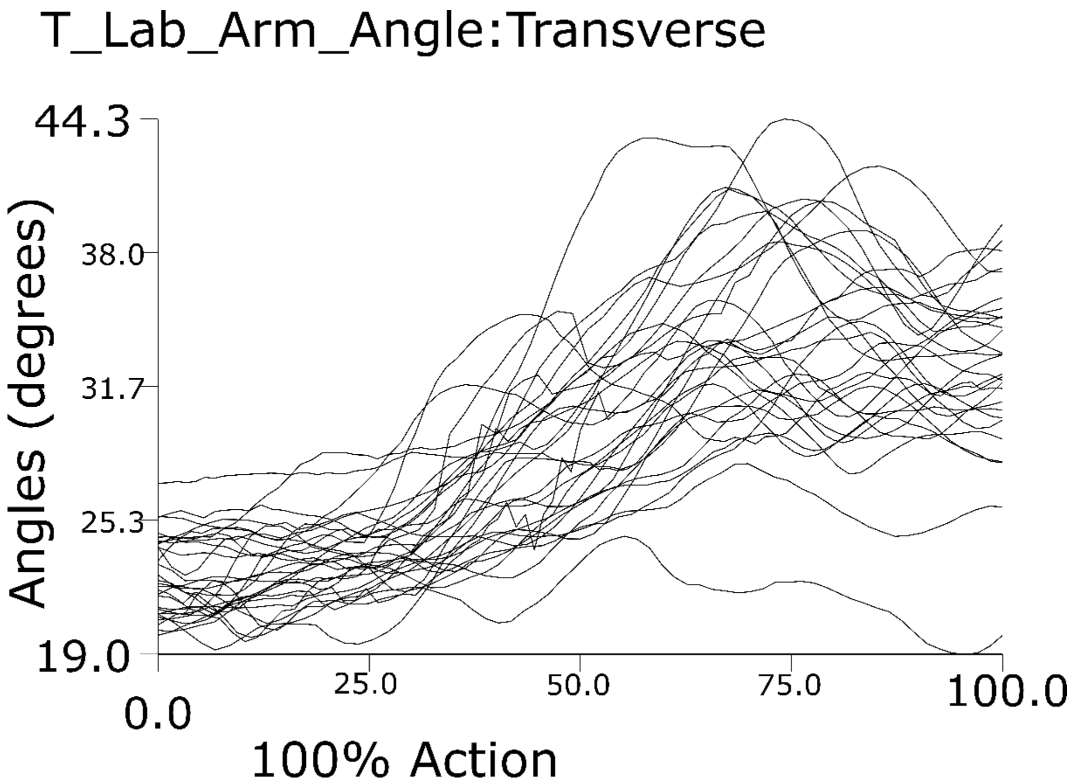


Figure 7-4 – Movement of the forearm in the transverse plane when the épée is held by the 3D printed device taped to the prosthesis simulator.

The gold standard starts with an initially internally rotated position and rotates externally as the action progresses. The left follows the same pattern but has a larger range of movement. The Prosthesis simulator conditions follow the same pattern as the gold standard however, are less consistent between trials.

4-6-5 – Additional

The trajectories of the gold standard and the left arm appear to be more consistent than those of the devices. This is likely due to the longer lever arm giving the illusion of the épée being heavier. This would likely not be as prominent with a participant with upper limb loss as the device would be positioned where the anatomical hand would be.

4-7 – Chapter summary

In summary, a terminal device was designed and manufactured via 3D printing for the sport of fencing. A basic, but essential, action was defined, the fencing lunge. This action was then recorded in the motion analysis lab for four conditions:

1- Using the dominant (right) hand – the gold standard.
2- Using the non-dominant (left) hand.
3- Using the device taped to the simulator.
4- Using the device glued to the simulator.

The left-hand condition was slower than the other conditions and had the highest failure rate for attempted hits. The prosthetic device was designed without wrist movement, despite this for both device conditions the movement of the forearm in relation to position in the lab are closer to the gold standard than the left-hand condition in all planes.

The next chapter will discuss the results for both the qualitative (Chapter 3) and quantitative parts of the project.

Chapter 5 – Discussion

5-1 – Chapter introduction

This chapter will discuss and contrast the results of both the interviews and motion capture sections of the project. The use of a mixed methods approach, such as the one applied in this case, has only formally been recognised as a means to acquire a rich picture of a subject analysis recently. However, it must be noted that despite of this, qualitative and quantitative approaches have been used simultaneously in previous studies [91]. In the qualitative analysis chapter (chapter 3) it was clear that some common themes were identified regarding the provision, prescription and usage of bespoke upper limb prostheses sports devices. The following section will outline some of these themes and identify areas that could potentially be improved with the increased availability afforded by the 3D printing process. The chapter will then go on to explore the motion capture results.

5-2 – Interviews: identified themes

The interviews collected data from a number of upper limb prosthetists who were able to provide information that could broadly be placed within specific themes. These were:

1- Highlighted Sports.
2- Currently available devices.
3- Cost.
4- Use of the contralateral hand.
5- Use of 3D printing.

5-2-1 – Highlighted sports

The sports highlighted by the participants were in line with recent literature [22]. Cycling and gym activities require the use of prosthesis for the user to participate effectively. The participant pointed out that swimming, however, is a matter of personal preference; some individuals like using a prosthetic fin on their residual limb whilst others swim without. It must be noted that prosthesis for swimming are not allowed in competition, so these would only be used for training or recreation. All participants mentioned cycling as an activity that they provide prosthetic devices for more regularly. The devices provided for this are a mix of commercial purpose made clamps and bespoke designs. Similarly, for gym activities a certain of TRS devices were highlighted, however due to the cost of these devices, participants reported that generally they produced bespoke designs for this purpose in their clinic workshop.

5-2-2 – Current prescriptions

Currently there are limited upper limb sports prosthesis being provided. The participants reported that they prescribed some devices from TRS [46] as the only example of commercial upper limb sports devices; however, they also stated that these devices are expensive and as such are in limited supply with NHS funding. They also reported that they more commonly created bespoke sports devices in the workshop, designed in conjunction with the technicians. These devices vary in design and functionality. The most common bespoke devices reportedly made by the participants were for use in cycling and going to the gym. The cycling devices were often some form of clamp attached to the end of the socket as seen in Figure 7 (figures 7-9 provided by a participant). The gym devices comprised of wooden or laminate semi-circular braces, often with straps to hold weights (figure 8) or rubber covered domes for push ups (figure 9)

Figure 7 – Example of cycling appliance [81].

Figure 8 – Example weights appliance [81].

Figure 9 – Example push up appliance [81].

The process of creating these bespoke prostheses was a lengthy one, as many versions had to be made before the required function was met. This is time consuming, as each time a new version is made the process of manufacture can take several days, depending on the design. It also consumes a large amount of resources, raising the cost of the final product.

The lack of currently available commercial devices may indicate a gap in the market suitable for bespoke or semi-bespoke 3D printed devices. These devices could be repeatable once a suitable design is produced as the CAD file can be saved and the devices can be easily adapted for individuals size and exact functional needs as the files can be manipulated on the computer.

5-2-3 – Cost

One area that was highlighted as a preclude for prescription and provision by some clinicians was the relatively high costs of available devices. One participant highlighted concerns that due to the cost of commercial prosthetic sports devices it is difficult to get funding for NHS patients to obtain provision of these devices. The cost of currently available devices is in the hundreds, or even thousands, of pounds (see section 3-4). By comparison, the 3D printed device manufactured for this study cost approximately £18.75 (see Appendix 2 section A2-5). This is a significant saving compared to current commercial devices, which anecdotal evidence suggest cost up to £4000, and could therefore allow for more widespread availability. This cost is not only affected by the cost of the materials and parts used for the device but the technician time to produce the socket and fit the parts together. Technician time is limited with 3D printing production as once the machine is set it can run overnight unattended. Furthermore, in the United Kingdom it has been found that, on average, an individual will spend £80 a year on sports equipment [92], by comparison just £18.75 is an affordable item. This also makes it mid-range for a replacement fencing grip [70].

