Design of a Wearable Bilateral Exoskeleton for Stroke Treatment in a Home Environment

Orla Gilson

University of Leeds

School of Electronic and Electrical Engineering

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Intellectual Property Statement

The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others.

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Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ADL	Activities of Daily Living
BEAST	Bilateral Exoskeleton for Arm Stroke Treatment
CAD	Computer-Aided Design
CRP	Cable Routed Pulley
D-H	Denavit - Hartenberg
DDAO	Dynamic Differential Annealed Optimisation
DOF	Degree of Freedom
EMG	Electromyography
FMG	Force Myography
HRI	Human-Robot Interface
HOQ	House of Quality
HTM	Homogenous Transformation Matrix
I2C	Inter-Integrated Circuit
IMU	Inertial Measurement Unit
M2VIP	Mechatronics and Machine Vision in Practice
MHRA	Medicines and Healthcare Products Regulatory Agency
PC	Polycarbonate
PETG	Polyethylene Terephthalate Glycol
PLA	Polylactic Acid
PWM	Pulse Width Modulation
QFD	Quality Function Deployment
ROM	Range of Motion
SEA	Series Elastic Actuator
TRS	Tendon Routed Sheath

Chapter 1

Introduction

1.1 Background

Stroke is the fourth largest cause of death in the United Kingdom (UK) [1]. It is caused by the interruption of blood flow to the brain or parts of it. Survivors of a stroke can be left with varying levels of disability depending on the area of the brain affected and the length of time that the blood flow was stopped for. Strokes cause five main types of disability: paralysis or weakness in the muscles; disturbances in the senses; issues using or understanding language; difficulties with memory and thinking; and emotional disturbances [2]. The most common of these is paralysis or weakness in the muscles, usually in one side of the body, and can affect the arm, leg and/or face [2]. The side of the body that is affected by the weakness is known as the inactive side, with the unaffected side of the body being referred to as the active side.

There are currently over 1.2 million stroke survivors in the UK alone [3]. With 100,000 people suffering from a stroke every year, this number is only going to grow [3]. The methods used for rehabilitation after stroke therefore need to adapt to the growing number of patients. Rehabilitation has the most impact when begun as soon as the patient is stable; sometimes within 24 hours of the stroke occurring; with the best methods of rehabilitation being focused and repetitive movements [2].

Rehabilitation can potentially continue for many years after the initial stroke, making it a time consuming and expensive situation for many patients. As the nature of the disabilities caused by stroke often affects patient's movement, it can also be difficult for patients to reach the hospital or rehabilitation centre, with some incurring additional costs to travel to and from rehabilitation sessions.

1.2 Motivation

With such sharply rising numbers of people needing rehabilitation after stroke; it has become more important than ever to find a new approach to this issue. The main motivation behind this research is to increase not just the number of patients that can access rehabilitation, but also the speed in which they can access it, and the frequency they can use it. With the crucial point of stroke rehabilitation being within the first 24 hours, it is vital that therapists are able to interact with patients during this early stage. Being able to reduce therapists workload of existing patients would allow them to see more new patients without compromising on the care of those existing ones.

By introducing robotic rehabilitation in a home environment, the amount of time that therapists would need to spend with each patient could be dramatically reduced. Of course, this would need to be done in a manner that does not have a detrimental impact on a patients rehabilitation. The hope is that by creating an exoskeleton that can be used independently in a home environment; therapists would be able to remotely track patients progress, receiving updates and making adjustments to the training plan where appropriate.

One important factor of creating an exoskeleton for patient use, is the consideration of the needs of the patients and medical professionals involved in the rehabilitation process. Many of the existing devices are designed from an engineering perspective first, and redesigned after receiving medical perspective after clinical trials. These two perspectives need to both be taken into consideration at the beginning of the design stage for a more optimised device.

1.3 Aims & Objectives

The aims of this research are to design a wearable bilateral exoskeleton for stroke treatment in a home environment; investigate patient needs and how they affect the design of an exoskeleton; and to create an optimised design based on patient needs. This will be done through the following objectives:

- Research current literature to identify gaps in research.
- Design a novel bilateral exoskeleton for stroke rehabilitation in a home environment.
- Validate the design in both theoretical and practical ways.
- Design and carry out a patient needs survey with medical professionals and patients.
- Analyse survey results and use to create an optimisation algorithm for the exoskeleton design.

1.4 Contributions to Research

There are three main contributions to research laid out in this thesis, each of which aims to bring a novel concept to the use of exoskeletons in stroke rehabilitation.

1. Design of a novel cable-driven bilateral exoskeleton for the upper limb.
    - Consider current literature to identify gaps in research; wearable bilateral cable-actuated exoskeletons for use in the home, IMU bilateral sensing systems, and patient needs considerations during exoskeleton design.
    - Design a bilateral 7 DOF exoskeleton for the upper limb.
    - Validate the design using workspace analysis and test proof of concept through a prototype.
2. Investigation into the needs of stroke patients during rehabilitation.
    - Write two surveys focused on the use of exoskeletons within stroke rehabilitation.
    - Collect survey data from medical professionals and patients.
    - Analyse the collected data and use to create an optimisation strategy.
3. Optimise the exoskeleton design based on the patient needs data collected.
    - Carry out quality function deployment optimisation.
    - Carry out kinematic optimisation.
    - Determine changes to the exoskeleton design based on the optimisation.

1.5 Thesis Arrangement

This thesis consists of seven chapters, arranged in the order that the work has been completed. Following on from this introduction is the literature review chapter, where existing literature has been discussed and evaluated to ensure that the work done in this thesis is making relevant contributions to the field of rehabilitation robotics. Chapter 3 details the initial design process for the 7 DOF exoskeleton, with the validation process of this design laid out in Chapter 4. Chapter 5 outlines the process of designing the

patient needs based surveys, and the collection and analysis of the data. Chapter 6 illustrates how the survey data has been used within optimisation algorithms, and the resulting design changes. Finally, Chapter 7 draws the final conclusions and discusses potential further work.

Chapter 2

Literature Review

2.1 Introduction

One of the most important aspects of a new invention is the consideration of the existing literature. This section investigates the current exoskeletons, technology, and patient needs surveys that have been consulted during the search for novel ideas, as well as considering the background of stroke rehabilitation.

With over 100,000 people suffering from a stroke every year and 38,000 deaths, it is a leading cause of death and disability in the UK [1]. Due to this, the number of new and existing patients that require access to physiotherapy is growing rapidly. There are currently 1.2 million stroke survivors in the UK, with two thirds of them leaving hospital with a disability [1]. This leads to an estimated cost of £26 billion a year; and with the average age of someone having a stroke decreasing, and the survival rate after stroke increasing; this number is only going to increase [1]. It is suggested that the number of stroke survivors living with a disability will increase by a third by the year 2035 [1]. With such a large increase in patients requiring care after stroke, rehabilitation will need to adapt in order for patients to continue receiving a high calibre of care.

Robotics could make physiotherapy more accessible to these patients for a variety of reasons. When used in a hospital environment robotic devices could allow physiotherapists to oversee several patients at the same time. Each device would be set up for a patients specific needs, allowing them to run through a series of exercises that are relevant to their stage of rehabilitation. The physiotherapist could then check in at intervals but would not need to be supervising the patients every move. A robotic device would also be capable of measuring and tracking a patients movements and then presenting their progress in a quantitative manner. Exercises would not only be more consistent when using an exoskeleton, but more accurate in their movements as well.

Many robotic devices currently exist to help with rehabilitation after stroke. Some of these devices focus on a single joint while others include several joints, though the majority of them are limited to either the upper or lower limb rather than the whole body. The rest of this chapter discusses a lot of these exoskeletons, from their overall use to more specific aspects of their design such as their actuation and sensing systems.

2.2 Evolution of Upper Limb Rehabilitation

Traditional rehabilitation has always been manually carried out by physiotherapists. Still used today, it is an effective method of rehabilitation, although it does have its drawbacks; physiotherapists are only able to work with a single patient at a time; there is no way of measuring improvements in a quantitative way; and no measure of consistency over patients. This can lead to less effective rehabilitation. Traditional therapy sessions therefore have some room for improvement. This is where robotic rehabilitation methods could help.

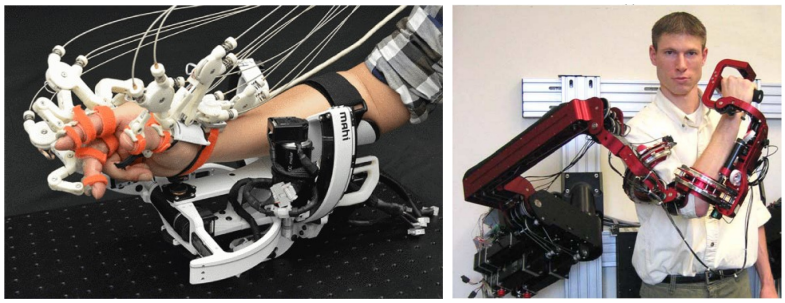
The first types of robotic rehabilitation devices invented were end effector robots. These types of robot use a single point of contact between the human and the robot. They use the end effector to position the rest of the upper limb through movement of the patients hand. They move mainly in the horizontal plane on a tabletop and are therefore most effective at rehabilitating the wrist and the elbow. End effector robots are grounded with a base that anchors them to the floor in front of the user. This allows for the use of heavy or bulky actuation systems. These end effector robots are simple to design and manufacture as the joints of the robot are not required to match the joints of the human user. No adjustment is required from one user to the next, and they can therefore be seen as a universal solution to rehabilitation.

The issue with a universal solution is that not all patients have the same needs. Patients that have suffered from a stroke are very unlikely to have the same rehabilitation requirements. This means that a more personal solution is required, and this is where exoskeletons have started to replace end effector devices. Exoskeletons have a higher complexity and are more difficult to manufacture, but are capable of more effective treatment methods. The complexity of exoskeletons stems from the need for them to be attached directly to the limb, where the joint axes of the human limb must align with the joint axes of the robot exoskeleton. If the joint axes of the exoskeleton do not match with that of the human user, injuries are likely to happen as the workspace of the exoskeleton may end up outside of the natural workspace of the human arm. Despite this, exoskeletons are more favourable due to their ability to individually control each joint of the exoskeleton; therefore allowing more exact and controlled movements. They also include movement of the shoulder and hand into rehabilitation exercises as they can be independently controlled. Exoskeletons allow for a larger range of movement over more joints and can be made more compact than end effector robots, especially if they

Table 2.1: Unilateral Exoskeletons

Exoskeleton	Joints	DOFs	Type	Actuation
HandSOME II [4]	Hand	15	Wearable	Elastic Springs
Graspy Glove [5]	Hand	4	Wearable	Cables
Soft Robotic Glove [6]	Hand	-	Wearable	Soft Pneumatics
Rutgers Master II [7]	Hand	20	Wearable	Pneumatics
CAFE [8]	Hand	3	Wearable	Cables
SafeGlove [9]	Hand	18	Wearable	Cables
ArmAssist [10]	Hand & Wrist	3	Grounded	Springs
SCRIPTPassive [11]	Hand & Wrist	6	Wearable	Leaf Springs
OpenWrist [12]	Hand, Wrist & Forearm	3	Grounded	Cables
Upper-Limb Robot [13]	Hand, Wrist & Elbow	3	Grounded	DC Motors
Wearable Device [14]	Forearm, Elbow & Shoulder	5	Wearable	Cables
Wrist Rehab Device [15]	Wrist	-	Wearable	Soft Pneumatics
e-Wrist [16]	Wrist	1	Wearable	DC Motors
Wrist Gimbal [17]	Wrist & Forearm	3	Grounded	Cables
RiceWrist-S [18]	Wrist & Forearm	3	Grounded	DC Motors & Cables
EFW-Exo II [19]	Wrist, Forearm & Elbow	4	Grounded	DC Motors
MAHI [20]	Wrist & Elbow	5	Grounded	Linear
Upper-Limb Device [21]	Wrist & Elbow	3	Wearable	DC Motors
4 DOF Exo [22]	Wrist & Elbow	4	Grounded	DC Motors
(CADEN)-7 [23]	Wrist, Elbow & Shoulder	7	Grounded	Cables
ChARMin [24]	Wrist, Elbow & Shoulder	6	Grounded	DC Motors
CAREX-7 [25–27]	Wrist, Elbow & Shoulder	7	Grounded	Cables
NEUROExos [28, 29]	Elbow	4	Grounded	Hydraulic Cables
AVSER [30]	Elbow	1	Grounded	SEA
Elbow Rehab Device [31]	Elbow	1	Wearable	Linear SEA
NESM [32]	Elbow & Shoulder	4	Grounded	DC Motors
LIGHTarm [33]	Elbow & Shoulder	5	Grounded	DC Motors
LIMPACT [34]	Elbow & Shoulder	4	Grounded	Hydraulics
5 DOF Exo [35]	Elbow & Shoulder	5	Grounded	DC Motors
Parallel Actuated Exo [36]	Shoulder	2	Grounded	SEA
Shoulder Elevation Device [37]	Shoulder	1	Grounded	Pneumatics
Shoulder Rehab Device [38]	Shoulder	6	Grounded	Linear
Novel Shoulder Exo [39]	Shoulder	4	Grounded	DC Motors

are ungrounded. Ungrounded, or wearable, robots are attached solely to the patient, and so allow the user to move around a space during exercises. They require light, compact actuation systems to ensure they do not inhibit the user's movement. This is in comparison to grounded exoskeletons, where the device is stabilised on the floor of the treatment room, preventing travel during use. Figure 2.1 shows two grounded exoskeletons; OpenWrist [12], and (CADEN)-7 [23].



(a) OpenWrist [12] (b) (CADEN)-7 [23]

Figure 2.1: Grounded Exoskeletons

When exoskeletons were first introduced, they all used a unilateral training method. This training method focused on moving only the inactive arm with the exoskeleton, using similar exercises to traditional physiotherapy. Table 2.1 shows the unilateral exoskeletons that were found during the literature review. It outlines the joints, DOFs, type of actuation and whether the device is grounded or wearable.

Research has expanded further with the introduction of bilateral training methods, where both arms are involved in the rehabilitation process. Most of the existing exoskeletons used in bilateral training have been initially designed as a unilateral exoskeleton, with further work being done to convert them for use in bilateral training. In many cases this involved simply adding sensors to the active limb in order to track its movements so that the inactive limb could follow the same trajectory.

2.3 Principles of Bilateral Training

Bilateral training has become more popular in recent years, and is accepted by researchers as an effective method of rehabilitation [40][41]. It is carried out by using both the inactive and active limb, completing either symmetrical or cooperative exer-

cises. The movement of the active limb is used to control the movement of the inactive limb, allowing patients to actively participate in their own rehabilitation from the very beginning. Bilateral training has more of a focus on carrying out exercises that mirror the ADLs, the majority of which require the cooperation of both of a person's upper limbs.

There are six main ADLs; feeding, bathing, dressing, grooming, toileting, and walking/transferring [1]. Some of these activities only require the use of one arm, but many of them require the use of two arms. For example, feeding oneself may only require one arm to actually eat something, but two arms would be needed when preparing food. Both arms would need to work in cooperation while carrying out separate tasks, such as one hand holding a piece of food while the other chops it. The ADLs are the benchmark for patients being able to live independently after a stroke.

Bilateral training can be carried out in a variety of different ways. It can be either symmetrical or cooperative. Symmetric movements consist of the two upper limbs moving in the same way. This can be through mirroring, where the arms would both move inwards/outwards from the centre of the body; or through shadowing, where the arms would both move to the left or right. Cooperative movement involves both arms moving completely independently from each other to complete a task; a type of movement that is much more common in everyday life. It is likely that cooperative exercises would be much more effective in stroke rehabilitation, but is very difficult to implement with robotic devices. Figure 2.2 shows the Omega.7 system using a virtual reality (VR) system, one of the only types of bilateral devices that is capable of cooperative exercises [42].

When a stroke occurs, it can sometimes affect a person's dominant side. This can make rehabilitation more difficult, as actions that were previously carried out single-handedly may now require the use of both arms. Waller and Whitall explain that this is a justification for the use of bilateral training within rehabilitation [43]. A person's dominant arm carries out the majority of single-handed tasks such as writing, and pouring drinks. Although most people would be able to do these tasks with the non-dominant arm, the movements are likely to be more unstable and take longer to carry out. If the dominant arm is affected by stroke, the patient is likely to find recovery more difficult as they are relying on the non-dominant arm to take over these tasks; a process that requires a large amount of re-learning [43]. When the non-dominant arm

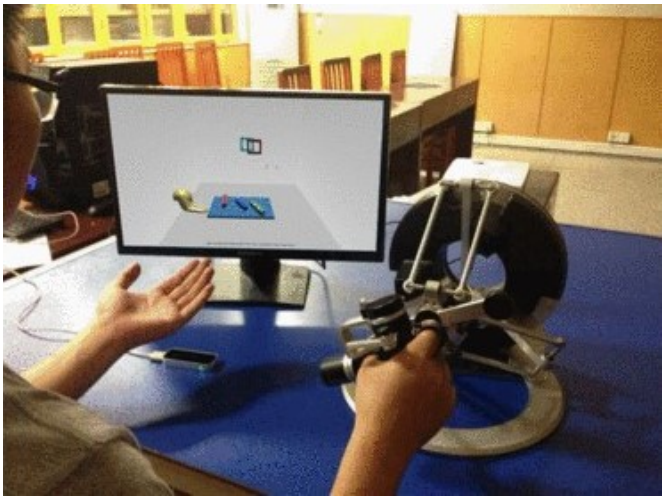


Figure 2.2: Virtual Reality System With the Omega.7 [42]

is affected by stroke, the patient can still carry out a large number of tasks as they did prior to the stroke [43]. Unilateral training could still be an effective method of treatment in this case, whereas bilateral training is more likely to be effective when the dominant arm has been affected. This is because the patient is more likely to use both arms in cooperation to carry out tasks that they might previously have done single-handedly [43].