The bespoke nature of these devices means that they are unlikely to be used for long periods, which may affect the rationale for prescription. However, it should be noted that the effect of being able to participate in a selected sport can have a profound impact on the life and enjoyment of an individual. Since the cost of 3D printed devices is far less than that of a commercial device, then these may be more freely available to any and all who need it. Individuals with access to these devices will then have the opportunity to receive the benefits afforded by physical activity (as highlighted in chapter 2). As these benefits include the prevention of other health conditions, the ability to participate can be seen as a preventative measure and reduce costs related to these potential health conditions, saving more money in the long run.

5-2-4 – Handedness

Whether individuals chose to re-train for a sport with their contralateral hand when the naturally dominant hand is absent, or if there is just a lack of appropriate prostheses, is unclear from the literature. One participant claimed that all those with upper limb loss switch their dominant hand to be their biological hand (see section 3-4-4). This does not align with research showing that handedness is linked to the nervous lateralisation of the brain [57,58]. This participant questioned the need for devices made for one handed sports such as fencing (the sport in this study). The accuracy of the motion capture shows that the rate of successful hits was less than half of all attempted hits with the left (non-dominant) hand. This is significantly lower than that of the gold standard and of both device conditions. This suggests that prosthetic provision for one handed sports is worth considering in cases where the naturally dominant hand is missing. It is unknown if this is due to total lack of control, an issue of distance judgement or the awkwardness that comes with mirroring practiced actions, in any case it is not conductive to sporting success.

5-2-5 – Willingness to use 3D printing

All participants agreed that 3D printing could have a place in the clinic with regards to the manufacture of bespoke upper limb sports prosthesis. Whether as a full prosthetic device or as part of the design/prototyping procedure was not agreed upon. Some were sceptical about providing a full 3D printed device without research backing the safety of the printed devices, however this proves that further research is warranted in this area. On this topic participants comments fell under 3 categories;

1- Safety

   Safety is an issue that the participants brought up as they were not aware of any documented 3D printed prosthetic device that have withstood the body weight of the user through continual use. There is a company called ProsFit that produce these devices [93] however the 3D printers they use are industrial machines that are not as readily available as the FDM (fused deposition modelling) 3D printer used in this study. The Printers used by ProsFit are MJF (Multi Jet Fusion) printers and build up objects from layers of powder [94], as such material choices are different from those used in this study.

   Devices made for non-weight bearing uses may be suitable to be manufactured via 3D printing, this may include cycling devices or racket sports, as suggested by one participant (see section 3-4-5).

2- Prototyping

   One participant suggested that 3D printing would be most useful for prototyping bespoke designs before sending the prototype to be manufactured (see section 3-4-5). This would cut the iterative process of designing a bespoke device as it would take a matter of hours instead of days to produce each iteration. The length of the process would then be governed by appointment slots instead of manufacture time. The issue of safety is not as crucial if the device is not leaving the clinic and is supervised by a clinician whist in use.

3- Saving designs

As with all CAD systems the ability to save designs makes them repeatable and could standardise prescriptions if all designs are saved to a shared database. In the same way one participant kept a photo log of bespoke devices [81], 3D printable devices can be kept digitally and can be replicated by anyone. This could be useful in sharing designs between clinics. The files can also be easily adjusted for size, to suit specific function or to fit a particular piece of sporting equipment.

5-3 – Kinematic Data

5-3-1 – Action times

The action time, the time from initiation of action to target contact, is important in the sport of fencing, especially épée, as it is a combat sport and to score a fencer must be faster than their opponent. If the fencer and their opponent initiate an attack at the same instance the first to hit will get the point unless they both hit within 40ms of each other, in this case both fencers gain a point.

The fastest condition on average was the glued device, this was unexpected, however the fastest times for all conditions were within 10ms. Between the fastest trial for the glued device and the fastest trial for the gold standard (right) there was only 9ms (G=0.589s, R=0.598s). The left was the slowest, with the difference between the slowest left trial and the slowest right trial being 62ms, this is important to consider when the difference between a clean point (just the fencer scores) and double points (both fencers score) is only 40ms [88].

For all conditions the difference between the fastest trials were within the double point bracket against the fastest gold standard trial. This shows that, when regarding speed alone all conditions are capable of achieving satisfactory results. Additionally, the fastest trials for all conditions achieved times able to achieve clean hits against the slowest gold standard trial.

The non-dominant (left) hand condition produced the slowest trial and had a slower “fastest” trial than all other condition, this may be due to a natural lack of coordination. When comparing the slowest times for each condition and comparing the with the gold standard, the non-dominant condition was to only one that would receive a clean hit against it when against the gold standard's slowest trial. The other conditions would only have clean hits against their slowest trials when against the gold standard's fastest trial.

5-3-2 – Hit Accuracy

The accuracy achieved in each condition is important as when fencing the aim is to score points by contacting the épée into the opponent's body. This could be a target as large as the torso or as small as the wrist. Assuming a high enough level of accuracy, the most efficient area to target is the opponent's wrist as this is the area closest to the fencer during a fight.

All hits for the gold standard (right) were within 8cm diameter with a favour to above the centre of the target, the furthest from the target being 6cm away from the centre of the target. Interestingly the gold standard showed the largest average distance from the target centre for successful hits, all average hit distances were, however, within 8mm of each other. 79% of all attempted hits landed on the target, those that didn't were due to misjudged distance.

The hits for the non-dominant hand were within a 6cm diameter, however 58.5% of attempted hits failed to reach the target altogether, showing a possible lack of control, or a fault in distance judgment possibly due to mirrored positioning. Whatever the reason, more than half the attempted hits failed, which would lead to the opponent having an opportunity to score. The left showed a favour for the left side of the target, this becomes more significant in fencing depending on if your opponent is left or right handed as defence is stronger on the side holding the épée.

Hits for the glued device were within a 12cm diameter, slightly larger spread than the gold standard, but the majority were within a 7cm diameter and evenly spread around the centre of the target. The glued device achieved the smallest average distance from the target centre, it did however, also have the hit furthest from the target centre. Of all attempted hits the glued device only showed 6% fail to hit rate, either indicating more control than the left hand or misjudged distance in favour of behind the target. In this case distance could be misjudged due to the simulator situating the épée in a more distal position than when gripped in the hand, creating longer reach than in the gold standard condition.

Hits for the taped device were within a 9cm diameter, slightly favouring the right side of the target. The taped showed 19.5% of attempted hits failed to reach the target, this is comparable to the gold standard. This is higher than the glued possibly showing instability of the joining method or misjudging of distance. Both devices showed a much lower failed attempt rate than the left.

5-3-3 – Arm-Sword Angles (Wrist movement)

These are the angles between the forearm and the length of the épée. The change in angle is provided by the wrist and finger joints. There may be a minor element that comes from the flexible nature of the épée blade.

Sagittal plane

In the sagittal plane the gold standard (right hand) showed a progressive ulnar deviation (see graph 2-1), this means that the tip of the épée was progressively being lowered in comparison to the wrist as described in section 4-2.

The left shows initial ulnar deviation followed by radial deviation returning to roughly the starting angle (see graph 2-2). This indicates that the tip of the épée had dipped below the target and had to be readjusted to hit. It also shows that the ideal position of hand at shoulder height and épée tip at chest height was not achieved. This may show a lack of control of the non-dominant hand.

Coronal plane

In the coronal plane, the gold standard (right hand) showed internal rotation of the épée in relation to the forearm (see graph 3-1). Between 25% and 37.5% of the action this switches to external rotation of the épée in relation to the forearm.

The left showed a similar (mirrored) pattern to the gold standard. The left showed a larger range of motion and the rate of change of the direction of the movement is dampened in comparison to the gold standard (see graph 3-2). This slower change in direction could indicate a lack of control.

Transverse plane

In the transverse plane, the gold standard (right) showed oscillation around a consistent angle with a deviation from the initial angle of about 6° in either direction (see graph 4-1). The right shows one trial that differs to the others, this trial shows the same pattern, however starts and progresses at a different angle to the majority of the right-hand trials. This shows that the épée travels along the same path throughout the movement, following the fencing line (see section 4-4-2).

The left showed a progressive internal rotation of the épée in relation to the forearm (see graph 4-2). This could indicate a difference in en garde stance, a difference in torso rotation (making the hand more laterally orientated in relation to the centre of the fencer's defence area) or another compensatory action. Any of these reasons can result in the deviation from the fencing line.