2.4 Recent Advancements in Exoskeleton Design

When considering the design of an exoskeleton, several aspects must be taken into consideration. The environment that the exoskeleton is going to be used in; the ability to store the exoskeleton if necessary; and how the patient may don and doff the exoskeleton are all considerations that need to be made. Regardless of what design decisions are made, the exoskeleton must be able to adjust to each user's individual needs and requirements; particularly being able to fit any patient regardless of size or side of the body affected by stroke. The aim of all these considerations is to make the device accessible to as many patients as possible.

The human arm consists of four main joints; the shoulder, elbow, wrist, and hand (where the hand includes all of the individual finger joints). It is important to consider not only how these joints need to be rehabilitated, but also the mechanics behind how

Table 2.2: Bilateral Exoskeletons

Exoskeleton	Joints	DOF	Actuation	Environment	Device	Type	Bilateral Sensing
BRAVO [44, 45]	Hand	2	DC Motors	Hospital	Wearable	Symmetric	EMG
Fabric Based Glove [46]	Hand	-	Soft Pneumatics	Home/Hospital	Wearable	Symmetric	Flex Sensors
Hand-Assist Robot [47]	Hand	18	DC Motors	Hospital	Grounded	Symmetric	CyberGlove Motion Sensor (VR)
CyberGrasp [48]	Hand	5	Cables	Hospital	Grounded	Symmetric	CyberGlove (VR)
RobHand [49]	Hand	5	Linear Actuators	Home/Hospital	Grounded	Symmetric	EMG
Robotics Assisted Device [50]	Hand & Wrist	2	AC Motors	Hospital	Grounded	Symmetric	Two Exoskeletons
Wrist Device [51]	Wrist	2	DC Motors	Hospital	Grounded	Symmetric	Two Exoskeletons
ULERD [52–55]	Wrist, Forearm & Elbow	3	DC Motors	Home/Hospital	Grounded	Symmetric	Phantom Premium
EXO-UL7/8 [56, 57]	Wrist, Elbow & Shoulder	7	Cables	Hospital	Grounded	Symmetric	Two Exoskeletons (CADEN-(7)[23])
Harmony [58, 59]	Wrist, Elbow & Shoulder	7	SEA	Hospital	Grounded	Symmetric	Two Exoskeletons
BLUE SABINO [60]	Wrist, Forearm, Elbow & Shoulder	5	DC Motors	Hospital	Grounded	-	-
Forearm Device [61]	Forearm	1	DC Motors	Hospital	Grounded	Symmetric	FMG
NTUH-II [62]	Forearm, Elbow & Shoulder	8	DC Motors	Hospital	Grounded	Symmetric	IMU
RECUPERA [63]	Forearm, Elbow & Shoulder	6	DC Motors SEA	Hospital	Grounded	Symmetric	Two Exoskeletons
ARAMIS [64, 65]	Forearm, Elbow & Shoulder	6	DC Motors	Hospital	Grounded	Symmetric	Two Exoskeletons
Elbow Device [66]	Elbow	3	SEA	Hospital	Grounded	Symmetric	Phantom Premium
BWRD [67]	Elbow	1	DC Motors	Hospital	Wearable	Symmetric	Two Exoskeletons
Master-Slave Device [68]	Elbow	1	Soft Pneumatics	Hospital	Wearable	Symmetric	Two Exoskeletons
PVSED [69–71]	Elbow & Shoulder	4	Cables	Home	Wearable	Symmetric	sEMG
Continuum Exoskeleton [72]	Shoulder	3	Soft Pneumatics	Hospital	Wearable	Symmetric	Two Exoskeletons

they move.

Using the biomechanics of the human arm, a workspace can be defined. This workspace is the area in which the human arm moves. The exoskeleton design must match this, and at no point limit or extend it. Limiting the workspace can lead to ineffective rehabilitation, while extending the workspace can lead to injury for the user. One of the other considerations within workspaces, is the possibility of singularities occurring. Singularities occur when the end effector doesn't move despite the movements made in the other joints. One method of moving a singularity outside of the workspace is to add passive joints to the exoskeleton. These passive joints are unactuated, and simply allow for extra movements within the workspace. A passive DOF is one that does not affect the relationship between the input and the output motion of the system [73] These passive joints can also be used in the actuation of the shoulder joint. This is due to the movement of the glenohumeral joint. As seen in Figure 2.3, as the arm raises above the head, the centre of the glenohumeral joint rises above it's original position. A passive joint can allow this movement to happen naturally.

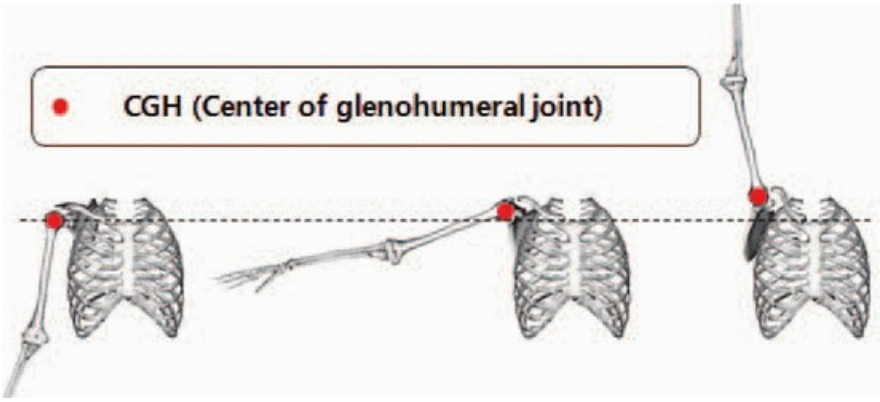


Figure 2.3: Movement of the glenohumeral joint [38]

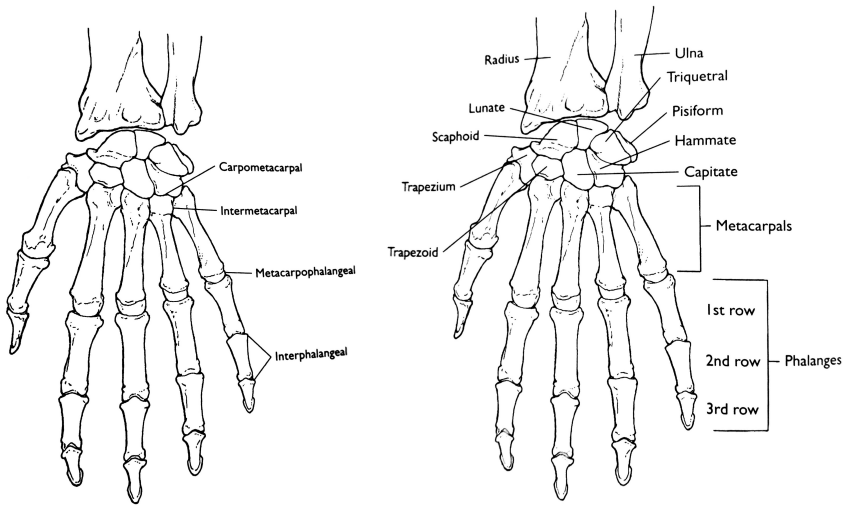
2.5 Biomechanics

Human biomechanics are an important factor to consider when designing an exoskeleton. This is due to the joints of the exoskeleton needing to match up with the joints of the human body. Joints that are not in line with each other can cause the range of motion of the exoskeleton to be severely reduced, or the patient can become injured

during unnatural movements. This section covers the bones of the upper limb, and the muscles that work to move those bones. Although covering the biomechanics of the upper limb in such depth is not entirely essential, it can be useful to know how the muscles in the arm are interacting through different movements. It can also help to ensure that none of the muscles needed for particular movements are impeded by the placement of the exoskeleton, particularly in the shoulder region.

2.5.1 Hand and Wrist

The hand is a complex system with many bones and muscles in a very small space. The carpometacarpal and intermetacarpal joints are gliding joints, except for in the thumb where the joint is a saddle joint[74][75]. It acts more like a ball and socket joint, allowing the thumb a large range of movement, while the rest of the fingers are more constricted by ligaments[74][75]. The metacarpophalangeal joints are condyloid joints, allowing for flexion, extension, abduction and adduction of the fingers[74][75]. The thumb is restricted to a hinge joint motion, as the bones are relatively flat and therefore only allow for flexion and extension[74][75]. Lastly, the interphalangeal joints are hinge joints, allowing for flexion and extension[74][75]. Figure 2.4(a) shows the bones of the hand. The hand has many muscles, 9 extrinsic ones and 10 intrinsic ones that are all used in various combinations to allow for the movements of the fingers[74][75].



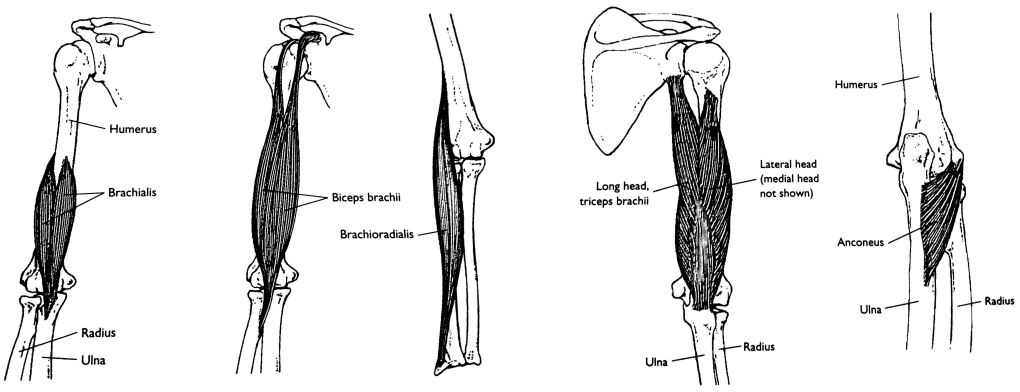
(a) Fingers (b) Wrist

Figure 2.4: Bones of the hand and wrist [74]

The wrist consists of the carpal bones of the hand, and the ulna and radius bones of the forearm[74][75]. It only has one joint, the radiocarpal joint[74][75]. The radiocarpal joint is a condyloid joint where the radius meets the carpal bones[74][75]. The wrist is capable of two main sets of movements; flexion and extension, and ulnar and radial deviation[74][75]. Flexion is controlled by the carpi radialis and the carpi ulnaris flexors[74][75]. Extension happens when the carpi radialis longus, carpi radialis brevis, and the carpi ulnaris extensors work together[74][75]. Ulnar and radial deviation is controlled by a combination of the flexor and extensor muscles [74][75]. Figure 2.4 shows the bones of the hand and the wrist.

2.5.2 Elbow

The elbow consists of three separate joints. The main joint of the elbow is the ulnohumeral joint; a hinge joint that allows for flexion and extension [74][75]. Adjacent to this is the radiohumeral joint; a gliding joint restricted by the proximity of the ulnohumeral joint [74][75]. The third joint is the proximal radioulnar joint; a pivot joint that allows for pronation and supination of the forearm, as the radius rolls over the ulna [74][75]. Flexion is controlled primarily by the brachialis, but also by the brachioradialis and the biceps brachii [74][75]. The triceps are the main extensor muscles, with assistance from the anconeus muscle [74][75]. The pronator quadratus muscle is responsible for pronation of the forearm, with the supinator responsible for supination [74][75]. Figure 2.5 shows the flexors and extensors of the elbow.



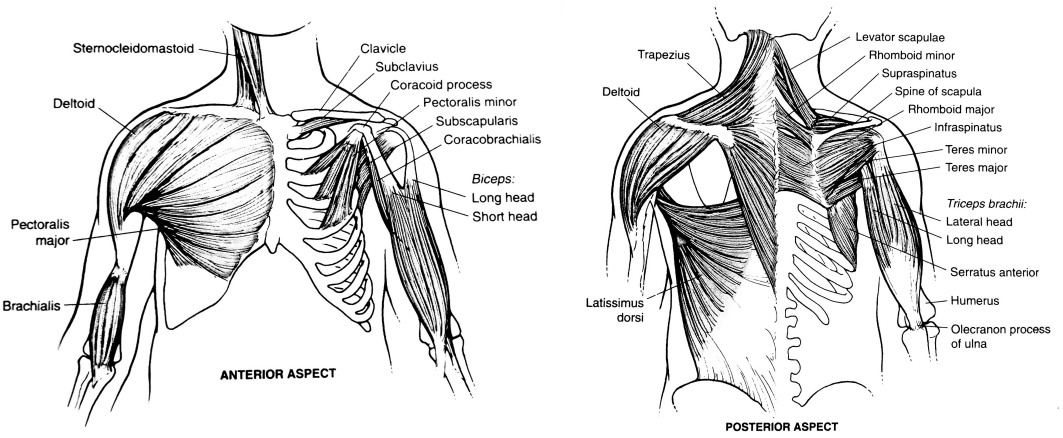
(a) Elbow flexor muscles

(b) Elbow extensor muscles

Figure 2.5: Muscles of the elbow [74]

2.5.3 Shoulder

The shoulder is the most complex joint of the upper limb, being made up of five individual joints; the sternoclavicular, acromioclavicular, coraclavicular, glenohumeral and scapulothoracic joints [74][75]. The sternoclavicular and acromioclavicular joints allow for rotation of the shoulder from the proximal and distal ends of the clavicle respectively [74][75]. The coraclavicular joint allows for little movement as it is made up of the ligament that binds the clavicle and scapula together [74][75]. The scapulothoracic joint is made up of mainly ligaments, and no bone [74][75]. It allows the shoulder joint to have a larger range of motion, as well as stabilising the shoulder during movement [74][75].



(a) Muscles of the anterior shoulder

(b) Muscles of the posterior shoulder

Figure 2.6: Muscles of the shoulder [75]

The main joint of the shoulder is the glenohumeral joint; a ball and socket joint that is the most freely moving joint in the entire human body [74][75]. It allows for flexion and extension, abduction and adduction, and horizontal abduction and adduction [74][75]. Flexion in the shoulder is controlled by the clavicular pectoralis major, the anterior deltoid, and the coracobrachialis [74][75]. Extension is controlled by the sternal pectoralis major, the latissimus dorsi, and the teres major [74][75]. Flexion is the movement of the shoulder that swings the arm forwards from a starting position next to the body. Extension swings the arm backwards from the same position. With a starting position of the arm up away from the body, abduction brings the arm further

upwards back towards the head, and adduction brings the arm back to rest against the body. Horizontal abduction brings the arm across the body, and horizontal adduction brings the arm backwards. Abduction is controlled by the middle deltoid and the supraspinatus; adduction by the sternal pectoralis major, latissimus dorsi, and the teres major [74][75]. Horizontal abduction is controlled by the pectoralis major, the anterior deltoid, and the coracobrachialis [74][75]. Horizontal adduction uses the middle and posterior deltoid, the infraspinatus, and the teres minor [74][75]. The shoulder joint is also responsible for the medial and lateral rotation of the humerus [74][75]. The humerus rotates inward when the subscapularis and the teres major work; with the infraspinatus and teres minor being responsible for outward rotation [74][75]. Although many of the movements of the shoulder involve the same muscles, they are used in different combinations allowing a large range of movement. Figure 2.6 shows the muscles of the shoulder, from both the anterior and posterior angles.

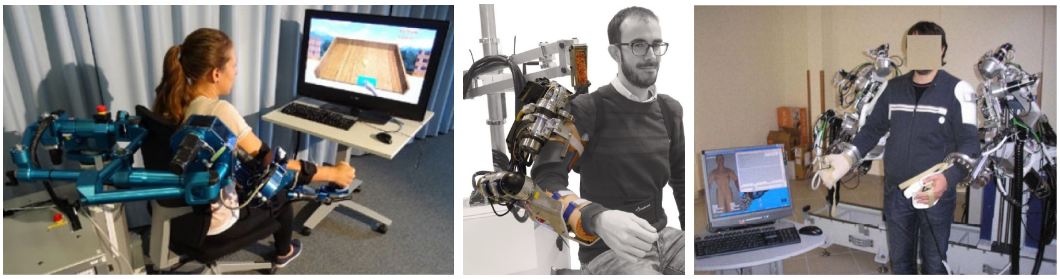
2.6 Actuation

There are many different type of actuation used in exoskeleton designs. Generally it does not matter if the exoskeleton uses unilateral or bilateral training; the actuation systems used are the same. Some of the more common types of actuation include direct current (DC) motors, pneumatics and hydraulics. These base designs have been adjusted and added to in order to create better actuation systems.

DC motors at their simplest are placed directly at the joint of the exoskeleton. Sometimes they also use a separate gearbox to increase the amount of torque that the motor can provide. DC motors are most often used in grounded exoskeletons such as EFW-Exo II [19], ULERD [52–55], and NTUH-II [62]. This is because the motors that are capable of providing the amount of torque required for an exoskeleton system, particularly at the shoulder joint, are large and heavy. They are also expensive, which leads to them being used in hospital-based systems, as seen in Figure 2.7.