Device trials

The arm-épée angles for both the taped device and the glued device were expected to show minimal movement. This is due to the design of the 3D printed device. To eliminate the need for a control harness, the device was designed without an articulating wrist or any moving parts. The use of a control harness would create compensatory movements in itself if successfully used throughout the needed range of motion. The range of movement for both taped and glued conditions, in all three planes, was below 10° (see graphs 2-3, 2-4, 3-3, 3-4, 4-3 and 4-4). The only exception to this being the taped device in the transverse plane, where a range of 17.3° was observed (see graph 4-4). This exception can be counted as an anomaly as it is a single trial that does not follow the pattern of the condition. It is thought that the movement observed is due to the flexible nature of the épée's blade as the pattern is the same in all three planes and angles are low (5° either side of neutral) and constant. With the exception of the maximum range in the transverse plane the glued device has a slightly larger range of motion than the taped device, it is possible that the movements performed were more aggressive as the glued device reportedly "felt sturdier". How the device feels to use is an important factor to consider, much like how the colours used in video games can affect performance [95,96]. This is due to how the colours make the player feel, and act accordingly, the same way if the prosthetic device feels sturdier the user may use it differently.

The device was not designed to facilitate wrist movement. This was due to security of grip being prioritised and lack of suitable control method (myoelectric unsuitable due to weight and possibility of motion artefacts, body powered unsuitable due to range of positions needed to move through whilst simultaneously controlling wrist). This results in an unnatural lack of movement, this is, however, predicted as controlled rigidity was chosen over uncontrolled movement. When comparing to the non-dominant hand it is still unclear if controlled rigidity is favourable.

5-3-4 – Lab-Arm Angles (movement within the lab)

Sagittal plane

In the sagittal plane the pattern of movement of the gold standard (right hand) and the two device conditions are comparable. The pattern of movement of the left differs from the gold standard.

The gold standard showed elbow flexion when lifting the épée (bringing the tip of the épée in line with the target) and elbow extension when approaching the target (see graph 5-1). The left shows an initially more flexed position followed by extension to the target and finally flexion to position the épée in line with the target (see graph 5-2). This could be related to the difference between the left and gold standard arm-sword angles in the sagittal plane (section 5-3-3). Whether the forearm movement or the wrist movement is responsible for the other compensatory movements is not clear, however, both arm-sword and lab-arm movements of the left differ from the gold standard.

Both the glued and taped devices had fluctuations in their progression (see graphs 5-3 and 5-4), this could be because of trajectory adjustments being made by the forearm due to lack of wrist movement. The range of starting angles for both device conditions is larger than the gold standard, showing a range of starting positions, however the range of end positions is small as the target is hit with comparable ranges to the gold standard. The range of the starting positions could be due to fatigue, the extra length of the device on the simulator creates a longer lever arm and therefore greater force from the weight of the épée. This would be negated with a true prosthesis as the device would be positioned where the natural hand should be, however, the effect may be felt by those with short residua. The fatigue could also be due to the number of successive lunges performed. A competition level fencing bout is fought to fifteen points over three periods. Each period is to five points or three minutes with a one-minute interval between each period [97].

Not taking into consideration the starting position as it differs from the gold standard in all conditions, the glued device and taped device follow the pattern of the gold standard, whereas the pattern of the left-hand trials do not. This shows that there are more compensatory movements in the left-hand condition than the two 3D printed device conditions.

Coronal plane

In the coronal plane the gold standard right shows internal rotation of the forearm from about 25% action until about 75% action.

The left (mirrored) and taped device show patterns comparable to the gold standard. The pattern of the left is more distinct than the taped device, this could be due to the restrictive nature of the laminated simulator. It could also be due to all micro adjustments in trajectory of the taped device coming from the elbow due to the lack of wrist movement.

The glued device showed a different pattern to the gold standard, this could also be due to the restrictions of the laminated socket or fatigue due to the weight of the device, however if this was so, the taped device would be expected to show the same.

Transverse plane

In the transverse plane the gold standard right forearm begins with an internally rotated position in relation to the lab (wrist more medial, elbow more lateral). As the arm progresses through the action the position of the forearm externally rotates to become parallel to the line of progression.

The left showed the same pattern (mirrored) as the gold standard but with a larger range of movement. The larger range of movement of the left could reflect a difference in initial stance or compensatory motion, however the motion is consistent through all left-hand trials and the pattern matches the gold standard.

The glued and taped devices both showed the same pattern as the gold standard. The range of motion of the glued device is closer to the left than the gold standard, this could be due to the lack of wrist motion. The taped has a smaller range of motion but deviates from the gold standard after about 50% action, where the variation between trials increases, some of which no longer follow the gold standard. This compensation could be due to the lack of wrist motion or fatigue due to the higher force of the long lever arm.

5-4 – Limitations

There were a number of limiting factors in this project. The main ones are outlined in this section.

The interviews were limited in the number of participants. Of those identified to meet the exclusion criteria only 3 prosthetists were able to participate due to their schedules. While it is possible more may have found the time to fill out a questionnaire, the two-way dialogue of a semi-structured interview provided a more flexible information gathering method than the rigid nature of a questionnaire and therefore was more suitable to gather professional opinions.

Originally two different 3D printed devices were designed, one that held the épée grip and strapped on and one that replaced the épée grip. These devices screwed into the wrist plate of the prosthesis simulator, a US wrist plate was used to benefit from the larger thread surface area compared to the EU wrist plate. Despite the use of the larger US thread the weight of the device plus the épée proved too much and the layers of printed plastic separated from each other. This could be resolved by printing the socket and terminal device in one solid unit as demonstrated by the body of the device having no signs of cracks or faults. There is also the possibility that the thread may have been stronger if the device was printed in a different orientation, so the layers of plastic were parallel to the length of the thread. This would have caused support structures to be printed along one edge of the thread and compromised its shape (for further details see appendix 2). Another option would be to use an SLA (Stereolithography Apparatus) printer where the layers are less noticeable. However, SLA printers take considerably longer to print than the FDM printer used, and the material options are limited to liquid resins that are less durable and their strength is affected by exposure to sunlight. Not only is the resin not as strong and durable as PLA but it is higher in price as well [98]. The failure of the printed thread led to the adaptation of the investigation conditions, only the grip replacement device was used, and the conditions changed to attaching the device via glue (to simulate a solid wrist unit) and attaching the device via tape (to simulate what users are thought to do).

The prosthesis simulator locates the wrist unit at the end of the hand balled into a fist. This adds extra length to the simulator in comparison to a true prosthesis where the terminal device would be positioned at the same distance from the elbow as the contralateral hand. This extra length provides a longer lever arm and as such an increased sense of weight due to the increased force from the greater distance. This would not be an issue with a true prosthesis if the user had a long residuum as the lever arm controlling the device would be close to the length of the prosthesis. If the user had a short residuum the controlling lever arm would differ from the lever arm of the prosthesis enough that control may become difficult due to the "weight".

It must be noted that the lead researcher was the participant for the motion capture section of the project. Whilst all possible measures were taken in an attempt to avoid it, it is possible this might have led to a small level of bias on the results.

5-5 – Chapter summary

In summary, the participants for the interviews highlighted sports which they regularly prescribe specialised devices for that agreed with the literature. They agreed that there are few sport specific devices commercially available and those that are available are expensive. This expense as well as lack of variety leads to bespoke prosthesis being made in-house. Although functionally good, there is no standard across clinics and designs greatly vary from user to user.

All participants agreed that 3D printing could have a role in the production of sport specific devices however a few issues were raised. The lack of documentation on the safety of these devices was highlighted as something that would prevent prescription. It was, however, suggested that 3D printing could be used to create prototypes within clinic that can then be sent to be manufactured. This could reduce the time for a design to be finalised. The designs can also be saved digitally, allowing for standardisation of treatment.

Despite the rigid nature of the 3D printed device, less compensatory movements were afforded in all three planes between the forearm and lab for both printed device conditions than the left-hand condition in relation to the gold standard.

The left-hand condition was slower than all other conditions and also had a higher failed hit rate than all other conditions.

Chapter 6 – Summary and Conclusions

6-1 - Summary

In summary, experienced prosthetists were interviewed and highlighted issues with current upper limb prescription options for sport and physical activities such as cost, lack of funding and having few sources for commercial components. The interviewees generally made bespoke sports prosthesis in the workshop in conjunction with technicians. The use of the contralateral hand was seen as the norm and in some cases thought to become the dominant hand. The use of 3D printing was generally well received, especially for prototyping and the ability to save designs digitally. There was a hesitance about the safety of the proposed devices and more research in this area is warranted.

The researcher performed a fencing lunge in the motion capture lab under 4 conditions;

1- Épée in dominant, right-hand (gold standard)
2- Épée in non- dominant, left-hand
3- Épée held in 3D printed device glued to simulator
4- Épée held in 3D printed device taped to simulator

The left-hand condition performed the action slowest and was also least accurate, hitting only 41.5% of all attempted hits.

The two 3D printed device conditions had limited movement in the épée-forearm joint as the device is not designed to allow this movement. Any movement observed in this joint is likely due to the flexibility of the épée.

The left-hand condition was comparable to the gold standard in the coronal plane, but compensatory movements were observed in the sagittal and transverse planes when compared to the gold standard.

Controlled immobility is preferable to uncontrolled compensatory movement. Lack of movement in the devices was predicted, the left-hand only being comparable to the gold standard in one plane was not.

The Lab-forearm angles for the 3D printed device conditions were comparable to the gold standard in the sagittal plane with deviations to compensate the lack of wrist movement. The left-hand condition showed compensatory movements in this plane.

The coronal plane showed comparable results between the left-hand, taped device and gold standard conditions with deviations in the glued device condition.

The transverse plane showed deviations from the gold standard only in the taped device condition.

6-2 - Conclusions

In conclusion there seems to be an opening in the market for affordable, reproduceable, semi-bespoke sports terminal devices that could be filled by 3D printing.

The device tested produced less compensatory movements in both conditions than the use of the non-dominant hand (excluding wrist movement). The device, in both conditions, were closer to the action time of the gold standard than the non-dominant hand. The device, in both conditions, had accuracy comparable to the gold standard whilst the non-dominant hand did not. Due to this the use of a sports prosthesis appears to be superior to the use of the non-dominant hand, at least initially.

Further research is needed in the areas of the safety of 3D printed devices, long term use of these devices' vs long term training with the non-dominant hand, trials using devices designed for a range of other sports and physical activities and trials with trans-radial users.

Appendix 1 - Interview Guide

Greet and give a brief explanation as to the general content and reason for the interview.

Invite any questions before beginning.

Written consent will be obtained and confirmed before beginning.

1- Background with regards to prosthetic levels of amputation
    1- What proportion of prosthesis users were upper limb within your clinics?
    2- What were/are the key differences with respect to prescription options between upper and lower prosthesis.
2- Sports prescription and Upper Limb
    1- Which components do you frequently use for upper limb sports prosthesis?
    2- What are the most common sports you supply upper limb prosthesis for?
    2b- Which components did you prescribe for these sports and why?
    3- Are there any sports you have guided people to / pushed people towards?
    3b- If so which sports and why?
    4- Are there any cases where you have been unable to provide a prosthesis for a specific sport due to lack of componentry?
    4b- Which sports?
    4c- In these cases what did you do?
    5- Have you seen people make their own devices for sports?
    5b- If so, what were they like and what did you think of them?
3- The contralateral limb
    1- Of those using sports prosthesis, how many are missing their dominant hand?
    1b- Of these, have any considered re-training with their non-dominant side?
    2- Have you had patients who use their contralateral limb in one-handed sports?
    2b- Were some of these people missing their dominant hand?
    2c- Have any of these people expressed that they would rather use a sports prosthesis on their dominant side? Opinions?
4- Example model.

1- A patient of relative physical fitness attends your clinic saying they wish to take up the sport of Fencing. What do you prescribe and why?

2- What criteria would they have to meet for this to be successful?

3- What contra-indications would you look out for?

5- Changes or introductions you believe should be made to enable better provision of sports devices?

1- If there were no components available for a patient's request would you consider 3D printing a bespoke component?

1b- If yes, tell me more?

1c- If not, why not?

2- What has feedback from patients who have been supplied upper limb sports devices been like?

2b- Have there been any stand out components? Good or bad?

2c- What was reportedly good/bad about them?

6- Anything else you would like to comment on.

Appendix 2 – Constructing the 3D printed terminal device

A2-1 – Manufacture of simulator

A prosthetic simulator was created to mirror the type of device used by a transradial prosthesis user, and to enable the assessment of each terminal device accordingly. The

Figures 10-14 left to right – Casting and prosthesis simulator.

researcher created a prosthesis simulator from a cast of their dominant right arm using traditional methods of lamination. Lamination is the standard manufacturing method for the production of upper limb prosthetic sockets. The cast was taken by a qualified prosthetist/orthotist. The device terminates in a single knob rotary wrist to allow the fitting of multiple standard terminal devices. This is a standard component used in clinics and provided by currently used prosthetic manufacturing companies. The simulator was manufactured on site by a prosthetic technician to a clinical standard.

The socket consists of an outer hard laminated shell with attached wrist unit and Velcro straps and a laminated inner that is thinner and therefore more flexible to ease donning and doffing. The trim lines provide an open anterior to allow donning and doffing and extend just over the olecranon and humeral epicondyles. The proximal trim line is such to recreate the trim similar to a north-western style trans-radial socket [99] with a slightly lowered posterior wall to allow full extension. This lowered posterior wall would not be suitable for all individuals with upper limb loss as those with a short residual limb would need a higher trim to facilitate suspension unless a harness system was used [100].

A2-2 – 3D printed device

The 3D printed device was then designed to fit the prosthetic simulator. The adaptor plate on the wrist unit imbedded into the simulator was a standard plate with a US internal thread as found in the Steeper's catalogue [101]. Standard commercial terminal devices have a threaded attachment; this same thread was used when designing the 3D printed device. The US adaptor plate was used as the standard US threaded adaptor has a larger thread diameter than the standard EU threaded adaptor. The adaptor plate with the larger diameter threaded plate was chosen to reduce the risk of breakage of the thread as this was identified as the weakest part of the device due to its relatively small surface area.

A2-3 – The Printing system

FDM (fused deposition modelling) 3D printers manufacture objects by heating up materials in filament form until they become viscus, then extruding the material in thin layers to produce the object specified by the chosen STL file (3D file exported from CAD software). These materials are usually types of plastic but any material that turns viscus before fully melting can be 3D printed. The smaller the layer height, the higher the resolution of the object, the smoother and more detailed the object is.

The Raise 2N+ is a desktop printer with a build space of 305mm by 305mm by 610mm, this is a large build area capable of printing full prosthesis in a single print if desired. It is equipped with duel extruders to allow simultaneous printing of two materials of different colours and/or properties. It has a heated bed up to 110°C. High resolution capabilities with a up to 10micron layer height and 12.5micron X/Y precision [102]. The nozzle is 0.4mm in width as standard but can be swapped out for a smaller or wider nozzle as required. The enclosed design of this printer is essential for making use of its large print volume, this is because the temperature can be carefully controlled inside the enclosed environment [103]. This temperature control is especially important when printing more exotic materials with special properties such as flexible materials and nylon composites. This feature could be employed in the future to create devices or sockets with areas of flexibility and reinforcement.

A2-4 – Material selection

The material used in this project is Polylactic Acid (PLA) [104]. PLA is a relatively easy material to print and failed prints are more commonly due to design/human error than material difficulties.

PLA starts to melt at 170°, this is lower than other printable plastics. This lower temperature means less heating up of the extruder therefore lower print times and less electricity used when printing a piece, lowering the price of overall manufacture. It does mean, however, that it is not suitable to make any object expected to experience high temperatures during use. This also means that if a printed item needs to be re-shaped, heat can be applied to the area and re-shaping is possible. This is also helpful with objects that can be printed flat (fast) and only hot water from a kettle is needed to mould to shape.

Alternatively, another commonly used material when 3D printing is ABS [105]. In comparison to PLA, ABS is stronger, however PLA is harder. ABS is more difficult to print as it required a higher temperature, it cannot be printed without a heated bed and the temperature during print must be more closely regulated. ABS is also a more toxic composite than PLA and as such may give off fumes when melted and should not be ingested.