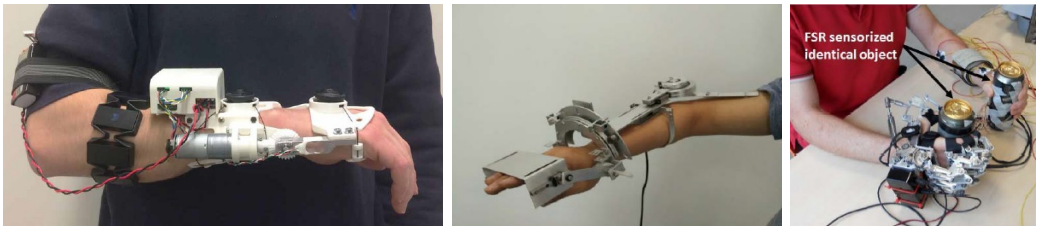
There are a small number of wearable exoskeletons that use DC motors directly at the joint. As can be seen in Figure 2.8, these wearable systems are hand and wrist exoskeletons. They need very little torque compared to the shoulder and elbow; so the motors required are much smaller, lighter, and less expensive.

DC motors are also used to power cable systems and series elastic actuators (SEAs). Cable systems have lots of pros in their designs when compared to DC motors. They



(a) ChARMin [24] (b) NESM [32] (c) ARAMIS [64]

Figure 2.7: Grounded Exoskeletons Powered by DC Motors



(a) e-Wrist [16] (b) Upper Limb Device [21] (c) BRAVO [44]

Figure 2.8: Wearable Exoskeletons Powered by DC Motors

are more efficient, capable of backdrivability, good for space-limited applications, and flexible [76]. They can also transmit loads over long distances without the friction or backlash that can come with the use of gears [76]. Cable systems do however come with added complexity and a need for additional mechanical parts [76]. There are two categories of cable actuation; cable-routed pulley (CRP), and tendon-routed sheath (TRS) systems [76]. CRPs can be either open-ended cables or endless cables, and TRSs can be Bowden cables or push-pull cables. Diagrams of each of these configurations can be seen in Figure 2.9.

The most popular cable system in literature seems to be open-ended CRP systems, with two cables used for each exoskeleton joint. The type of open-ended cables that tend to be used in exoskeletons can only 'pull' as they use a single actuator. Therefore each joint needs two motors and two cables, one to actuate the joint in each direction. It consists of a pulley at the motor, with the cable attached to a fixed point at the other end [76]. As the motor turns the pulley the cable is wrapped around the pulley, pulling the fixed end closer to the motor. The second motor would rotate in the opposite

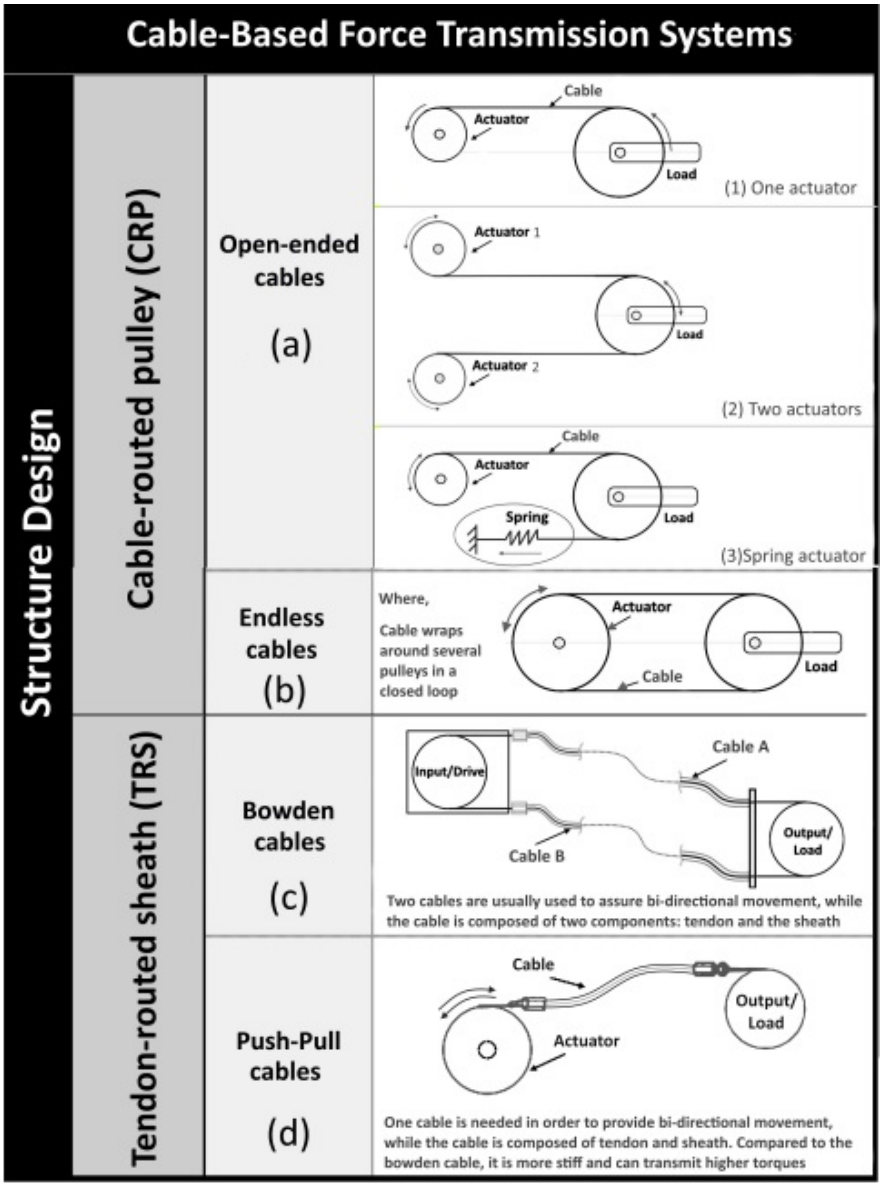
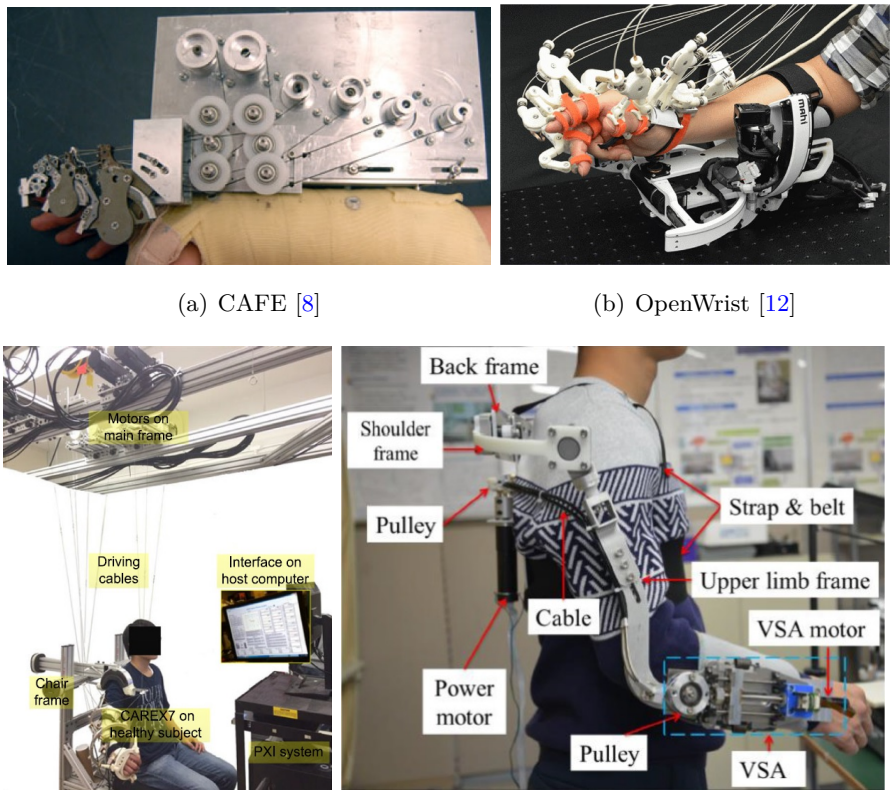


Figure 2.9: Types of Cable Actuation [76]

direction to release the cable on the other side of the joint. If the second motor did not rotate to uncoil the cable, the first motor would not be able to shorten the cable and the joint would not move. Endless cables only use a single actuator and cable, with a pulley on either end [76]. As the motor drives one of the pulleys the cable rotates the second pulley at the joint end. Endless cables are capable of bidirectional movement so



(a) CAFE [8] (b) OpenWrist [12]

(c) CAREX-7 [27] (d) PVSED [71]

Figure 2.10: Cable Actuated Exoskeletons

only need a single actuator for each joint. CRP systems must always be in tension in order to transmit force from the actuator to the joint by sliding over the pulleys [76]. They have higher forces than TRS systems as they have less friction, which leads to more predictable control of the cable movement; however they are also more complex and bulkier [76].

TRS systems use a stiff cable or 'tendon' that runs through the centre of a hollow wire coil or 'sheath' [76]. Force is transmitted from one end of the cable to the other as it slides through the sheath [76]. Due to the use of the sheath, TRS cables can be used in more restricted spaces and across longer distances than CRP systems [76]. There are two different kinds of TRS systems, Bowden cables and push-pull cables. Two Bowden cables would be required to allow bidirectional movement, with each cable creating each direction of movement as Bowden cables are not capable of 'pushing', only 'pulling'. Push-pull cables only require a single cable to create both directions of movement. This

is because they are stiffer and can transmit higher torques [76].

Figure 2.10 shows a number of cable actuated exoskeletons. All of the systems shown use a variation of a CRP system. There were no exoskeletons identified in literature that use TRS cables powered by a DC motor.

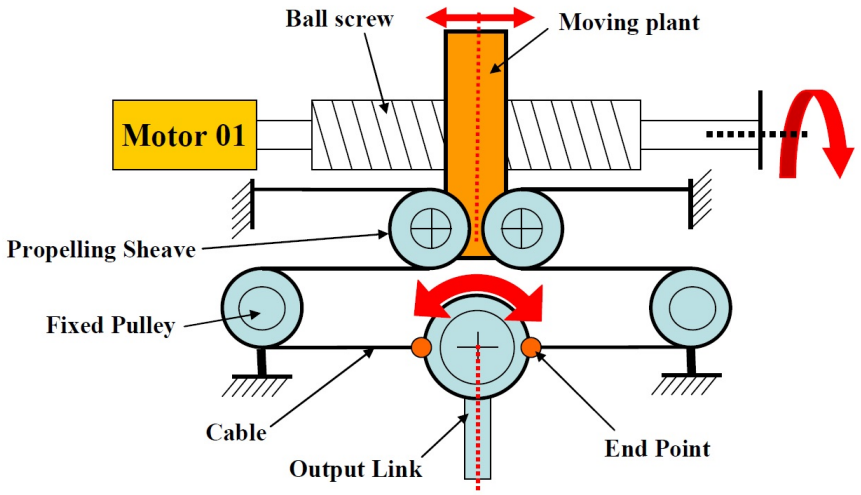


Figure 2.11: Diagram of the SEA used in the AVSER exoskeleton [30]

SEAs also use DC motors, and similar to cable systems, were designed to move the weight of the actuation units away from the joint of the exoskeleton and closer to the trunk of the user. Figure 2.11 shows the design of a SEA joint used in the AVSER exoskeleton [30]. The DC motor rotates, turning a ball screw, which causes the moving plant attached to it to move from side to side. As the plant moves, the cables on either side lengthen and shorten as the propelling sheaves move, turning the pulleys and rotating the output link. Although compact, SEAs can be fairly bulky, especially when placed directly on the joint of the exoskeleton.

Traditional hydraulic and pneumatic systems can be bulky and require an external water or air reserve; therefore these robots are generally only used in hospital settings as grounded systems. Hydraulics have been largely ignored as an option for exoskeletons as the water adds extra weight and requires extra safeguards to prevent leakages during use. NEUROExos was the only exoskeleton that was found in literature that uses hydraulics as a way of powering a cable system, as can be seen in Figure 2.12 [28, 29]. Pneumatic systems were originally used in a similar way to this hydraulic system. By increasing or decreasing the air pressure in a cylinder, the piston inside

the cylinder is displaced, creating linear movement which can then be converted to rotational movement through the use of gears. A device for shoulder elevation uses a pneumatic cylinder system that directly moves the joint [37]. Both of these hydraulic and pneumatic systems require external water and air reserves.

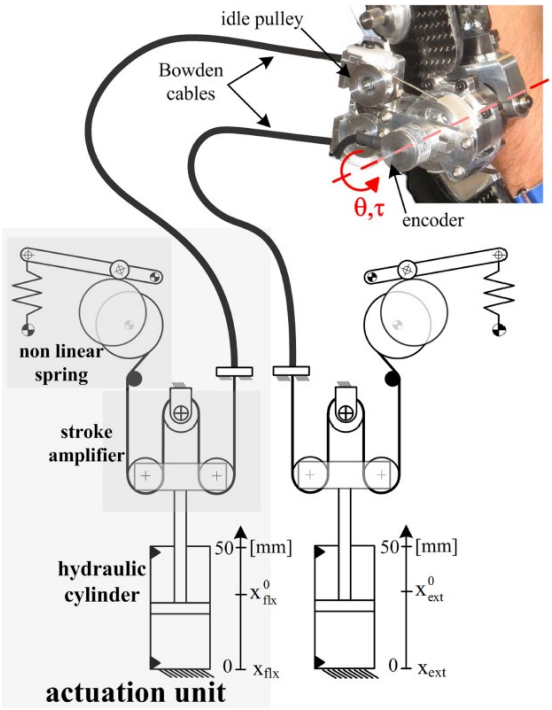


Figure 2.12: NEUROExos Joint Hydraulic Actuation System [28]

Pneumatics are now also being used in soft robotics. These systems provide actuation by controlling the direction that an artificial muscle inflates in. Pneumatic muscles have been developed for use in many different exoskeletons. Soft pneumatic muscles have been used for actuating several different joints of the upper limb, from the hand [6][46], to the wrist [15], to the elbow [68]. They are usually designed for a specific exoskeleton and so each design is different. Figure 2.13 shows two pneumatic muscles that are both used for flexion. 2.13(a) used for finger flexion, while 2.13(b) is used for wrist flexion. Actuation is controlled by increasing or decreasing the air pressure inside of the muscle. This change in pressure affects the shape of the muscle, depending on how it has been designed. Soft pneumatics have the advantage of being flexible and lightweight, but are not commercially available. Although cheap and simple to manufacture, testing is vital to ensure that the muscle works exactly as desired for

(a) Finger Flexion Muscle [6] (b) Wrist Flexion Muscle [15]

Figure 2.13: Soft Pneumatic Actuated Exoskeletons

its particular purpose; with several iterations often being necessary before a suitable design is reached.

2.7 Bilateral Sensing

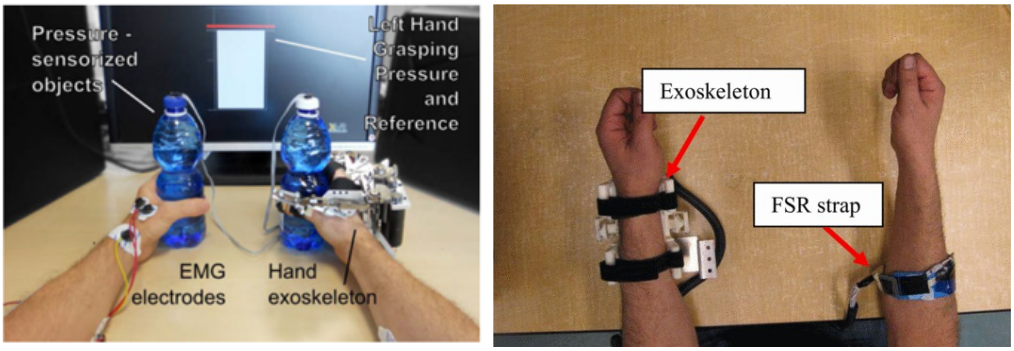
Bilateral training exercises can be carried out using several methods. The type of exercises used; either symmetrical or cooperative; can influence the design of the sensing system used for the exoskeleton. There are many different sensing systems that have been used for exoskeletons, with 4 main types of exoskeleton systems emerging:

- A single exoskeleton worn on the inactive arm, with a sensing system worn on the active arm.
- A single exoskeleton with external sensor(s).
- Two exoskeletons worn on both the active and inactive arms, with sensors integrated into the exoskeletons.
- Two exoskeletons worn in a master-slave configuration, with the patient wearing a single exoskeleton on the inactive arm, and the physiotherapist wearing an exoskeleton on the same side of the body as the patient to control movement.

There are many different types of sensors used within current exoskeletons, all of which have been tried and tested many times. These sensors can be split into

two main groups, wearable and external. Sensors that are attached to the exoskeleton or the users themselves, that are fully integrated into the exoskeleton design, fall into the wearable section and includes options such as electromyography (EMG), force myography (FMG), and inertial measurement unit (IMU) sensors. Any sensors that are used within the environment that the user interacts with while using the exoskeleton; such as motion sensors or force sensors; fall into the external section.

Wearable sensors are worn on the active arm to track the trajectory required for the inactive arm. EMG sensors measure the signals transmitted by motor neurons in the muscles as they contract [77]. As the muscle contracts, it sends an electrical pulse along the arm. This pulse is measured by an electrode worn directly on the surface of the skin. The measurements taken by the electrode can be used to determine the speed and strength of the signal, which in turn can be used to determine how the muscle is moving. The signals from the electrode can be interpreted in a way that shows how the arm is moving, allowing the exoskeleton to carry out the same movement. Studies have shown that EMG is a suitable method for recognising motion patterns in the human arm [77]. The EMG electrodes need to be placed in the correct place on the arm in order to measure the appropriate muscle, and so are generally used in hospital environments so that a medical professional can ensure the correct placement of the sensors. Figure 2.14(a) shows EMG electrodes attached to the active left hand. The electrodes on the BRAVO measure the movement of the active hand which is then used to control the exoskeleton on the inactive right hand; in this case being used to hold a plastic water bottle [45].