The company Open Bionics, who are currently manufacturing the first commercial 3D printed prosthetics for trans-radial users print their arms on Ultimaker [106] printers with a combination of PLA and flexible TPU filaments [107].

Since PLA is derived from corn and sometimes sugarcane it is long-term biodegradable and, if left in a composter, will break down after only a few years.

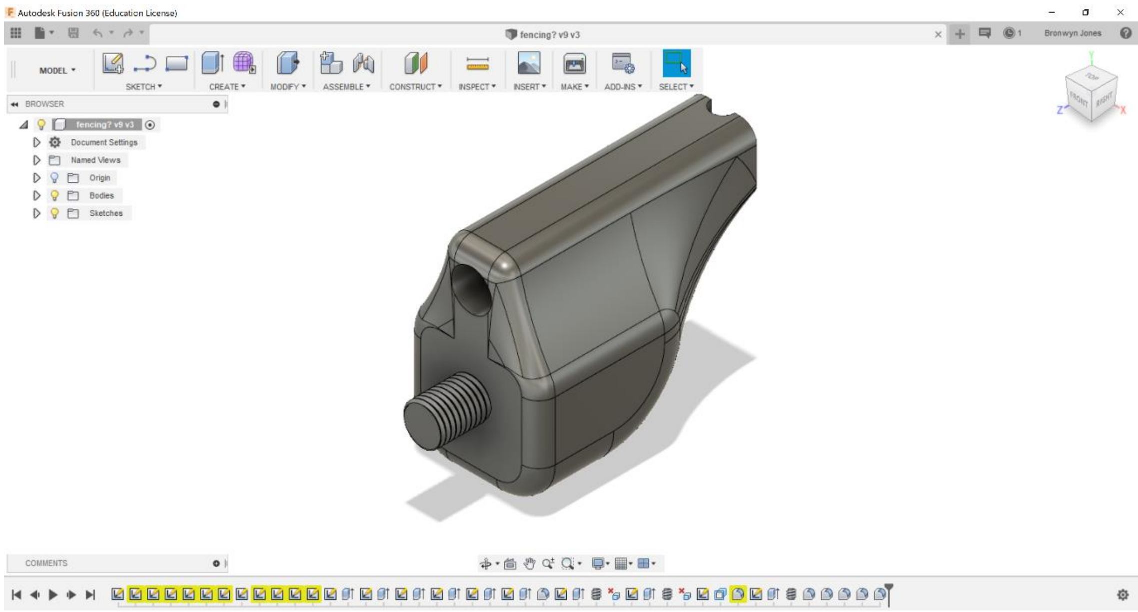
PLA comes in many bright colours and is easily painted with any commercial paint, such as acrylic. This makes it attractive for sports equipment as it can be made in team colours etc.

The plastic itself is FDA approved, meaning it is food safe and suitable to be given to small children likely to put objects in their mouth. This is offset after printing as, unless the extruder is sterilised, the PLA will become contaminated when melted and extruded.

The resulting printed object is also likely to contain pits and the layered nature of printed objects invites the breeding of bacteria if not cleaned regularly. Some colourings added to the plastic may also not be food safe [108].

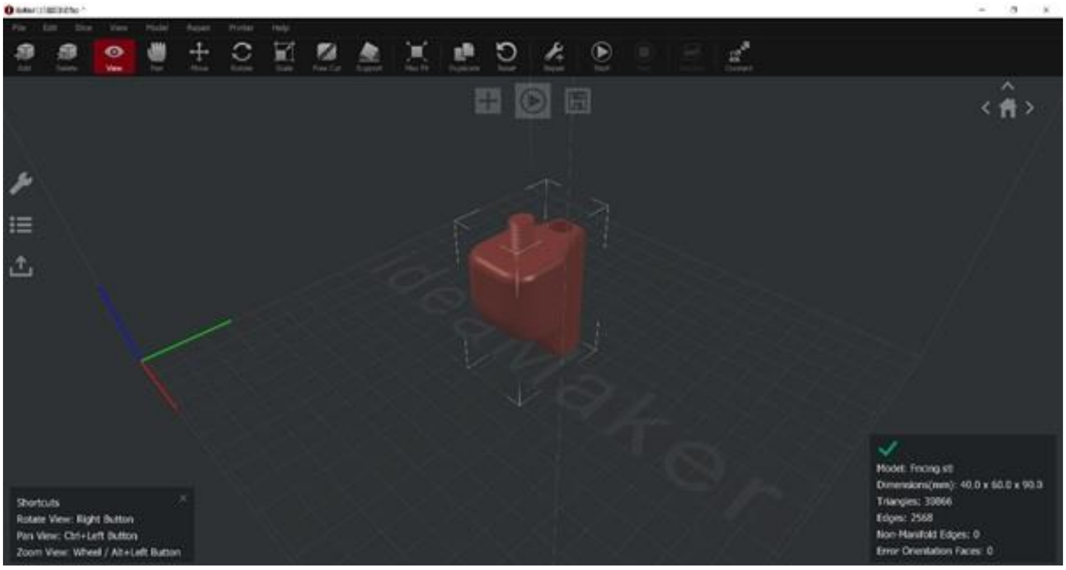
A2-5 – 3D Printing Process

When printing an object, the first thing to do is design the object using 3D CAD software (screenshot 1). The CAD software used for this project was Fusion360 [109]. Fusion360 is used in engineering fields from racing car design to robotics to ergonomic furniture design [110].



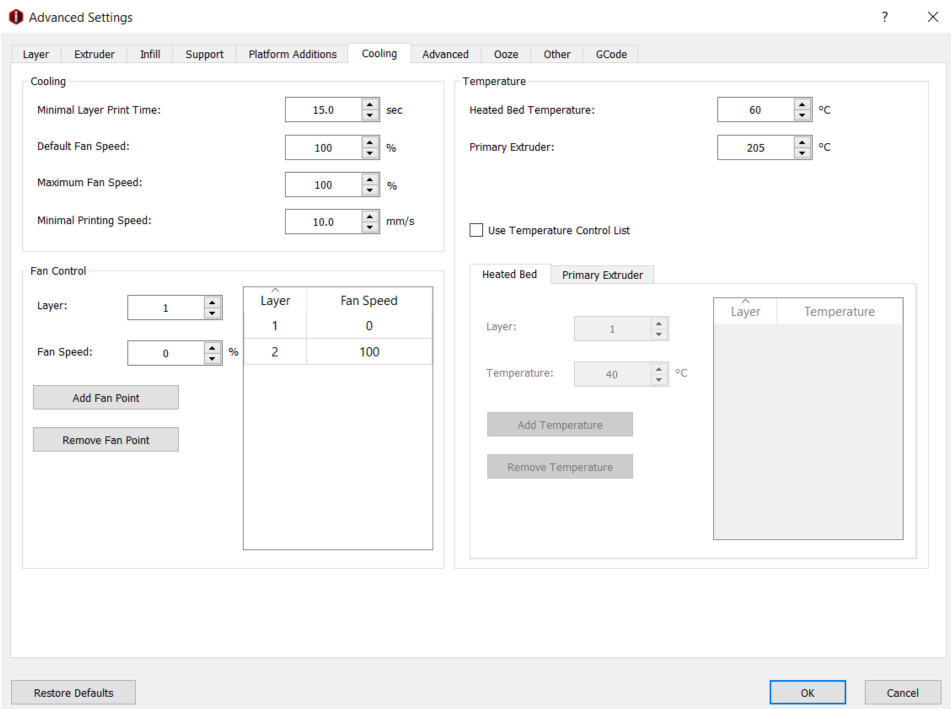
Screenshot 1 – Terminal device designed in Fusion360 software [106].

The object is then exported in stereolithography (STL) format [111]. Once in this format the STL can be opened into a slicer software (screenshot 2). The slicer is where all the settings for the print are set and tells the printer how to extrude the material to create the object. Slicer software is individual to the 3D printer used. Raise 3D printers use Ideamaker software [112].