(a) BRAVO Exoskeleton with EMG [45] (b) Forearm Exoskeleton with FMG [61]

Figure 2.14: Exoskeletons with EMG & FMG Sensors

FMG sensors work in a similar way to EMG sensors, however instead of measuring the electrical signals in the muscles, they measure the change in surface pressure of the skin. Figure 2.14(b) shows an FMG strap (labelled FSR) that has multiple FMG sensors in it. The forearm device uses the FMG sensors to measure the rotation of the active right arm in order to rotate the exoskeleton worn on the inactive left arm [61].

IMU sensors are the last type of wearable sensors that are popular in exoskeleton designs. They are small, lightweight and do not require as much accuracy in placement as EMG and FMG sensors. IMUs are made up of accelerometers, gyroscopes, and some also have magnetometers. They use a combination of the data gathered with these three allows the motion of the IMU chip to be measured quite accurately. As long as the IMU is always in the same position on the exoskeleton, it is possible to know what orientation the exoskeleton is in, which direction it is moving in, and how fast it is moving. This is a fair bit more information than other wearable sensors provide, although it does not give any direct feedback from the patient. IMUs could be used to track both the movement of the active arm to create the trajectories for the inactive arm; and the movement of the inactive arm to check it is moving as expected and make any adjustments to the movement that might be needed. Only one system was found in literature that used IMUs as a bilateral sensing system, the NTUH-II [62]. The IMU system for NTUH-II can be seen in Figure 2.15, where it is worn on the active arm with the NTUH-II exoskeleton seen in the background on the inactive arm. It is unclear why there are not more bilateral systems that use IMUs but they seem to work well for the NTUH-II system.

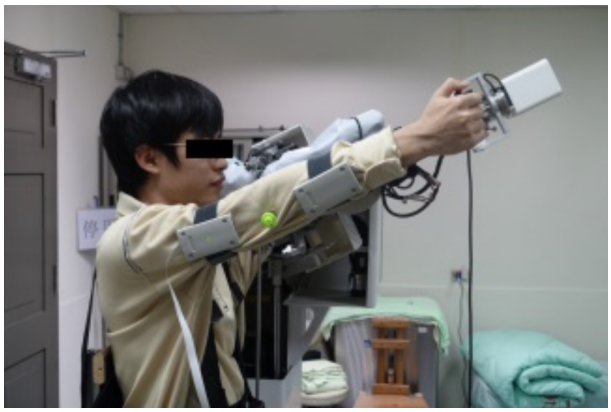


Figure 2.15: NTUH-II IMU system worn on the active arm [62]

External sensors are placed in a fixed location somewhere in the environment surrounding the exoskeleton wearer. While they can be used with a wearable exoskeleton, they do limit the patients ability to move around while wearing the exoskeleton as they must stay in range of the sensor. Force sensors are sometimes used as an external sensor, as can be seen in Figure 2.14(a); though in this case they have been used in conjunction with wearable sensors to give feedback to the patient on their movement. When using external sensors, patients are often given feedback through a VR system so that they can visualise how their arms are moving. The VR systems are generally game systems with the patient being required to move their arm to a certain position in order to complete an objective. These games can help with active participation as patients can carry out rehabilitation in a more engaging and exciting way. As external sensors require the patient to be in a fixed space, a VR system is able to be used on a screen in front of the patient. Motion sensors such as the LeapMotion sensor [42] use a camera to track the movement of the patients active hand or arm, in order to place it into a VR environment. The tracked arm is then placed into the environment alongside the arm wearing the exoskeleton, based on sensors in the exoskeleton, to allow the patient to carry out exercises.

Both wearable and external sensors are generally used with a single exoskeleton. These systems are lighter and more suited to a home environment than the systems that use two exoskeletons. These systems consist of an exoskeleton worn on each arm of the patient, one on the active arm that is able to freely move and uses sensors to track the movement. The other exoskeleton is worn on the inactive arm and follows the movement of the tracked exoskeleton. Some two exoskeleton systems use previously existing unilateral exoskeletons such as the EXO-UL7 [56], and EXO-UL8 [57], which both use two CADEN-(7) exoskeletons [23]. Due to the nature of these systems they tend to be large, bulky and most likely also heavy. The EXO-UL7 can be seen in Figure 2.16. The patient wearing the device can be seen sitting down, with a frame in the background supporting the weight of the exoskeletons. Two exoskeleton systems are mostly grounded systems due to their weight and size, and although this limits the movement possible during rehabilitation, it also increases the options for actuation and sensing systems for the same reasons. A two exoskeleton system has the added ease of not needing to be transferable between the left and right arms. Single exoskeletons need to either be built in two different configurations or in one configuration that can

be transferred from side to side. A two exoskeleton system can be used no matter which arm has been affected by stroke.

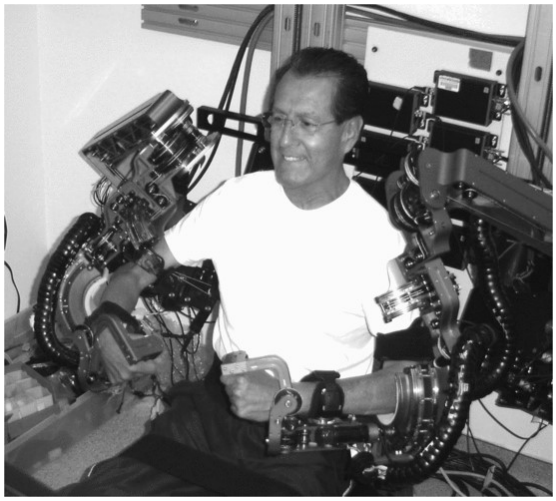


Figure 2.16: EXO-UL7, a two exoskeleton system being worn by a patient [56]

The final type of bilateral system is almost a hybrid between the single exoskeleton and two exoskeleton systems. The master-slave set-up consists of a two exoskeleton system that is worn by two individuals, generally the physiotherapist and the patient. The physiotherapist would wear the master exoskeleton which controls the movement of the slave exoskeleton worn by the patient. This allows the physiotherapist to be more in control of the rehabilitation, which can be useful if the patient is incapable of completing the rehabilitation on their own for any reason. Patients that do not have very good movement in their active arm for example, would be a great candidate for the master-slave exoskeleton system. As can be seen in Figure 2.17(a), the master and slave exoskeletons look almost identical to each other. Another type of master-slave system is one that uses a single exoskeleton alongside a device called Phantom Premium; a haptic feedback device that provides a range of motion for the lower arm. Seen in Figure 2.17(b), the Phantom Premium is used to control the ULERD wrist, elbow and forearm exoskeleton. The Phantom Premium can be used by the patient with their active arm, or it can be used by the physiotherapist; both options control the exoskeleton worn on the patient's inactive arm.

(a) Master-slave exoskeleton [68] (b) ULERD with Phantom Premium [54]

Figure 2.17: Exoskeletons using master-slave systems

2.8 Research Gaps & Limitations

The main gaps in research have been identified and summarised below:

- Wearable bilateral exoskeletons - many of the existing exoskeletons are either grounded or wearable but not often both.
- Bilateral exoskeletons for stroke rehabilitation in a home environment - with most existing exoskeletons being grounded systems they have been designed for use in a hospital environment.
- Cable-actuated wearable exoskeletons - the majority of existing systems use DC motors.
- Patient needs considerations during the design phase - most existing systems consider patient needs once they reach the clinical trial phase rather than during the design phase.

Some of the limitations have been highlighted here:

- Lack of studies on patient needs in exoskeleton design means it can not be said that no previous studies have included them at the design stage.
- Only a small selection of medical professionals and patients can be included in the surveys so the feedback that will be gained will be limited.
- Time constraints due to external factors limited the time that could be spent on practical testing and in-person surveys.

2.9 Conclusion

Bilateral exoskeletons are a growing area in current literature. Bilateral systems can be seen to have some advantages over unilateral systems, such as creating a more involved rehabilitation experience. By getting patients to actively control the exoskeleton on their inactive arm, they are participating in their own rehabilitation more than when using a unilateral exoskeleton. Another advantage of bilateral exoskeletons is that the ADLs are more closely linked with bilateral movements. Most ADLs require the use of both arms, so rehabilitating the arms in a cooperative manner is likely to give patients a headstart when it comes to regaining their independence. The majority of current exoskeletons are grounded, for use in the hospital. There is a distinct lack of wearable bilateral exoskeletons for use in a home environment.

With many different kinds of actuators being used in current literature, there are plenty of pros and cons to all of them. DC motors are simple and easy to use, but bulky and heavy when used directly at the joint. Cables are lightweight but more complicated. SEAs are compact but bulky. Traditional pneumatics and hydraulics are heavy, bulky, and require an external air or water reserve. Soft robotics are lightweight and can be accurate but are very complicated and not really commercially available. The chosen actuation system needs to be suitable for the type of exoskeleton that is being designed, in this case a wearable one. DC motors would be a decent option, but finding ones that are light enough for a wearable design that can also supply enough torque is going to be very difficult. With SEAs being bulky they also do not really lend themselves well to a wearable system. Pneumatics and hydraulics both require an external supply, which pretty much drops them off the list as well. Soft pneumatics could be an option, though at their current state of research they also still require an external air source. Which leaves cables as the main option for a wearable exoskeleton system that is lightweight and compact, despite being a potentially complicated system.

The sensing systems seen could theoretically all be used for a wearable system, however it could be argued that using external sensors could mean that the system is not actually fully wearable. Therefore, force sensors and motion sensors were not considered. Using a two exoskeleton system is also highly unlikely to allow the final product to be wearable as they are heavier, bulkier, and so need to be attached to a grounded frame to make it possible to use them. In order to use the exoskeleton in a home environment, a master-slave system would also not be suitable. This leaves the

wearable sensors identified, EMG, FMG and IMUs. Both EMG and FMG require specific placement on the arm in order to work correctly. Positioning the sensors slightly incorrectly could lead to the patient being hurt if the exoskeleton moves in an unexpected way. As the final device is aimed at being used in a home environment, it is important that the patient is able to put it on independently. This means patients would need to be sure they are correctly placing the EMG and FMG sensors every time which may not be the most suitable option. IMUs are therefore the best option for an exoskeleton being used independently in a home environment as they are wearable and do not require specific placement for them to work consistently.

From all of the literature seen, several gaps have been identified. Namely, wearable bilateral exoskeletons for use in the home that use cable actuation and an IMU sensing system. This type of exoskeleton could be a novel addition to current literature, not just in the way it is engineered but also in the way it is designed to consider how patients carry out rehabilitation. Bringing patients and medical professionals an exoskeleton option that can be used at home could improve how quickly patients are seen, how consistent rehabilitation is on the whole, and lower costs so that more patients have the option to receive life changing rehabilitation.

Chapter 3

Initial Design of the Bilateral Exoskeleton for Arm Stroke Treatment

3.1 Introduction

Most of this chapter has been presented at the 2021 27th International Conference on Mechatronics and Machine Vision in Practice (M2VIP) [78]. The system specifications section has been added, and further details have been added to all the other sections; in particular more detail on earlier designs, and a more in-depth kinematic analysis.

At this point in the development of exoskeleton technology, there is very little novelty in how they can be designed as a whole; the novelty lies in the intricacies of each individual system that make up the exoskeleton as a whole. The following chapter outlines the design process of the Bilateral Exoskeleton for Arm Stroke Treatment (BEAST). In particular it discusses the design of the actuation, sensing, and mechanical systems. The design of BEAST is novel in that it is a wearable, cable actuated, 7 DOF exoskeleton for the wrist, elbow and shoulder. There are many exoskeletons seen in the existing literature that contain several of these aspects, however none of the existing exoskeletons combine them all into a single design.

From the existing literature, it was clear that there were a number of gaps in bilateral exoskeleton design. Some of the gaps that were identified include a lack of cable actuated devices, home-based systems, and patient needs based designs. The only bilateral cable actuated device identified in existing literature was the CyberGrasp, a hospital-based grounded exoskeleton for the hand [48]. The Omega.7 is another hand exoskeleton, and one of the only systems presented in literature that is solely for use in a home environment [42]. There were no devices found in the literature that had a focus on a patient needs based design process. That is, none that appeared to consider patient needs before the testing or clinical trial phase.

The design laid out in the following chapter is a 7 DOF exoskeleton that has been designed to fill some of the gaps in the existing literature highlighted in Section 2.8. It aims to be lightweight, with patients being able to don the device independently, lending itself well for use in a home environment.

3.2 System Specifications

The first step of the design process is to consider the system specification. Table 3.1 outlines the specification for BEAST.

Table 3.1: Engineering Design Specification

	Design Aspect	Specification Points
1	Performance	The joints being actuated need to be able to rotate within the full range of normal human movement, with an actuation system that is capable of this movement. The exoskeleton itself is to be wearable and bilateral and so needs a functioning sensing system to allow for the bilateral movement.
2	Environment	The exoskeleton is to be used in a patient's home environment, and stored in both home and hospital environments between uses. This would require a space that is not much larger than the users range of motion, and a storage space roughly the same size as the exoskeleton. Both home and hospital environments would have a power source capable of charging the exoskeleton; a mains power plug.
3	Life Expectancy	It is expected that the exoskeleton could be used anywhere from once a week to once a day for between half an hour and an hour. It is therefore likely to used quite regularly and life expectancy would change depending on intensity of use.
4	Maintenance	Regular maintenance carried out between patient uses, with the hospital / company that supplies the exoskeletons being responsible for maintenance and repairs.
5	Target Product Cost	As low cost to hospitals and patients as possible. Ideally this would be less than £1000 per exoskeleton but future design considerations may change this.
6	Availability of Components	Readily available components, easily replaceable if any components become discontinued.
7	Manufacturing Facilities	3D printing available to create the frame of the exoskeleton. Electronics and mechanical workshops for any other manufacturing required.
8	Size and Weight	Size needs to be adjustable in some way to fit to each patient, general framework needs to be compact and lightweight to allow for wearability.

9	Aesthetics and Finish	Exoskeleton needs to look professional in a medical setting. Needs to be easy to clean in a home environment and easy to sterilise in a hospital environment.
10	Materials	The framework of the exoskeleton needs to be made from a lightweight material.
11	Product Life Span	Life span of approximately 10 years, possibly more depending on the advancement of the technology within medical robotics.
12	Standards and Specifications	Product is required to adhere to the relevant standards for a medical device in the UK.
13	Ergonomics	Needs to be comfortable for patients to wear for prolonged periods of time; and also easy for patients to put on and take off independently.
14	Quality and Reliability	High quality; reliable for patients to use at home and easily accessible repairs.
15	Processes	3D printing.
16	Safety	During the design process, all safety measures will be taken to ensure prototyping is carried out in a safe and secure manner. Manufacturing will be completed in a suitable laboratory space with correct safety guidelines and procedures followed. Both software and hardware stops will be included on the exoskeleton itself.
17	Market Constraints	Novel design compared to existing literature. Combination of wearable, cable-actuated, bilateral exoskeleton. Consideration of patient needs through a survey.
18	Installation and Operation	Hospital staff trained to fit the exoskeleton to the patients. Both hospital staff and patients trained in using the exoskeleton.

With the general specifications of the design laid out in Table 3.1, the specific requirements need to be considered in more detail. Many of the requirements for the design of BEAST have well established roots in exoskeleton literature. There are many aspects of the design that need to be considered as part of the specification, and these are covered in the following sections.

3.2.1 Performance

The main performance point of the exoskeleton are the joints that need actuating, the angles that these joints need to be capable of, and the torque required to actuate them. Within the upper arm there is the shoulder, elbow, wrist, and hand. The hand is a very complicated system made up of many smaller joints that needs an intricate exoskeleton system in order to rehabilitate it. It was decided not to include the hand in the design of BEAST due to these reasons, and also as there are many other hand exoskeletons that already exist in literature. Table 3.2 shows the different movements that each of the other joint actuates in, and the range of motion (ROM) for each direction.

Table 3.2: Joint Ranges of the Human Arm [79]

Rotation	**Shoulder**	**Elbow**	**Wrist**
Flexion	180°	160°	90°
Extension	50°	145°	70°
Abduction	180°	-	25°
Adduction	50°	-	65°
Horizontal Abduction	135°	-	-
Horizontal Adduction	45°	-	-
Pronation	-	90°	-
Supination	-	90°	-

3.2.2 Environment

The exoskeleton needs to be designed for use in both hospital and home environments. This is because although the main environment for the device is in the home; there will be a certain amount of training and introductory sessions carried out in the hospital to ensure that the patient is capable of operating the device correctly and safely. The home environments used by patients need to be large enough for the rehabilitation exercises to be undertaken, and they need to include a mains power supply in order to charge the exoskeleton. There also needs to be a storage space large enough for the exoskeleton to be safely and properly stored to avoid damage.

3.2.3 Life Expectancy

The life expectancy of the exoskeleton is difficult to pinpoint as it depends on the amount of use that the exoskeleton undergoes. As some patients may only need to use the exoskeleton once a week for half an hour; while other patients may need it every day for an hour, the intensity of use can differ massively. The best way to ensure that the device has a long life expectancy would be to alternate the device between a high intensity patient and a low intensity patient.

3.2.4 Maintenance

As a medical device, it would be expected that the hospital that provides the exoskeleton to the patient is responsible for any maintenance it may need throughout it's lifetime. This would include regular maintenance between patient use, and also any emergency maintenance while a patient has the device in their own home. This may include the option for the patient to have the device collected and replaced with another device so that their rehabilitation is not interrupted by the necessary maintenance.

3.2.5 Target Product Cost

The exoskeleton aims to be made at as a low of a cost as possible in order for hospitals to supply as many patients as possible with the ability to carry out their rehabilitation at home. Patients could be supplied through hospital via either a rental scheme or a purchase scheme, depending on the needs and situation of the patient. If only a rental system was in place then patients could provide a one-time deposit for the exoskeleton, paid in either a single payment or over the course of a payment plan, that they would then have returned to them when they no longer need the exoskeleton. This would ensure that patients return the device as well as making it as accessible as possible to patients. If there was a rental system in place alongside a purchase option, patients would have the option between monthly payments for a rental of the device for patients that may only need the device for a short amount of time, or a one-time payment; again with the option of a payment plan; for patients that may need continued rehabilitation for a number of years.

3.2.6 Availability of Components

Readily available components and easy to manufacture parts make the cost of the device much cheaper as well as making maintenance and parts replacement simple. Components with common requirements are also easy to replace if a manufacturer discontinues a component. Using 3D printing also makes parts easy to manufacture and replace if necessary.

3.2.7 Manufacturing Facilities

The facilities at the University of Leeds are vast enough to cover most potential requirements for the manufacturing of the exoskeleton; from 3D printing to electrical and mechanical workshops. When considering manufacturing at a production scale, the facilities required would be much larger and further investigation would need to be done to determine the type of facility that would be needed.

3.2.8 Size and Weight

In order for an exoskeleton to be effective, the centre of rotation for each exoskeleton joint needs to align with the centre of rotation of the equivalent joint in the human arm. Therefore the size of the exoskeleton needs to match with the size of the patient as closely as possible. During the initial design phase of BEAST it was decided to use the size of an average person to create the prototype. At a later point, the design could also include a system that allows the size of the exoskeleton to be adjusted to fit each individual patient. The average size data for the prototype was gathered from a survey on anthropometrics that the US Army carried out in 2012 [80]. The survey measured over 94 different parts of the human body with over 6000 participants [80]. Table 3.3 gathers the relevant data from the survey into two sections, one showing the measurements that may be needed to design the exoskeleton joints, and the other section showing the data that may be necessary when designing the human-robot interface (HRI) of the exoskeleton.

Table 3.3: US Army Anthropometric Data - Measured [80]

Measurement - Arm	**Females**			**Males**		
(cm)	*Min.*	*Max.*	*Mean*	*Min.*	*Max.*	*Mean*
Acromion-Radiale Length	24.90	37.10	31.12	27.00	39.30	33.52
Biacromial Breadth	28.30	42.20	36.53	33.70	48.90	41.57
Bicep Circumference	21.60	43.50	30.56	24.60	49.00	35.81
Forearm-CoG Length	25.80	39.20	31.77	29.00	41.60	34.90
Forearm Circumference	20.00	34.20	26.41	23.30	40.20	31.01
Forearm-Hand Length	34.20	52.70	43.99	40.00	57.40	48.02
Hand Breadth	6.70	9.20	7.82	7.40	10.50	8.83
Hand Circumference	15.20	21.40	18.66	17.90	24.80	21.23
Hand Length	14.50	22.00	18.11	16.40	23.90	19.33
Palm Length	8.80	13.00	10.87	9.50	14.00	11.65
Radiale-Stylion Length	16.90	29.70	24.13	21.60	32.80	26.79
Shoulder-Elbow Length	27.10	39.80	33.43	29.80	42.30	36.37
Shoulder Length	10.70	17.50	13.54	11.30	18.50	14.98
Wrist Circumference	12.40	18.30	15.48	14.10	21.60	17.59
Measurement - HRI	**Females**			**Males**		
(cm)	*Min.*	*Max.*	*Mean*	*Min.*	*Max.*	*Mean*
Abdominal Extension Depth	15.50	35.80	22.97	16.30	45.10	25.47
Bicristal Breadth	19.70	36.20	27.33	21.90	33.40	27.54
Bideltoid Breadth	35.70	55.80	45.03	37.40	63.70	51.04
Chest Breadth	21.30	34.80	26.93	23.10	36.30	28.94
Chest Circumference	69.50	126.60	94.69	77.40	146.90	105.87
Chest Depth	17.00	35.30	24.74	17.60	38.30	25.38
Hip Breadth	27.60	47.30	35.38	26.40	45.20	34.57
Hip Breadth, Sitting	30.70	54.10	39.90	28.00	50.90	37.93
Waist-Back Length	34.50	53.20	42.54	38.30	59.80	47.76
Waist Breadth	21.20	46.10	29.99	23.20	45.90	32.64
Waist Circumference	61.10	133.40	86.09	64.80	137.90	94.06
Waist Depth	13.80	36.70	21.30	15.10	40.60	23.78
Mass (kg)	**35.80**	**119.60**	**67.76**	**39.30**	**144.20**	**85.52**

As part of the survey, some of the data was derived from the measured data so that a comprehensive list of human body measurements could be found in one place. Table 3.4 shows these derived measurements relevant to the human arm. These derived measurements were calculated using the mean values of the measured data, which will also be used for the prototype design. If at a later date the ability to adjust the exoskeleton was incorporated, the maximum and minimum values from the survey can be used.

Table 3.4: US Army Anthropometric Data - Derived [80]

Body Measurement - Arm	**Females**			**Males**		
(cm)	*Min.*	*Max.*	*Mean*	*Min.*	*Max.*	*Mean*
Acromion-Axilla Length	5.80	14.50	9.61	6.80	16.40	11.17
Arm Length	56.70	86.60	72.20	66.20	96.10	78.65
Clavicle Link	14.20	21.10	18.29	16.90	24.50	20.81
Elbow Wrist Length	18.70	31.00	25.88	23.50	35.50	28.69
Functional Grip Reach	55.10	84.30	69.30	59.50	94.30	75.69
Vertical Grip Reach Down	47.80	73.30	60.69	55.80	79.20	66.32

3.2.9 Aesthetics and Finish

In order to be used in a medical setting, the device needs to look professional; with all of the actuation and sensing systems integrated into the design. This means no visible wires or exposed mechanical parts. A professional device would need to look safe to use so that patients feel comfortable using it. It must also be pleasing to the patients as they will not only have to use it but also have the device in their home. With the exoskeleton being 3D printed there is plenty of options for colour and shape of the exoskeleton to ensure it meets these requirements. The finish of the exoskeleton must be smooth and easy to clean and sterilise by both patients and hospital staff between uses.

3.2.10 Materials

It was decided that the BEAST exoskeleton would be a 3D printed design for several reasons, such as; ease of prototyping, lightweight materials, and ability to build the

exoskeleton to a patients specific size requirements. Some initial 3D printing was carried out of the wrist-elbow section of the exoskeleton in various different materials. The aim was to use these prints to test both the strength of the materials, and also the strength of the design itself. Unfortunately due to both time constraints and limited lab access, this testing was never carried out. The test prints can be seen in Figure 3.1. The materials that were chosen for testing were ABS, PLA, tough PLA, PC, PETG and CPE. All of the filaments were from Ultimaker and were printed on an Ultimaker printer.

Figure 3.1: 3D Printed Test Links

3.2.11 Product Life Span

The device must have a reasonably long life span to make it worthwhile for the hospital to invest in it. The aim would be for the device to have a life span of at least 10 years; or more if the technology used does not become obsolete in that time.

3.2.12 Standards and Specifications

In order for a device to be used in hospitals in the UK it is required to meet the Medicines & Healthcare products Regulatory Agency (MHRA) standards, directives and regulations [81–83]. These standards ensure that all medical devices manufactured

in the UK are safe and suitable for their intended use [81]. A UK approved body will carry out a review before a device can be put on the market; including reviewing scientific and clinical data, the manufacturing process, and the quality management [81]. An exoskeleton for rehabilitation use would be classed as a IIa device as it is an active device that administers or exchanges energy [84].

3.2.13 Ergonomics

Ergonomics is the interaction between humans and their environments. In this case it refers to the way patients will interact with the exoskeleton device. The exoskeleton needs to be easy for patients to put on and take off; especially considering that patients using the device may have very limited use of the affected arm. This includes easy to use fastenings that are also comfortable if the exoskeleton is being used for prolonged periods of time. This also extends to the design of the back brace; which needs to be sturdy and comfortable but also lightweight.

3.2.14 Quality and Reliability

In order to be used as a medical device the exoskeleton needs to be high quality and very reliable. The 3D printing materials and various components therefore need to be of a high quality. In order for the device to be reliable it needs to undergo regular maintenance as well as being well manufactured.

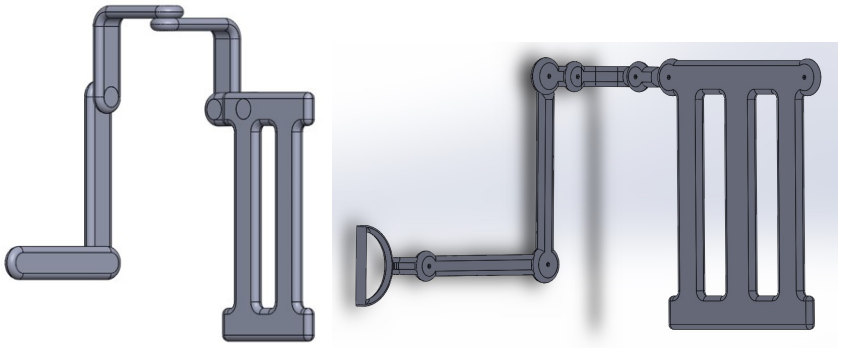
3.2.15 Safety

There are many safety measures that can be put in place for the use of the exoskeleton. Hardware stops for each joint are necessary to prevent the joints from being rotated beyond what the human arm is capable of. Software stops within the control system can limit the ROM of each joint to what the patient is currently capable of. The hardware stops are an added measure in case of a failure in the software system. The human-robot interface needs to be suitably designed so that the device is well fitted and therefore is safe to wear when in use. Ensuring that all the electrical and mechanical components are suitably covered as part of the design is also an important safety feature. Proper manufacturing processes need to be followed throughout to ensure the safety of those doing the manufacturing. The safety of participants completing the surveys also needs to be taken into account in terms of their privacy and data collection. This will be

done through the use of an ethical approval form and by following standard privacy guidelines.

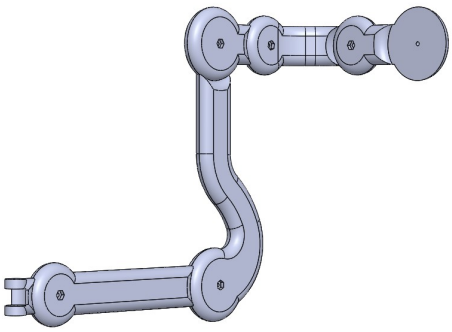
3.3 Mechanical Design

The mechanical design of BEAST has been through several iterations before reaching the final design. Figure 3.2 shows each iteration of the design, and this section explains how they were developed. Both the existing literature and the system specifications were taken into account throughout the design phase. 3D printing was used to test the validity of small sections of the designs, as well as full-scale designs. Throughout the design phase, when referencing degrees of movement, 0° is always assumed to be when the arm is hanging loose at the side of the body.



(a) BEAST Version 1

(b) BEAST Version 2



(c) BEAST Version 3

Figure 3.2: Initial Designs for BEAST

3.3.1 Biomechanics of the Human Arm

Before designing an exoskeleton, the biomechanics of the human arm need to be fully understood to ensure a suitable design. Human biomechanics will impact the size and shape of the exoskeleton, the amount of torque needed for the actuation system, and the workspace that the exoskeleton needs to move in.

3.3.2 BEAST Version 1

The first step for the design of BEAST was to consider the movement that the exoskeleton needed to be capable of. In this case, that would be the amount of rotation that each joint of the arm needs to be capable of, and the direction of that rotation. Table 3.2 shows the joint ranges of the human arm, with the aim that BEAST would be able to match them.

BEAST Version 1 (V1) was started at the elbow as it has the simplest joint movement. It needed to be capable of 0° to 160° of flexion. This design used overlapping sections so that each link did not prevent the next link from rotating, and can be seen in Figure 3.2(a). The elbow joint was designed as a simple rotational joint, and was capable of the full 160° movement.

A lot of mistakes were made during this first design attempt, most of which centre around the shoulder design. Each type of rotation at the shoulder was individually considered, flexion/extension, abduction/adduction, and horizontal abduction/adduction. So individually V1 is capable of these movements, however when all put together it has some limitations. Each of the shoulder movements was created using a single rotational joint, with an extra rotational joint added between the first link and the back brace of the exoskeleton in an attempt to mitigate the movement of the glenohumeral joint. This extra joint however, resulted in a different movement than originally planned. The V1 design was 3D printed on a small scale so that the movements could be seen and understood in the real world. This proved vital as the issues with the design became clear very quickly. Firstly, the additional joint that was meant to allow for movement of the glenohumeral joint was completely incorrect. It did not just raise the shoulder, but also pulled the entire arm closer to the body; a completely unnatural and potentially impossible movement. Secondly, the abduction/adduction movement of the shoulder ended with the part of the exoskeleton that sat on top of the shoulder to rotate into the users head; obviously a situation that is less than desirable. Thirdly, when carrying out

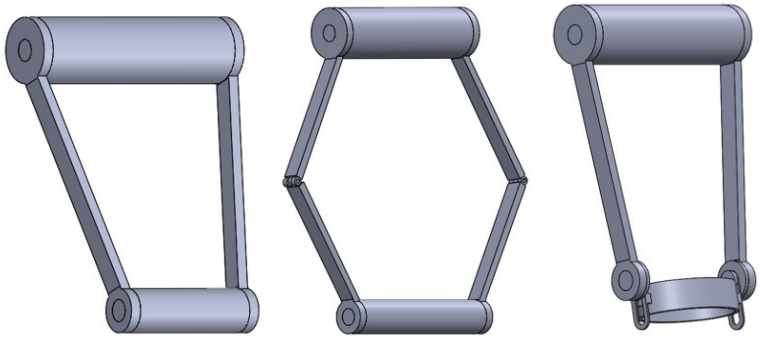
movement of more than one of the joints, the links did not move very smoothly, almost catching on each other as they rotated. And finally, the wrist joint was not included in the design at all.

V1 was more of a feasibility design to consider how the joints all interacted together, and also to give a starting point for a more thorough design. At this point in the design process the links were only capable of being slotted together rather than properly connected together. The next version needed to be able to be fully built, the shoulder joints needed to be redesigned, and the wrist joint needed to be added.

3.3.3 BEAST Version 2

Version 2 (V2) of BEAST, seen in Figure 3.2(b), took the basic design of V1 but expanded on it. Firstly, the wrist joint was added. The wrist joints needed to be capable of both flexion/extension, and abduction/adduction. The two movements would need to be controlled in different places on the wrist, as placing the two rotational joints on top of each other was not possible. For this reason, a handle was designed that the user would hold onto. This would serve as both an anchor point for the end of the exoskeleton. The handle is connected to the next link by a rotational joint that allows for flexion/extension of the wrist. Further down the link, the next rotational joint would be placed almost directly on top of the human wrist joint. This would allow for abduction/adduction of the wrist. This design of the wrist joint proved to have two issues. The first issue was that as the wrist was flexed, the handle naturally moves further away from the wrist. This would either pull the entire exoskeleton toward the hand of the user, or the movement would cause harm to the user by moving it in a dangerous way. For the V2 design to work, it would require the link between the two wrist joints to be at least slightly flexible, however it would have to be flexible in only one direction. If it was flexible in all directions, it would not be rigid enough to make the wrist move when attempting to carry out abduction/adduction movements.

A few other wrist designs were considered during the V2 design to try and fix the issue of the flexion/extension movement. These can be seen in Figure 3.3. Version 2.2 consisted of a bar going across the top of the wrist, with the flexion/extension rotation. The handle in this design also allowed for passive rotation so that the user could the handle without it rotating in their hand. The initial handle design would have rotated in the hand during use and could have resulted in irritation and discomfort to the



(a) Wrist Version 2.2 (b) Wrist Version 2.3 (c) Wrist Version 2.4

Figure 3.3: Alternative Wrist Joint Designs for BEAST V2

user. Version 2.2 did not have a joint that allowed for abduction/adduction, so Version 2.3 was created. This added two joints, one on each side of the hand. As one side straightens, the other side bends to pull the hand to the side and back again. However, these side joints stick out from the hand and are small enough that actuation is likely to be an issue. Therefore Version 2.4 moved the abduction/adduction joint down to the wrist. It had the same rotational joint for the flexion/extension but added two slider joints on either side of the wrist. This aimed to create the same movement as in Version 2.3, but from the wrist which would allow more actuation options as the actuation system could be fixed to the forearm.

The general design of the elbow was unchanged from V1, however the links were redesigned to allow them to be mechanically connected together using nuts and bolts. This was so that the design could be 3D printed again and properly assessed for its feasibility. Each section of the rotational joints had half the joint connected to one link, and the other half connected to the next link. This can be seen in Figure 3.4, which shows one of the shoulder joints from above with one one link being transparent to show how they fit together. The idea here was that when adding actuation at a later date, it could be attached to one of the links and rotate the next link directly at the joint. It also allowed for a potential cable system to be designed that could fit inside the links, allowing the cables to run through the middle of each rotational joint.