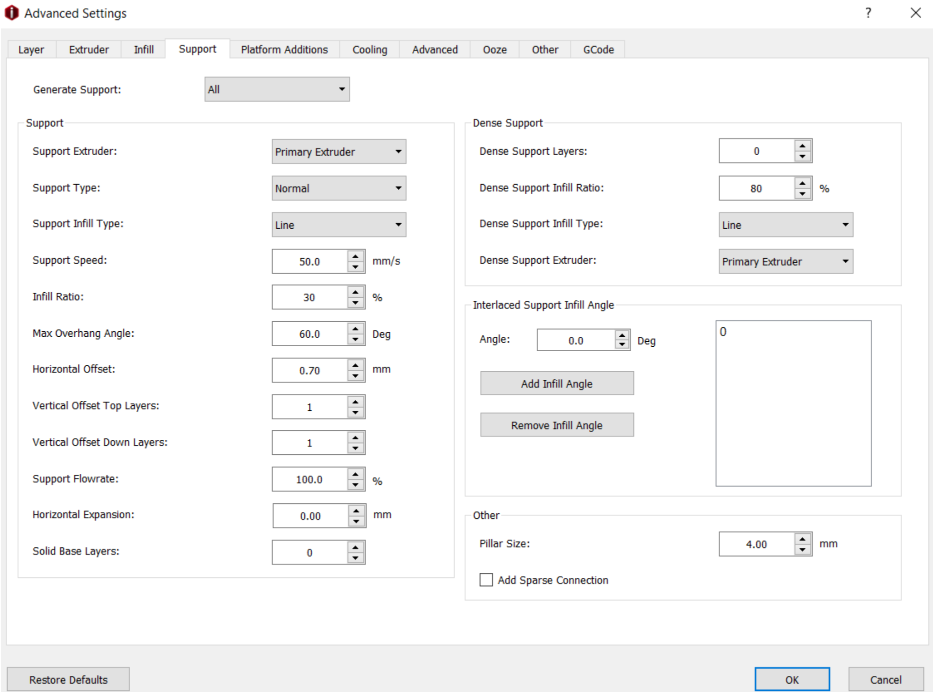
Screenshot 2 – Terminal device positioned in printing orientation in Ideamaker software.

In this software the confines of the print space are shown, the object will print as it appears on screen. The object can be re-scaled and re-orientated at will. It is possible to print multiple objects at a time as long as they fit in the build space. The printer cannot print in the air, any sharp overhangs are compensated by building sacrificial structures known as supports. This device is oriented so that there are no external supports needed. The overhang is gradual enough that the printer can layer the PLA without supports. There are supports on the inside of the channel running the length of the device; this channel is where the épée will be attached and has a stop midway to tension the bolt.



Screenshot 3 – Temperature control options in Ideamaker software.

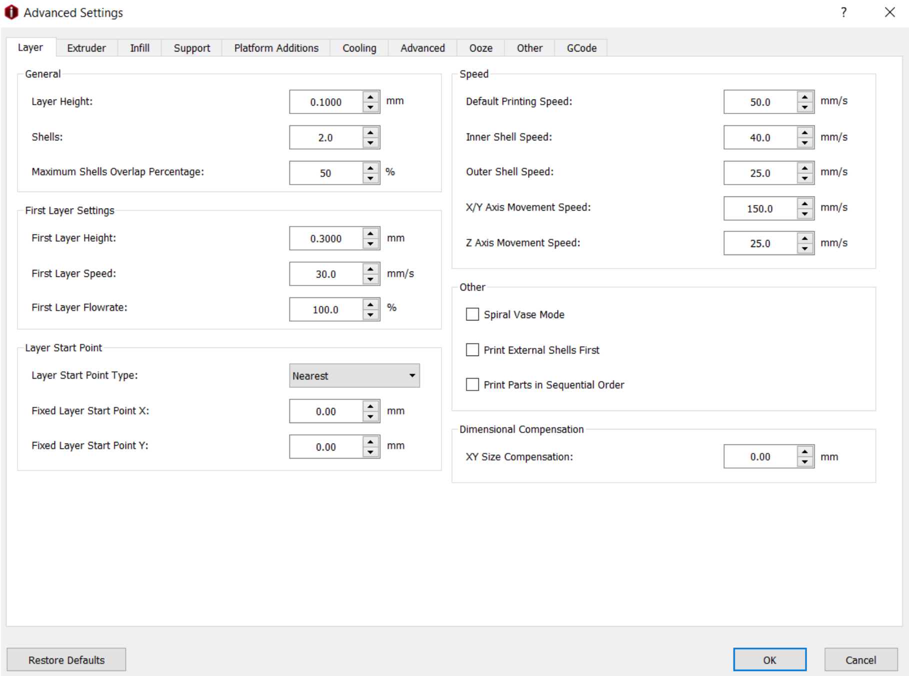
The temperature of the heat bed and extruders can be adjusted according to the material to be printed (screenshot 3). In this case the heated bed was set to 60° and the extruder to 205°. The ideal temperature range for printing PLA is 190°-220° [113], this depends on brand, colour (pigments change the composition) and the external temperature, printing with extruder at 205° and bed at 60° places this print at mid-range. The fan speeds can also be adjusted on this screen, the fans cool the extruded PLA to solidify it. The heated bed prevents the print from prematurely peeling off and also creates an ambient temperature in the enclosed space of the printer.



Screenshot 4 – Support options in Ideamaker software.

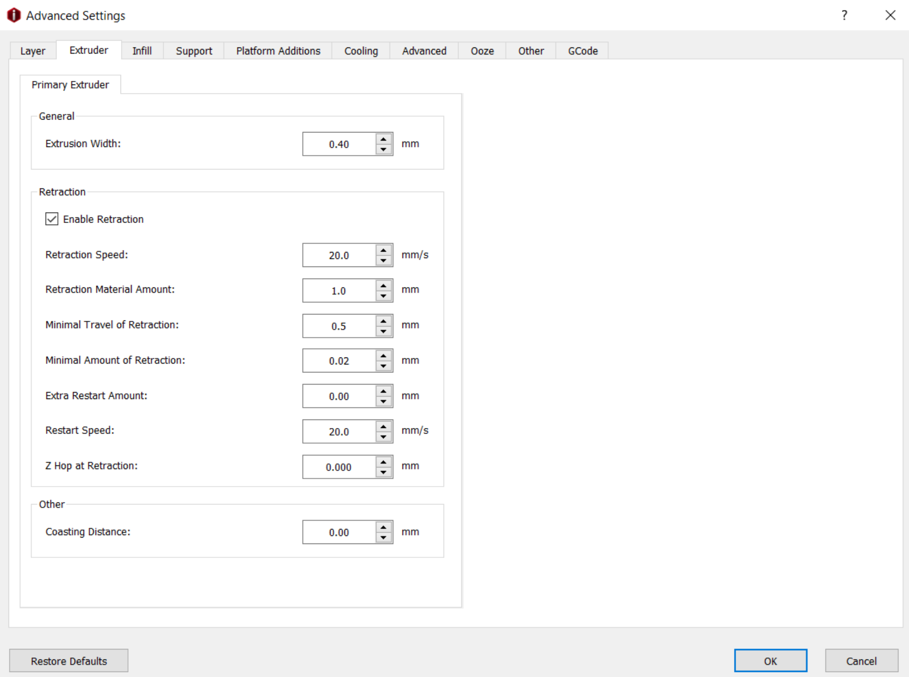
The software detects where supports are necessary and print settings can be adjusted of the supports separately to the main object. On this screen there is the option to build the supports with the primary or secondary extruder, this is because water soluble materials can be used to print supports on complex objects. This allows the supports to be completely removed by submerging in water, leaving no rough edges and from areas difficult to access otherwise. This was not necessary for this print but could be used for more complicated device designs.

The layer height determines the resolution of the object (screenshot 5). The higher (smaller number) the resolution the smoother the object. The higher the resolution the longer the print will take, this is because there will be more layers.



Screenshot 5 – Layer options in Ideamaker software.