The shoulder joint in V2 was designed to have the exoskeleton links running behind the shoulder rather than over the top of the shoulder. This was done to remove the issues with V1 where the links moved into the users head during certain movements.

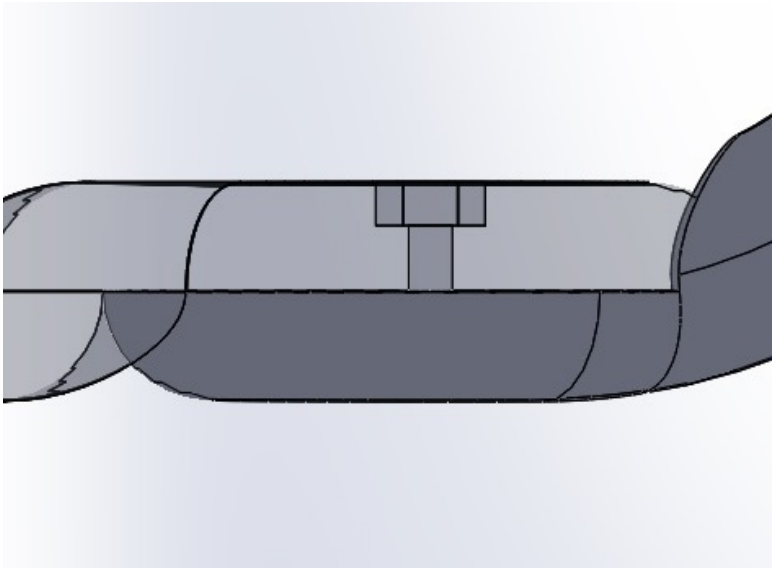


Figure 3.4: Side View of a Joint Showing Two Links Fitting Together

With the links behind the shoulder, they no longer moved into the body of the user during normal movements. The joint however, is still capable of all the necessary movements; flexion/extenson, abduction/adduction, and horizontal abduction/adduction.

3.3.4 BEAST Version 3

Version 3 (V3) of BEAST, seen in Figure 3.2(c), started off with removing the handle from V2. This was done after conversations with some physiotherapists who discussed issues that were not previously considered. The main issue is that stroke patients are usually discouraged from carrying out gripping motions with the hand because it can cause spasticity to develop or make it worse if already present. It was made clear by the physiotherapists that the type of handle designed in V2 would be inappropriate for use in stroke rehabilitation. It was decided that a soft strap made out of fabric and velcro would be used instead to secure the exoskeleton at the hand, alongside similar straps on each of the links to secure the exoskeleton at various points on the arm.

Most of the design stayed the same between V2 and V3. Minor changes were made to the sizes of the links, to ensure the exoskeleton had the right measurements. V3 in particular was based off the measurements shown in Tables 3.4 and 3.3 for the average female.

The elbow joint in V2 was found to be capable of approximately 113° instead of the required 160°. This was because as the elbow flexed, the links of the exoskeleton on the upper and lower parts of the arm were colliding before the full ROM could be achieved. The link on the upper arm was therefore redesigned with a curve in the link to allow for the full amount of flexion without the links touching. This new design allowed the full 160° flexion of the elbow.

The shoulder joint in V3 was not changed from V2 as it already met all of the requirements for the design. However, the back brace was removed from the CAD drawing. This was due to the realisation that the shape of the back brace designed would not be comfortable for a patient to wear as it was not shaped to the back in any way. Instead, other options were considered for the back brace system. It needed to be comfortable for patients to wear for an extended period of time, especially while carrying the weight of the exoskeleton and its attached systems such as the battery and electronics. It also needed to be easy for patients to be able to put the exoskeleton on independently in order for it to be used in a home environment. The main idea was to use the same system as a hiking rucksack as this has already been designed to be comfortable to wear for extended periods with a decent amount of weight on the back. Hiking rucksacks have been ergonomically designed, with padded back supports, padded shoulder straps, and hip and chest straps to help with weight distribution. With the exoskeleton moving the patients arm, the shoulder needs to be able to move freely. Therefore, being able to transfer as much weight as possible off the shoulder is going to be beneficial. It's also theoretically possible for patients to put on a rucksack without help, though this would need some further testing with actual patients in order to check the feasibility of the idea fully, particularly once the weight of the exoskeleton was added. The method of fastening the straps of the rucksack and exoskeleton would need some practical research as well.

3.3.5 BEAST Version 4

Up until this point in the design process, the plan was to build a prototype and then carry out some testing with healthy participants first, and later stroke patients if time allowed. Unfortunately, with COVID-19, this plan had to be adjusted to a more realistic plan due to the circumstances. After over a year of very little progress and waiting for the world to return to normal, a decision had to be made on whether in person

testing was going to be possible. It was decided that the safest option would be to assume that it would not be possible and to establish a new plan that did not involve face-to-face meetings. Therefore, instead of a full size prototype that could be worn by a person, a small version of the design would be built on a frame; called version 4 (V4) for clarity's sake. The smaller size was mainly due to the 3D printer access that was available at the time. An Ender 5 Pro printer was used with a printing plate size of 220x220x300mm. This did not allow for a full size exoskeleton to be created and so the design was adjusted to fit the 3D printing space that was available. The size of the entire system was reduced by the same ratio so that the prototype had the correct proportions.

BEAST V3 was first reduced to the correct size for the 3D printer while keeping the same ratios. A frame was then designed for the exoskeleton to connect to. This can be seen in Figure 3.5. The frame was designed to enable all of the joint motions of the exoskeleton to be carried out without interference while it sits on a tabletop. The frame had to be printed in several sections in order for it to fit on the 3D printer so had to be fully assembled once printed. As the exoskeleton was being mounted on a frame rather than a human participant, a plate was added to the back of the frame to mount the actuation system on; seen in more detail in Figure 3.6. The plate was designed to fit ten motors on, in five sets of two. Each set of two motors would control one joint. Holes were cut in the plate to allow the pulleys to be positioned correctly so that they could freely rotate. Cable tubing holders were also designed to help route the cables from the motors to the relevant joint. Figure 3.7 shows the cable routing system attached to the exoskeleton arm. Each routing section gets smaller as it goes past each actuated joint as less cabling is needed. Section 3.5 explains the actuation system in more detail.

3.3.6 BEAST Design Contributions to Research

The design of BEAST differs from the current literature of bilateral exoskeletons in several ways. The literature that was explored in Chapter 2 highlights that there are very few wearable bilateral exoskeletons. Of those, only one has been designed for home use, PVSED [69–71]. It is also the only one that uses cables as the actuation system. However, PVSED is only designed for the elbow and shoulder joints with 4 DOF [69–71]. Therefore, the wearable design of BEAST being for the wrist, elbow

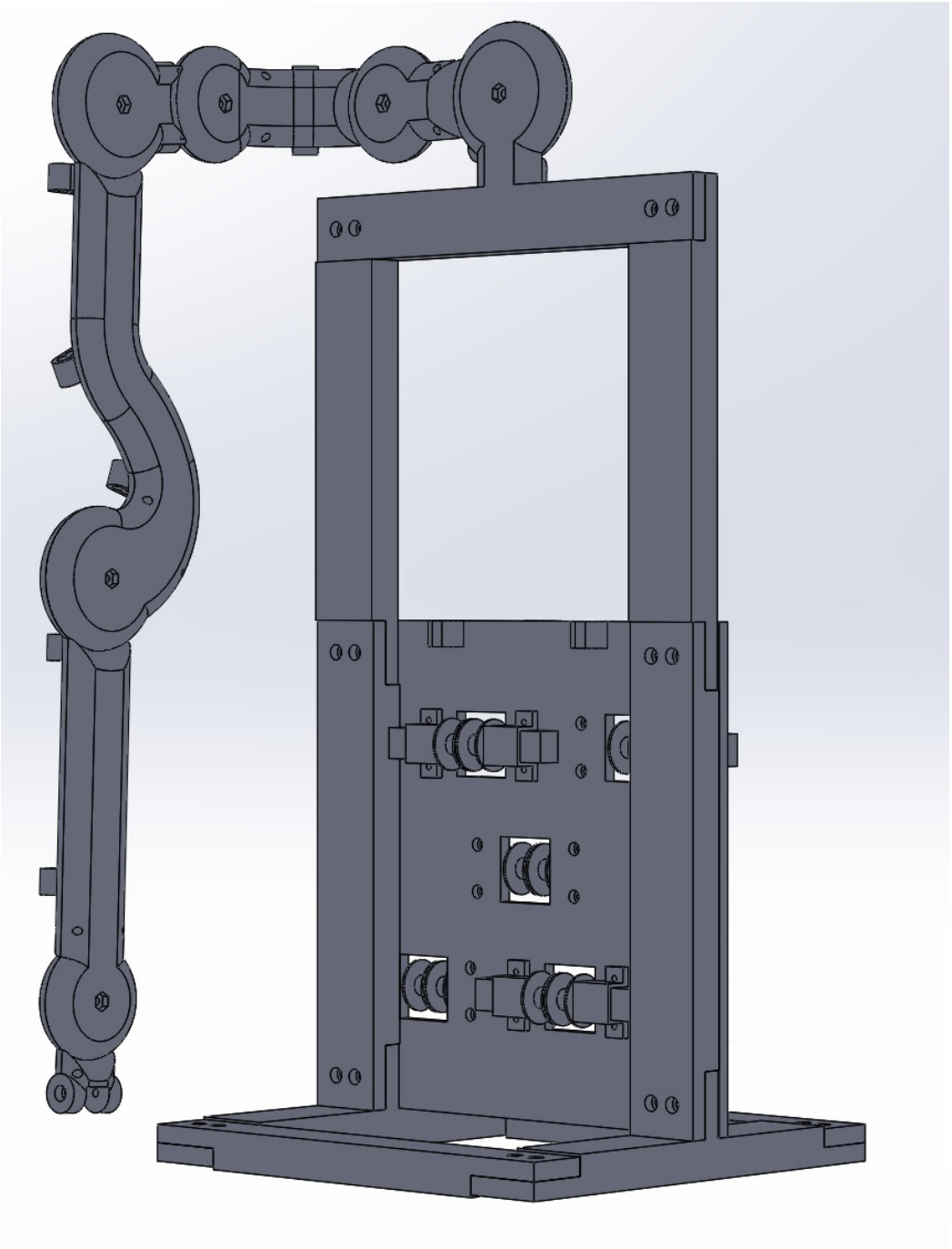


Figure 3.5: CAD design of BEAST V4, tabletop stand and plate holding the actuation system.

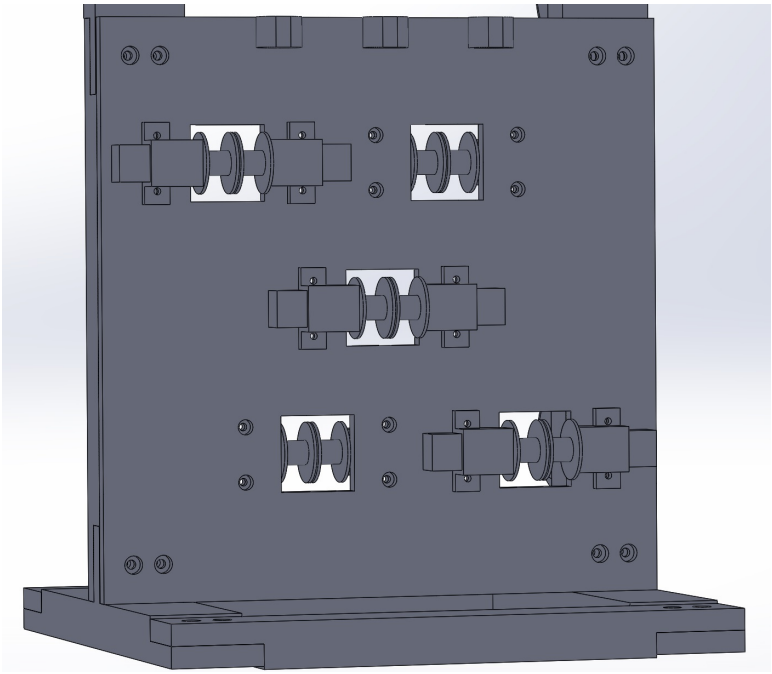


Figure 3.6: Close up view of the CAD design of the plate holding the actuation system. Holders attached to the top of the plate route the cable system down to the motors and pulleys on the plate. Holes in the plate allow the pulleys to freely rotate.

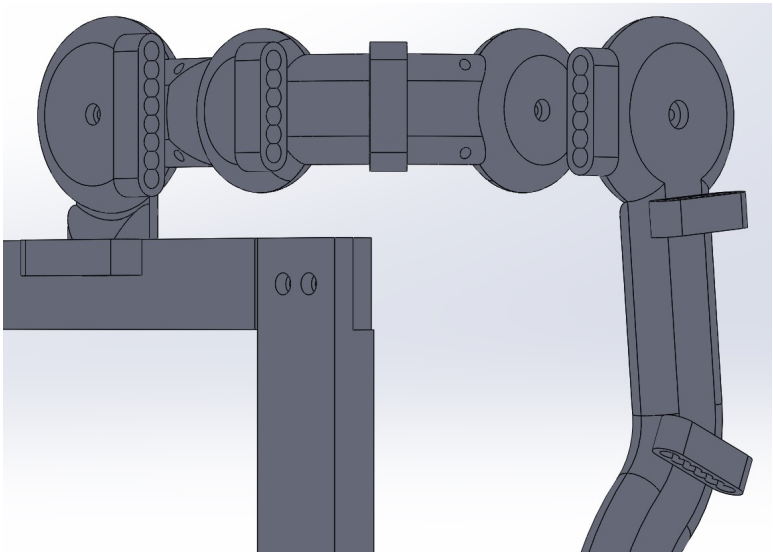


Figure 3.7: Close up view of the CAD design of the cable routing system.

and shoulder with 7 DOF and being cable actuated is a novel design within bilateral exoskeletons. It takes well established aspects of exoskeleton design and combines them into a single exoskeleton that is ideally suited for the home environment, with the ability to rehabilitate the entire range of motion of the arm. BEAST contributes a new design for a wearable bilateral exoskeleton to the field of research.

3.4 Kinematics

With the exoskeleton fully designed through various iterations, it is important to check the ROM and workspace. This has been done with a kinematic analysis of the device. In this case, the Denavit-Hartenberg (D-H) notation was used to define the links and joints of the BEAST V4 [85]. D-H requires each of the joints to be assigned its own directional axis, depending on the direction of rotation and with respect to the previous link. The Z-axis of each joint points in the direction rotation, with the X-axis intersecting the previous Z-axis at a perpendicular angle [85]. Starting at joint 1 and following these rules gives the full notation shown in Figure 3.8; with joint 1 being the first shoulder joint, and joint 8 being the wrist joint of the user. For BEAST to be fully defined in this way, an additional joint needed to be added at the right angle of the shoulder; joint 3. This joint was treated as a normal joint in the calculations but was given no range of motion. However, it was given a fixed value of 90° for both θ_i and α_i in order to give it a fixed right angle position as shown in Figure 3.8.

Once the axis notation for each joint has been determined, the rest of the parameters needed to be defined. There are four parameters within D-H, two for rotation, θ and α; and two for displacement, a and d [85]. Where θ is the direction of rotation from x_{n-1} to x_n, around z_{n-1}; and α is the direction of rotation from z_{n-1} to z_n, around x_n [85]. And where a is the distance from the origin of the $n-1$ frame to the n frame, along the x_n axis; and d is the distance from x_{n-1} to x_n along the z_{n-1} axis [85]. Table 3.5 shows each parameter's values as specific to BEAST.

The initial D-H parameters shown in Figure 3.8 and Table 3.5 have been determined directly from the exoskeleton design. In order to carry out the kinematics and workspace analysis, the Peter Corke Robotics Toolbox was used in MATLAB [86]. This required some changes to the D-H parameters based on how the toolbox assigns axes. Figure 3.9 shows the D-H parameters created for BEAST V4 in the robotics toolbox. An extra joint had to be added to the parameters to account for the attachment to the frame.

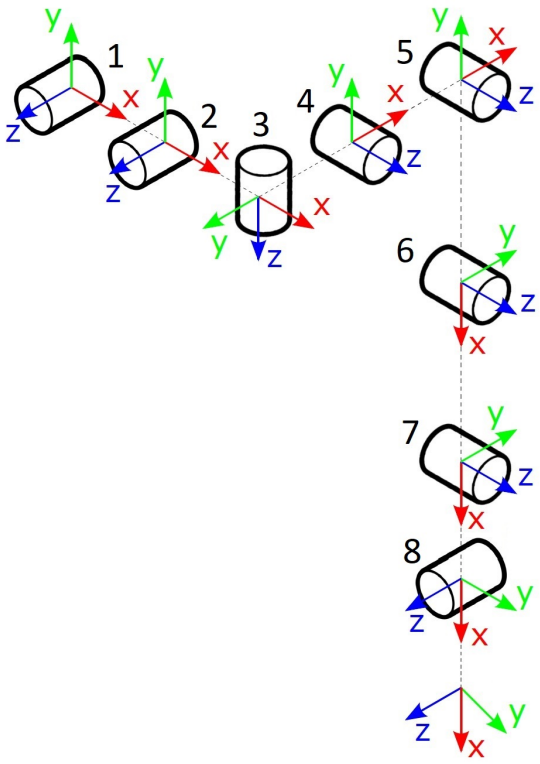


Figure 3.8: Denavit Hartenberg Notation of Beast Version 4

Table 3.5: Denavit-Hartenberg Parameters of BEAST Version 4

Joint i	$\theta_i(°)$	$\alpha_i(°)$	$a_i(mm)$	$d_i(mm)$
1	θ_1	0	60	0
2	θ_2	-90	50.5	0
3	90	90	50.5	0
4	θ_4	0	55	0
5	$\theta_5 + 90$	0	180	0
6	θ_6	0	160	0
7	θ_7	-90	35	0
8	θ_8	0	35	0

This was mainly added as the initial joint in the toolbox is automatically in a vertical orientation, however the first joint of BEAST is in a horizontal orientation. Adding the extra joint with a 90° rotation to α allows the actual first joint of the exoskeleton to

be correctly aligned. Figure 3.10 shows the kinematics plot of BEAST with the elbow joint at 90° of flexion from the 'natural' position, i.e. when the arm is relaxed at the patients' side. The additional first joint can also be seen, with the actual first joint of the exoskeleton overlaid in the correct orientation. The parameters in 3.9 have been assigned in order to create the correct orientation of the exoskeleton joints before the range of θ values is applied. The joints are labelled 1-9 with 1 being at point $(0, 0)$ in the plots. The offset shown in Table 3.9 rotates the joint by a fixed amount to create a new starting point for the rotation of the exoskeleton link as specified by the range of θ. Firstly, α_1 is set as $\pi/2$ in order to rotate joint 2 into the horizontal orientation; joint 2 is rotated by $\pi/2$ with respect to joint 1. As joint 3 is in the same orientation as joint 2, α_2 is 0. To create the corner joint of BEAST, α_3 and α_4 are both $\pi/2$. In order to get the corner joints to be positioned correctly in the position of the shoulder, the offset of joint 4 is set as $-\pi/2$. To get the 'natural' position of the arm at rest, the offset of joint 6 has been set as $\pi/2$. The wrist joints have been added the flexion and extension movement first, followed by the abduction and adduction movement. Therefore, α_7 and α_8 have both been set as $\pi/2$ to rotate them into the correct orientation.

The values for the ranges of each θ have been taken from Table 3.2; though the exact values needed to be adjusted within the toolbox to create the correct range and direction of movement. For example, the shoulder flexion range from Table 3.2 is -50° to 180°; while the range used in the MATLAB code is -90° to 140°. The overall range is the same, it has just been shifted as the 0° point has been assumed to be at the 'natural' resting position of the arm while in MATLAB the 0° point is in a different position.

Using these values for θ, the forward and inverse kinematics can be calculated. Forward kinematics can be calculated through the values in Figure 3.9 using a series of matrices [85]. Equation 3.4 is used to find the homogenous transformation matrix, A_i, for each joint using four transformation matrices; two rotational matrices and two translation matrices [85]. Each A_i matrix for BEAST can be seen in Equations 3.2 to 3.9. Once each individual transformation matrix has been created, they can be multiplied together to create the overall transformation matrix, T_9^1, for BEAST; seen in Equation 3.10. The matrix T_9^1 also gives the coordinates of the end effector at the value of θ used to create the matrix.

The robotics toolbox [86], has been used to run the forward kinematics calculations

and plot the position of the end effector for a particular value of θ. Figures 3.11, 3.12 and 3.13 show the forwards kinematics positioning of individual joints as plotted in MATLAB for a specific value of θ; in particular, either end of the ROM each joint is capable of.

$$A_i^{i-1} = R_{z,\theta_i} Trans_{z,d_i} Trans_{x,a_i} R_{x,\alpha_i} \tag{3.1}$$

$$= \begin{bmatrix} cos\theta_i & -sin\theta_i & 0 & 0 \\ sin\theta_i & cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos\alpha_i & -sin\alpha_i & 0 \\ 0 & sin\alpha_i & cos\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} cos\theta_i & -sin\theta_i cos\alpha_i & sin\theta_i sin\alpha_i & a_i cos\theta_i \\ sin\theta_i & cos\theta_i cos\alpha_i & -cos\theta_i sin\alpha_i & a_i sin\theta_i \\ 0 & sin\alpha_i & cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_1^0 = \begin{bmatrix} cos\theta_1 & -sin\theta_1 & 0 & 60cos\theta_1 \\ sin\theta_1 & cos\theta_1 & 0 & 60\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.2}$$

$$A_2^1 = \begin{bmatrix} cos\theta_2 & 0 & sin\theta_2 & 50.5cos\theta_2 \\ sin\theta_2 & 0 & -cos\theta_2 & 50.5sin\theta_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.3}$$

$$A_3^2 = \begin{bmatrix} cos(\theta_3 - \frac{\pi}{2}) & 0 & sin(\theta_3 - \frac{\pi}{2}) & 50.5cos(\theta_3 - \frac{\pi}{2}) \\ sin(\theta_3 - \frac{\pi}{2}) & 0 & -cos(\theta_3 - \frac{\pi}{2}) & 50.5sin(\theta_3 - \frac{\pi}{2}) \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.4}$$

$$A_4^3 = \begin{bmatrix} cos\theta_4 & -sin\theta_4 & 0 & 55cos\theta_4 \\ sin\theta_4 & cos\theta_4 & 0 & 55sin\theta_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.5}$$

$$A_5^4 = \begin{bmatrix} cos(\theta_5 + \frac{\pi}{2}) & -sin(\theta_5 + \frac{\pi}{2}) & 0 & 180cos(\theta_5 + \frac{\pi}{2}) \\ sin(\theta_5 + \frac{\pi}{2}) & cos(\theta_5 + \frac{\pi}{2}) & 0 & 180sin(\theta_5 + \frac{\pi}{2}) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.6}$$

$$A_6^5 = \begin{bmatrix} cos\theta_6 & 0 & sin\theta_6 & 160cos\theta_6 \\ sin\theta_6 & 0 & -cos\theta_6 & 160sin\theta_6 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.7}$$

$$A_7^6 = \begin{bmatrix} cos\theta_7 & 0 & sin\theta_7 & 35cos\theta_7 \\ sin\theta_7 & 0 & -cos\theta_7 & 35sin\theta_7 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.8}$$

$$A_8^7 = \begin{bmatrix} cos\theta_8 & -sin\theta_8 & 0 & 35cos\theta_8 \\ sin\theta_8 & cos\theta_8 & 0 & 35sin\theta_8 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.9}$$

$$T_8^0 = A_1^0 A_2^1 A_3^2 A_4^3 A_5^4 A_6^5 A_7^6 A_8^7 \tag{3.10}$$

BEAST:: 9 axis, RRRRRRRRR, stdDH, slowRNE

j	theta	d	a	alpha	offset
1	q1	0	0	1.5708	0
2	q2	0	60	0	0
3	q3	0	50.5	1.5708	0
4	q4	0	50.5	1.5708	-1.5708
5	q5	0	55	0	0
6	q6	0	180	0	1.5708
7	q7	0	160	1.5708	0
8	q8	0	35	1.5708	0
9	q9	0	35	0	0

Figure 3.9: Denavit-Hartenberg parameters table generated in MATLAB; d and a are in mm; alpha and offset are in radians.

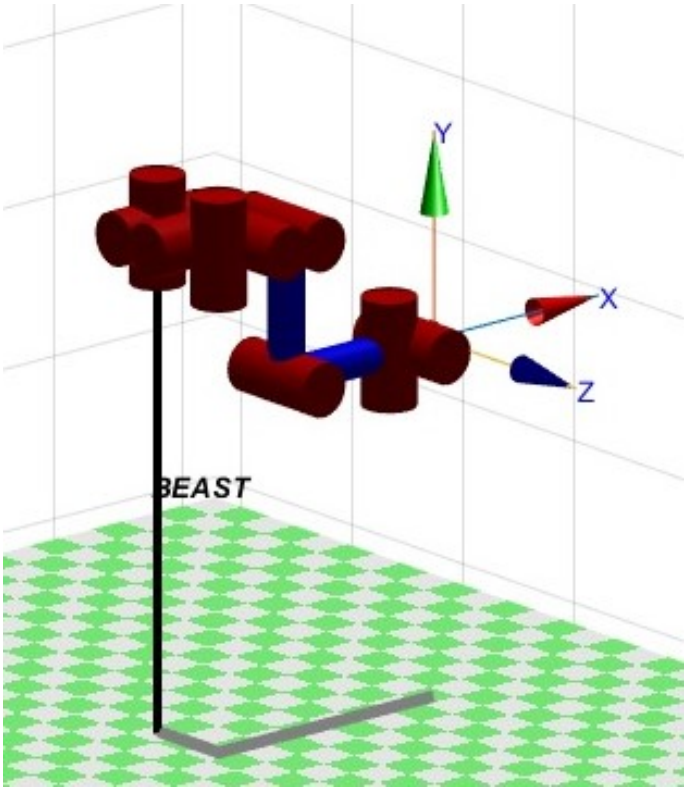
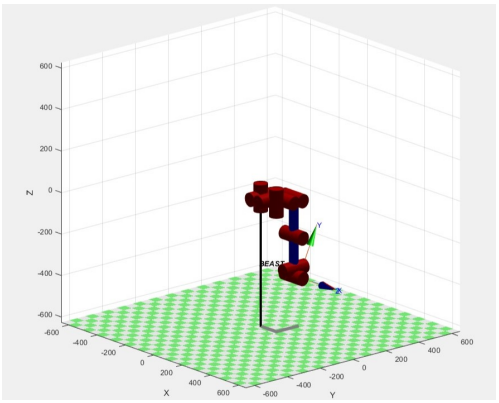
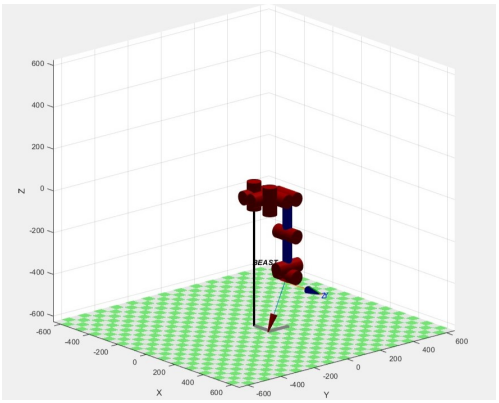


Figure 3.10: Kinematics plot of BEAST V4 with the elbow joint flexed by 90°. Joint 1 is attached to the black line and is at point (0,0).



(a) Wrist abduction 25°



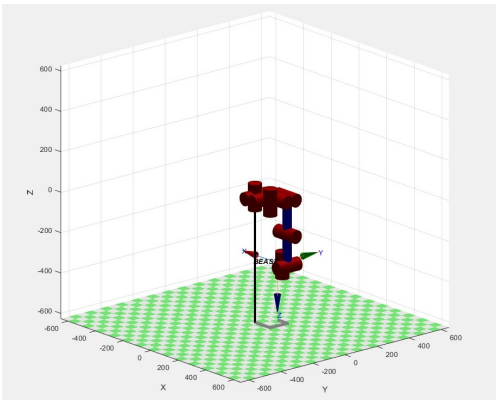
(b) Wrist adduction 65°

```
>> Robot.fkine([0 0 0 0 0 0 0 -0.436332])

ans =
         0         0    1.0000  110.5000
   -0.4226    0.9063         0   90.7100
   -0.9063   -0.4226         0 -406.7000
         0         0         0    1.0000
```

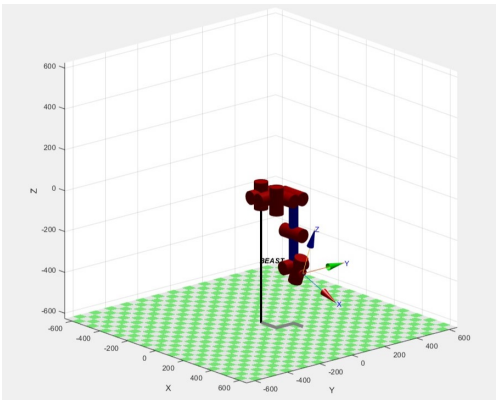
(c) Wrist abduction forward kinematics

```
>> Robot.fkine([0 0 0 0 0 0 0 1.13446])

ans =
         0         0    1.0000  110.5000
    0.9063    0.4226         0  137.2000
   -0.4226    0.9063         0 -389.8000
         0         0         0    1.0000
```

(d) Wrist adduction forward kinematics



(e) Wrist flexion 90°



(f) Wrist extension 70°

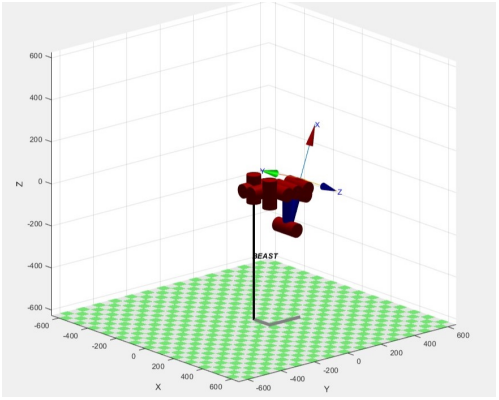
```
>> Robot.fkine([0 0 0 0 0 0 0 pi/2 0])

ans =
   -1.0000         0         0   40.5000
         0    1.0000         0  105.5000
         0         0   -1.0000 -340.0000
         0         0         0    1.0000
```

(g) Wrist flexion forward kinematics

```
>> Robot.fkine([0 0 0 0 0 0 0 -1.22173 0])

ans =
    0.9397         0    0.3420  176.3000
         0    1.0000         0  105.5000
   -0.3420         0    0.9397 -363.9000
         0         0         0    1.0000
```

(h) Wrist Extension forward kinematics

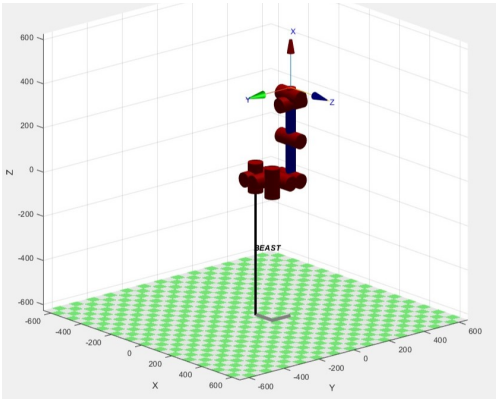
Figure 3.11: Forward kinematics plots and matrices for the wrist.



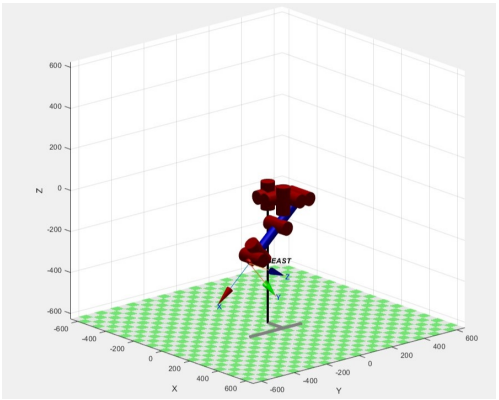
(a) Elbow flexion 160°

```
>> Robot.fkine([0 0 0 0 0 0 -2.79253 0 0])

ans =
         0         0         1     110.5
    0.3420   -0.9397         0     184.2
    0.9397    0.3420         0     36.13
         0         0         0         1
```

(b) Elbow flexion forward kinematics



(c) Shoulder flexion 180°



(d) Shoulder extension 50°

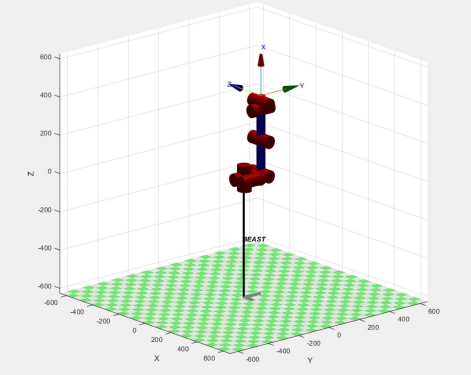
```
>> Robot.fkine([0 0 0 0 0 pi 0 0 0])

ans =
     0     0     1   110.5
     0    -1     0   105.5
     1     0     0     410
     0     0     0       1
```

(e) Shoulder flexion forward kinematics

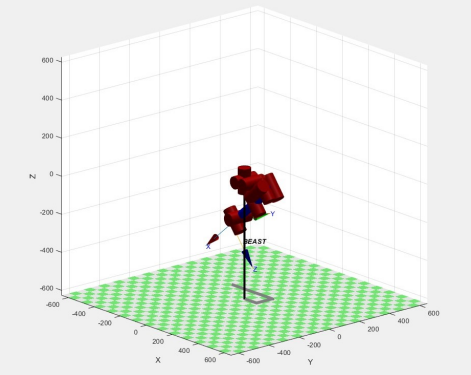
```
>> Robot.fkine([0 0 0 0 0 0.872665 0 0 0])

ans =
         0         0         1     110.5
   -0.7660    0.6428         0    -208.6
   -0.6428   -0.7660         0    -263.5
         0         0         0         1
```

(f) Shoulder extension forward kinematics

Figure 3.12: Forward kinematics plots and matrices for the elbow and shoulder.