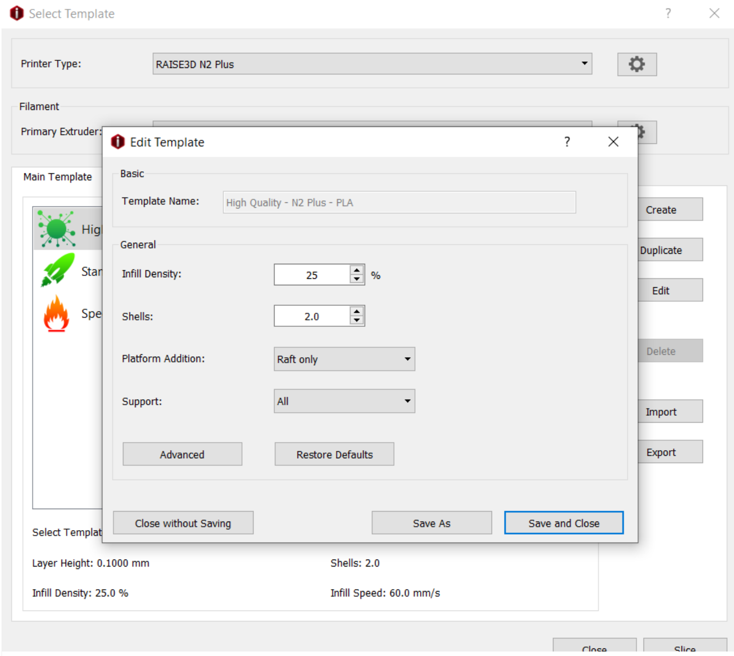
The extrusion width is determined by the physical nozzle on the printer. Again, the smaller the nozzle the longer the print will take but the higher the resolution will be. This is because with a larger nozzle, more material can physically fit through at once so less layers are required. The retraction speed is how fast and far the printer retracts the material when moving from one place to another, this prevents the molten plastic from stringing when the nozzle moves, however if it is too high it can cause problems when re-starting the print in a different area. The printer used has a 0.4mm nozzle, this is the



Screenshot 6 – Extruder options in Ideamaker software.

most common nozzle size, the smallest nozzle available is 0.1mm and the largest 1mm [114].

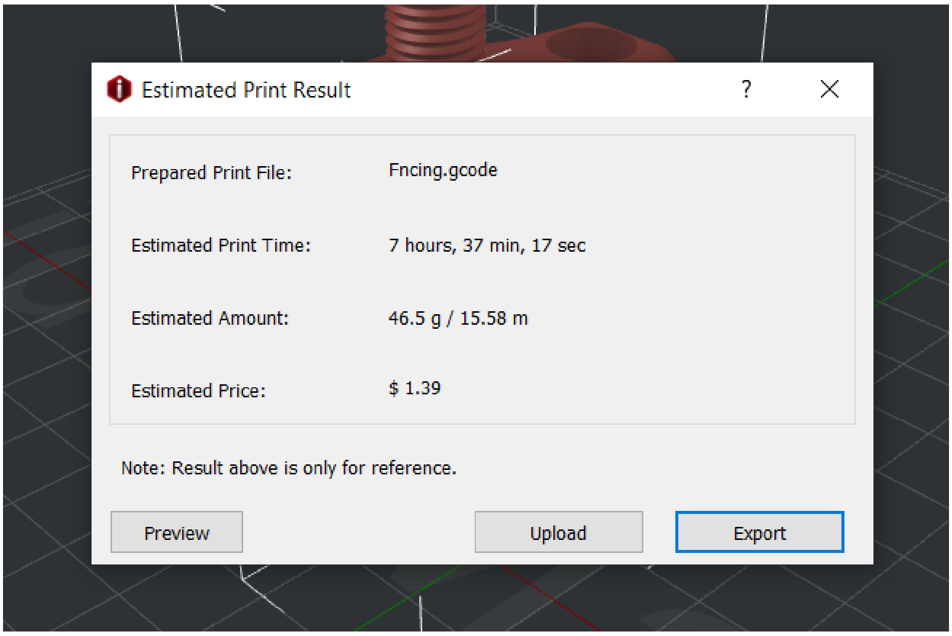
The infill density determines how much of the object is solid. The interior of the object is made in a squared pattern. This pattern differs depending on user choice, by default the most common patterns are hexagons, triangles and squares. The default infill is 10%, this print has been increased to 25% as this gives an even structure within the thread. When tested the thread was not strong enough when under the weight of the épée, the break was between layers, however, therefore increasing the infill is unlikely to prevent this (further discussed in chapter 5).



Screenshot 7 – Basic infill and raft options in ideamaker software.

The Raft is a sacrificial plate that is printed under the object. The raft ensures the material is flowing correctly before starting the object, it also guarantees a flat surface is achieved before printing the object. The orientation of this device allowed for a small raft area, this means only a small portion of the print time was spent constructing the sacrificial raft.

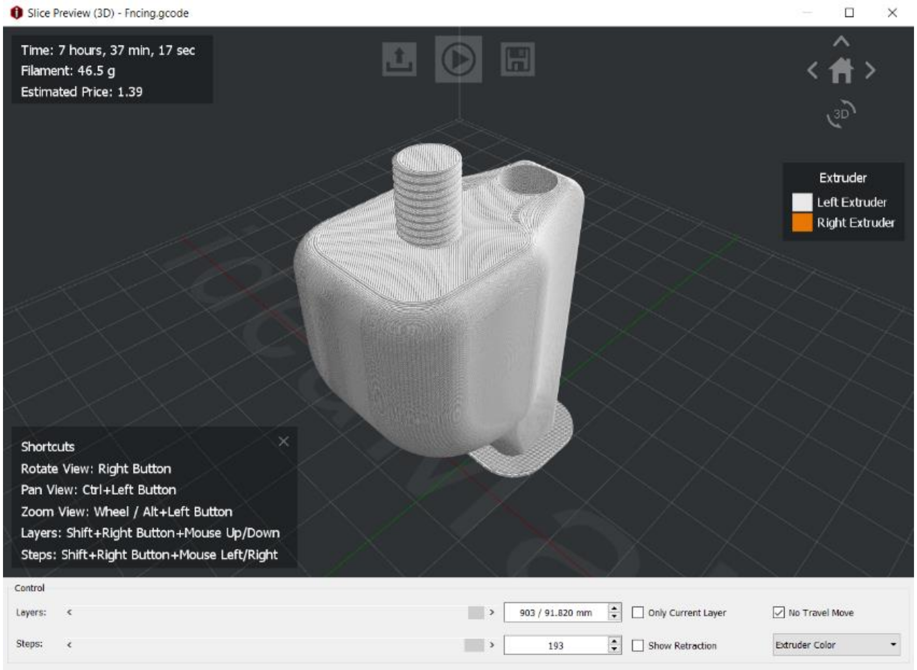
This print, though only a maximum of 40mm by 60mm by 90mm, took 7hours, 37minutes to print. This is an estimate and is generally about 10% under or over the actual print time. An estimated weight and price are also provided, this is calculated from average material prices (screenshot 8). This object uses PLA worth approximately £1.10 [115]. The Warrington FabLab [116] has donated the use of their 3D printer for this project, their usual price for use of the 3D printer is £2.50 an hour. This price includes PLA and electricity to run the machine. This device would cost a total of £18.75 for complete manufacture by this pricing. Anecdotal evidence states that a commercial body powered prosthesis could cost up to £4000. Even with price up for profit the price of the 3D printed device is considerably lower than currently available commercial terminal devices of this nature.



Screenshot 8 – Print file overview in Ideamaker software.

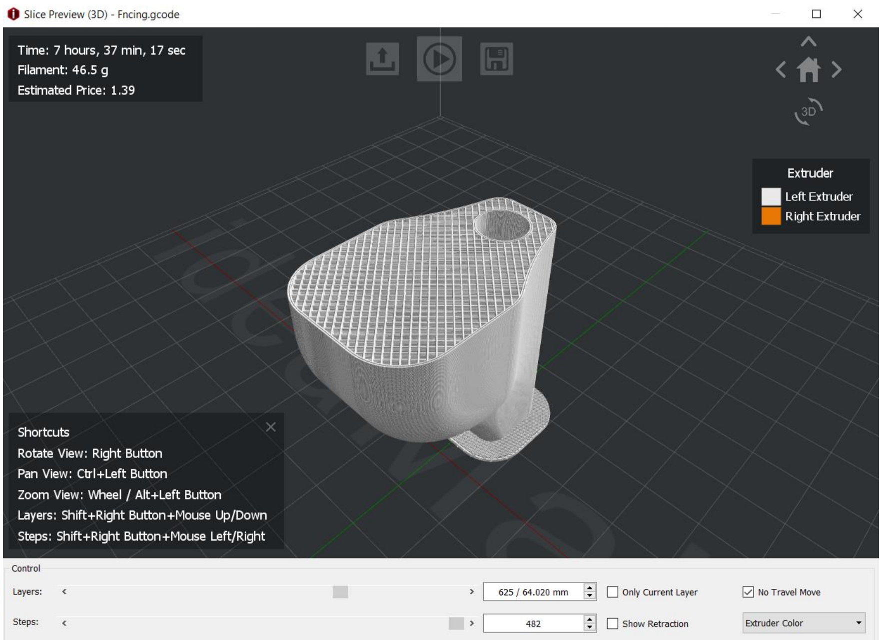
A preview of the object can be viewed before printing. This will show how the material will be layered, it will also show if and where supports will be added as well as any predicted abnormalities from the design that may not have become obvious so far

(screenshot 9). This shows no external supports, at this stage it is possible to add supports manually if there are worries that it will not successfully print, however the printer being used is capable of printing this shape. There were no obvious abnormalities at this stage. Unlike traditional manufacturing methods this allows for the inspection of the object before manufacture. At this stage it is quick and easy to fix any problems before manufacture.



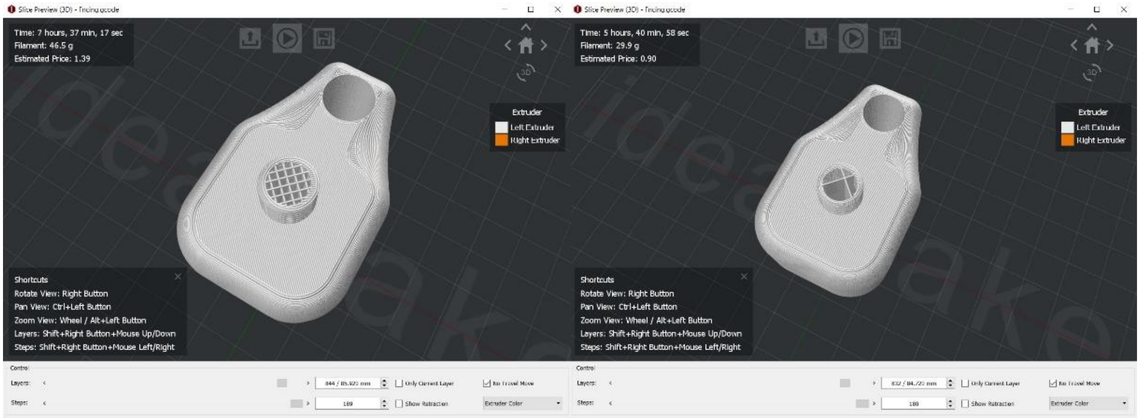
Screenshot 9 – Print preview of device in Ideamaker software.

In this preview the slider at the bottom allows the inspection of all layers and cross-sections of the object (screenshot 10). This allows inspection of parts that may normally be obscured from view and distribution of infill. The default infill is 10%, This allows for the printed object to be light but still retain its strength.



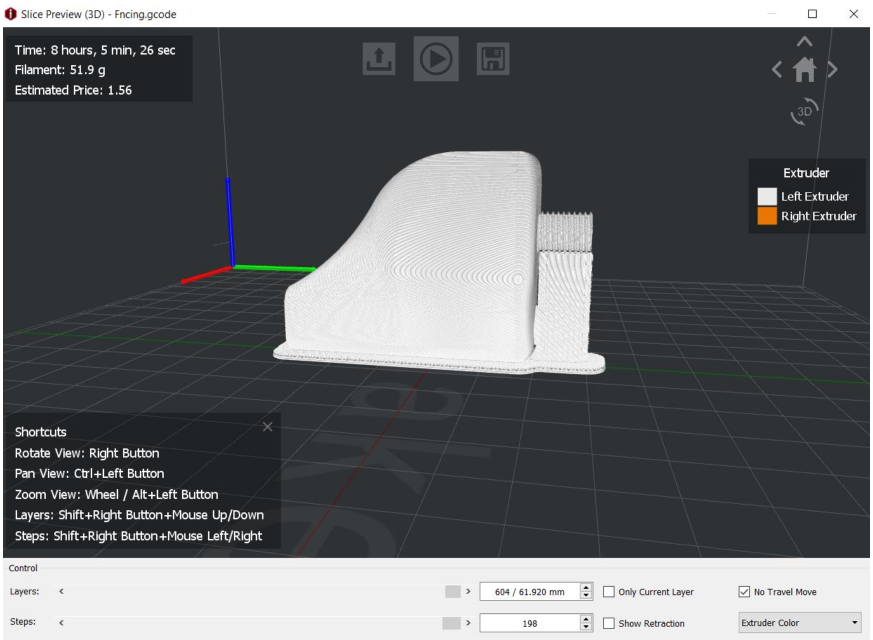
Screenshot 10 – Distribution of infill, 25% infill with square pattern in Ideamaker software.

The first slice of the device was set at the default 10% infill, the preview revieled the lack of infill in the thread and as a result it was decided to increase the infill to 25%. This provided an even infill in the thread without increasing the weight of the device significantly (screenshot 11).



Screenshot 11 – Distribution of infill in the thread at 25% infill (left) and 10% infill (right) in Ideamaker software.

The orientation of the object is important as the addition of supports may influence how the object has to be printed. If this object is oriented on it's flat edge supports are needed under the thread, these are unlikely to be able to be removed cleanly on such a sculpted edge and therefore the thread will be less effective or unuseable (screanshot 12). At this stage, with 25% infill it was believed that the thread would be strong enough.



Screenshot 12- Demonstration of supports in alternate configuration in Ideamaker software.

The orientation of the object can also affect the time it will take to print. If this object is on it's side, partialy due to the addition of supports, it will take an extra 30 minutes to print.

When on its end this object needs no supports as the gradient of the overhang is gradual enough that the printer can build out without supports and the thread is free to be made accurately.

Once the object is sliced, the file is exported as a GCode file with all the printer settings. This is loaded onto a memory stick or the computer is wired directly to the printer. Once the file is selected on the printer's touch screen display it only needs to be checked for errors every so often. The first few layers of the print are critical; it is important that it is checked to ensure the raft is adhering to the bed, the PLA is flowing and layering correctly. If any of these things is incorrect the print will have to be stopped and adjusted. If the bed or the extruder is not hot enough the raft will not adhere to the bed, if the extruder is too close to the bed the PLA will not flow and block the extruder, if the extruder is too hot the PLA will assume a liquid state and flow too fast, preventing the controlled layering of the print.

Once about a centimetre of the print is layered the printer can be left with only occasional checks as by this point any problems should have been spotted. The printer should heat the material to a molten, viscous state before extruding it through the nozzle. The nozzle is suspended over the heated bed and moved on the X and Y axis to create the object layer by layer. When each layer is complete the bed is moved down on the Z axis, in this case by 0.1mm each time, and the next layer is created.

Once the print is completed, the object is pulled off the heated bed. The raft peels off easily with the use of pliers and any small imperfections can be filed.

A2-6 – CAD in current prosthetics

Currently in clinical use are such CAD systems as the Omega Tracer CAD system [117]. These systems are designed specifically to create prosthetic sockets and orthoses in combination with a scanner or tracer and do not give the freedom to create from scratch, therefore this design would not be able to be created using this software.

Appendix 3 – Ethical approval

Health Research Ethical Approval Panel

Amendment Notification Form Please complete this form and submit it to the Health Research Ethics Panel that reviewed the original proposal: Health-ResearchEthics@Salford.ac.uk
Title of Project: An investigation into the validity of 3D printing as a method to produce upper limb sports prosthesis for specialised sports.
Name of Lead Applicant: Bronwyn Jones   *School:* School of Health Sciences
Date when original approval was obtained: 30-4-18   *Reference No:* **HSR1718-060**
Please outline the proposed changes to the project. ***NB.*** *If the changes require any amendments to the PIS, Consent Form(s) or recruitment material, then please submit these with this form highlighting where the changes have been made:* New version of interview guide, with prompts.
Please say whether the proposed changes present any new ethical issues or changes to ethical issues that were identified in the original ethics review, and provide details of how these will be addressed: The new version of the interview guide has been attached for approval.

Chair's Signature: 

Approved: 20-07-2018 ✓

Version 1.0 – 19 June 2017

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