(a) Shoulder abduction 180°



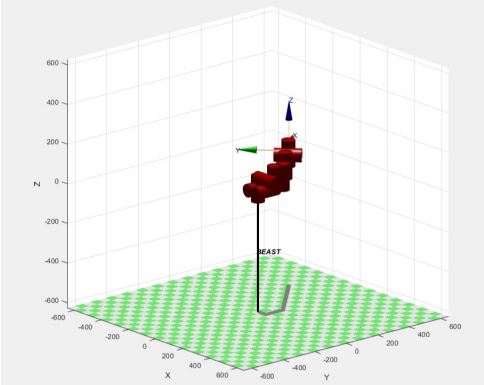
(b) Shoulder adduction 50°

```
>> Robot.fkine([0 0 pi 0 0 0 0 0])

ans =
     0     0    -1     9.5
     0     1     0   105.5
     1     0     0     410
     0     0     0       1
```

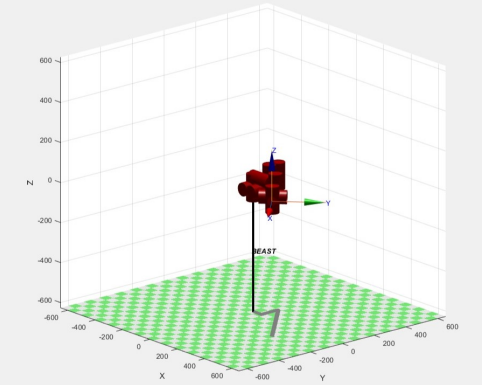
(c) Shoulder abduction forward kinematics

```
>> Robot.fkine([0 0 -0.872665 0 0 0 0 0])

ans =
   -0.7660         0    0.6428   -221.6
         0         1         0    105.5
   -0.6428         0   -0.7660   -302.2
         0         0         0        1
```

(d) Shoulder adduction forward kinematics



(e) Shoulder horizontal abduction 135°



(f) Shoulder horizontal adduction 45°

```
>> Robot.fkine([0 0 pi/2 0 0 -2.35619 0 0])

ans =
   -0.7071   -0.7071         0   -229.9
    0.7071   -0.7071         0   395.4
         0         0         1    50.5
         0         0         0       1
```

(g) Shoulder horizontal abduction forward kinematics

```
>> Robot.fkine([0 0 pi/2 0 0 0.785398 0 0])

ans =
    0.7071    0.7071         0    349.9
   -0.7071    0.7071         0   -184.4
         0         0         1    50.5
         0         0         0       1
```

(h) Shoulder horizontal adduction forward kinematics

Figure 3.13: Forward kinematics plots and matrices for the shoulder

3.5 Actuation System

The actuation system for the design was chosen as a cable actuated system. There are many existing designs that use cable actuation such as GraspyGlove [5], CAFE [8], and SafeGlove [9]; all of which are exoskeletons that actuate the hand. The use of cables in this type of design allows for the fingers to be fully actuated without bulky actuation units at the hand. WristGimbal [17] and RiceWrist-S [18], both actuate the wrist and forearm as grounded systems. There are a number of other exoskeletons that use cables, most notably within the bounds of this thesis; (CADEN)-7 [23], and CAREX-7 [25–27], that actuate the wrist, elbow, and shoulder. These exoskeletons are most like BEAST, with the same joints and type of actuation used. The difference between the existing exoskeletons and BEAST in terms of actuation, is that BEAST is wearable, while the other two are grounded exoskeletons. This means that BEAST can be used in both a smaller hospital environment and, more importantly, a home environment. BEAST is also a bilateral exoskeleton, whereas (CADEN)-7 [23], and CAREX-7 [25–27] are unilateral exoskeletons.

The first step of the design of the actuation system was to determine the amount of torque required to actuate each joint. The torque required to actuate each joint is dependent on the weight of the arm that is being actuated. Table 3.6 shows a selection of data from the book 'Basic Biomechanics' that lists the weight of each segment of the arm as a percentage of the total body weight [74]. Using this and the weight data in Table 3.3, the torque required for each joint of the exoskeleton has been calculated.

Table 3.6: Body Segment Weights as a Percentage of Total Body Weight; and Centre of Gravity Locations as a Percentage of Segment Length Measured from the Proximal End [74]

Segment	**Females**	**Males**	**Females**	**Males**
	Weight (%)		*Centre of Gravity (%)*	
Upper Arm	2.90	3.25	45.8	43.6
Forearm	1.57	1.87	43.4	43.0
Hand	0.50	0.65	46.8	46.8

The torque required for each joint was calculated using Equation 3.11. The force used in this equation was the weight of each segment of the arm, and the distance was

measured from the centre of the joint to the centre of gravity of each segment. The measurements for the various lengths of the arm segments have been taken from Table 3.3. Throughout the following calculations, all of the data used was for the average female. The weight used was therefore 67.76kg.

$$Torque = Force \times Distance \tag{3.11}$$

The simplest torque to calculate was the torque required for the wrist joint, as only the weight of the hand segment needed to be taken into account. The first step of calculating the torque was to calculate the mass of the hand. The hand segment is 0.5% of the total mass of the human body, as seen in Table 3.6. This mass has then been used to calculate the weight of the hand by multiplying by the gravitational field strength; 9.81N/kg. The weight of the hand acts at the centre of gravity of the segment, in this case 46.8% along the length of the hand from the proximal end.

$$Mass = 67.76kg \times 0.5\% = 0.34kg \tag{3.12}$$

$$Weight = Mass \times 9.81 = 3.32N \tag{3.13}$$

$$Distance = 0.18m \times 46.8\% = 0.085m \tag{3.14}$$

$$WristTorque = Force \times Distance = 0.28Nm \tag{3.15}$$

When calculating the torque required for the elbow joint, both the forearm and hand needed to be taken into consideration. The weight for the hand segment is the same as in Equation 3.13; the distance however is the distance calculated in Equation 3.14 plus the length of the forearm segment. The torque required to lift the hand segment by the elbow joint is shown in Equation 3.16; and Equations 3.17-3.20 show the torque required by the elbow joint to lift the forearm segment.

$$Torque = Force \times Distance = 1.74Nm \tag{3.16}$$

$$Mass = 67.76kg \times 1.57\% = 1.06kg \tag{3.17}$$

$$Weight = Mass \times 9.81 = 10.44N \tag{3.18}$$

$$Distance = 0.44m \times 43.4\% = 0.19m \tag{3.19}$$

$$Torque = Force \times Distance = 1.99Nm \tag{3.20}$$

The overall torque required for the elbow joint is therefore 3.74Nm, as seen in Equation 3.21.

$$ElbowTorque = 1.74Nm + 1.99Nm = 3.74Nm \tag{3.21}$$

Following the same process as the other joints, the torque for the shoulder has been calculated by taking into account the forearm and hand segments as well as the upper arm segment. Equation 3.22 adds together the calculated torques for the hand, forearm and upper arm segments in that order; giving the total torque for the shoulder as 11.29Nm.

$$ShoulderTorque = 2.86Nm + 5.48Nm + 2.95Nm = 11.29Nm \tag{3.22}$$

When deciding on the components needed to create the design, the torque calculated for each joint can then be used to determine what type of motor is required. It allows for a different motor to be used at each joint, one that is capable of the required torque but not too much more. This will help cut down on weight and cost as the larger and more powerful motors are more expensive. Instead of using the exact torque as calculated in the above equations, it is best to include a safety factor to ensure that the torque the motors are capable of is more than enough to carry out the rehabilitation movements. This keeps patients safer as the device is safer to use.

3.6 Conclusion

The mechanical design of BEAST started out as a very simple design that only aimed to have the range of motion needed for rehabilitation exercises. Although it did mostly achieve this it had some issues with the full range of motion of the shoulder. V2 improved both the aesthetics and the shoulder joint design, particularly taking into

account the movement of the glenohumeral joint. A handle was added, and a more robust back brace was designed. V3 fixed issues with the range of motion of the elbow joint and removed the handle and back brace as 3D printed parts. Instead of a back brace, a material strap system would be attached to the 3D printed parts.

V4 was a small redesign of V3, mainly in order to allow the design to be built as a table-top test rig. It also added an actuation and cable routing system. Each of the changes made between V1 and V4 created a better and more feasible design, particularly in terms of improving the range of motion; but also in terms of improving the aesthetics and patient experience. Although proper testing will be carried out in the following chapter, the initial feasibility tests show promising results for BEAST V4. This includes the very light movement testing that was done by printing the exoskeleton, as well as the kinematics analysis that was carried out. The kinematics analysis proved that the exoskeleton was capable of the full range of motion for each joint of the arm.

The actuation system was also considered in this chapter, particularly the torque calculations. It was found that a torque of 1.99Nm would be necessary to actuate the wrist; 3.74Nm would be needed to actuate the elbow; and 11.29Nm would be required for the shoulder joint as a whole. As these calculations were done using the measurements for the average female, the torque required is going to be significantly higher for a larger person, and would also need to include a safety factor on top of this.

The overall design of BEAST V4 includes several novel factors, namely the design of a wearable system that is actuated through cables. It meets many of the specification points laid out at the beginning of the chapter; the performance, target product cost, availability of components, manufacturing facilities, size and weight, materials, and market constraints. Other aspects of the specification would need to be further investigated to check that the design adheres to them, particularly through in-depth testing with patients.

Chapter 4

Design Validation

Due to the COVID-19 pandemic starting in 2020, the following chapter had to include various adjustments to the original prototype plan due to the lockdown restrictions. The original plan consisted of building a prototype and carrying out testing with stroke patients. The new plan needed to take into account the inability to access University premises, manufacturing lab spaces, and patients. Fortunately a 3D printer was available at home during this time, albeit with a smaller print capacity than was ideal. Not being able to access patients posed more of an issue, particularly with no knowledge of when this would be possible again. By the end of 2020, with no confirmation of when the world would get back to normal, there were two options. One, to assume that access to patients would be possible within the year; or two, to assume that access to patients would not be possible. In this case, option number two seemed like the best one as nothing could be guaranteed. Therefore, the exoskeleton prototype was designed and 3D printed with the at-home printer on a smaller scale. The following chapter outlines the scale version of the prototype, including the electronics, and some basic testing that was carried out.

4.1 Prototype

Several prototypes were built throughout the design process in order to check the feasibility of the designs. BEAST V1 was printed as a very small and quick print to check that the initial design could move as expected. BEAST V2 was printed to test the new shoulder joint. It was printed at what was supposed to be full size but due to an error that was made in the measurements when setting up Solidworks the print actually came out as a small version again. It was however bigger than the V1 print, and was still good enough for the testing purposes of the print. BEAST V3 was printed full size with a new elbow-shoulder joint. At this point in the prototyping there was a change in the aims of the project due to Covid-19 and so the prototyping was halted for some time. The next prototype was BEAST V4 which was the adjusted design shown in Figure 3.5. It was printed on an Ender 5 Pro, a printer that has a print bed size of 220 x 220 x 300mm. The size of the printer bed means that the exoskeleton could not be printed full size, and therefore needed to be adjusted to fit the size of the print bed. The frame for the stand was also designed in order for it to fit within the print bed, allowing the prototype to be fully printed and assembled from home. Tough PLA was used to print the exoskeleton parts, as it is one of the easiest materials to print and

every printer is capable of printing it. Without the material testing that was initially planned, it was not possible to determine whether a different printing material would have been more suitable.

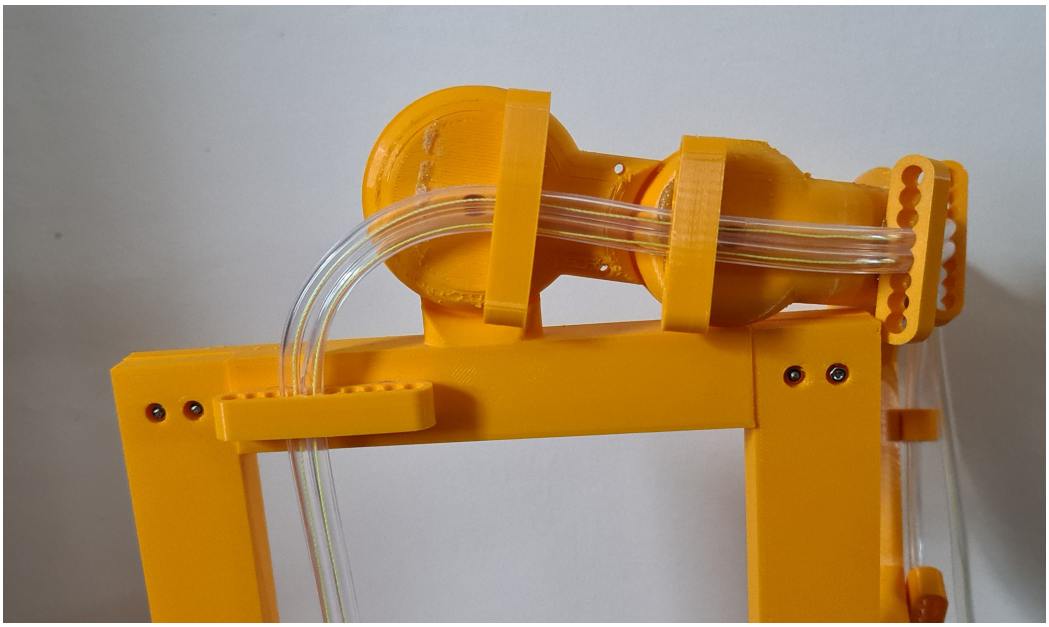


Figure 4.1: Initial prototype of BEAST, focusing on the cable routing system

The prototype was printed and built, and can be partially seen in Figure 4.1, with the cable actuation system added. Initially only the cables were added, using PVC tubing to route the cables from the joint to the motor. The cable chosen for the prototype was 0.44mm polyethylene braided fishing line that is capable of a maximum load of 70lb. This was chosen over stainless steel cabling as it is more flexible, lighter, and thinner. Previous exoskeleton designs have generally always used steel cabling [12][23][69]. With a few cables set up, a quick test showed that the plastic tubing was too inflexible to allow for the movement necessary. Pulling the end of the cable that would be attached to the motor moved the exoskeleton very minimally. Although the cable moved freely, the tubing did not bend to allow for movement of the exoskeleton. The routing system needed to be redesigned to remove the tubing so that the exoskeleton joints could move. The holes on the routing system were reduced in size so that the cable fit through on its own without the tubing. Figure 4.7 shows the new routing system with the cables added.

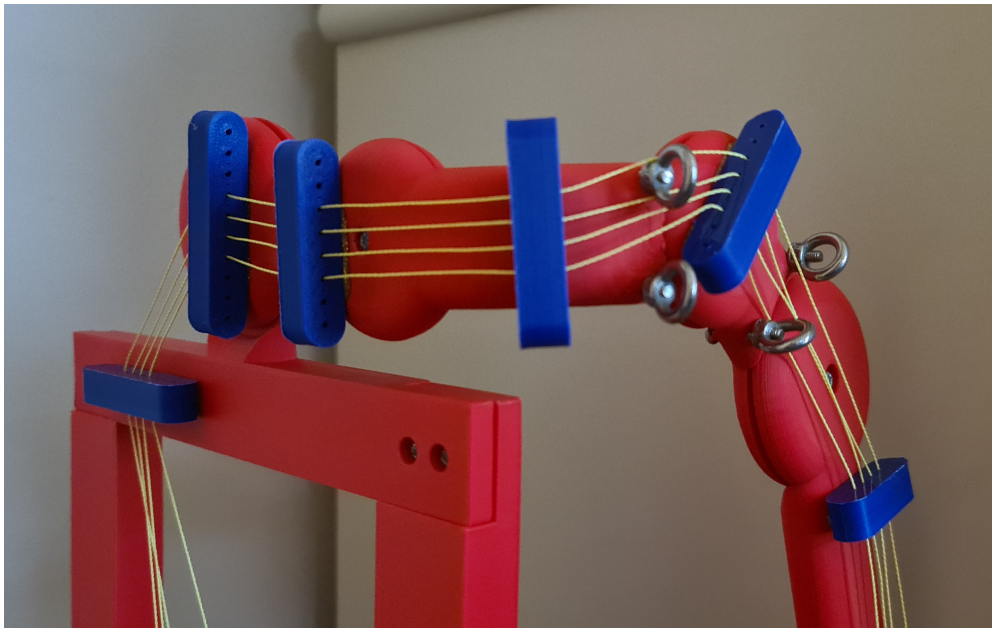


Figure 4.2: Final prototype of BEAST

One end of each cable was attached to a hook eye bolt, and the other to the pulley and motor. The centre of the pulleys were too large for the motor shaft so a small cylinder was 3D printed and fitted to the inside of the pulleys to allow the motor shaft to be properly attached. Micro metal motors were chosen due to their high torque compared to their size, particularly as their overall size is very small [87]. The 100:1 high power micro metals are capable of a torque of 1.7kgcm, which should theoretically be plenty for the test prototype. If a full size exoskeleton was being built that was going to be worn by a patient, these motors would be much too small, and alternatives such as Maxon motors would need to be considered. Maxon motors are also small compared to their torque capabilities but are very expensive with a starting price of almost £100 compared to the approximately £15 price tag of the micro metal motors. The pulleys used are sewing bobbins used for thread on sewing machines. They are small, lightweight, easily accessible, and cheap. The holes on the sides of the bobbins allow for the cable to be tied on, and the cable can then wrap around the bobbin as the motor turns. Two motors are used for each joint, one for each direction of movement. As the cable on one side is reeled in, the other is let out to allow for the movement.

When building the prototype and beginning to test the cable system, it became apparent that there were some fairly large flaws in the system. Particularly, that the

micro metals were so fragile that just building the prototype seemed to have damaged some of them. They were either burnt out and would whine when turned on without turning, or would simply not turn on at all. Without enough spare motors to replace the ones that had burnt out, it was not possible to properly test the prototype system. The cables were also catching on the hook eye bolts, so the cables would need to be moved to new anchor points that would prevent other cables from getting caught. The new anchor points would need to be positioned on the links directly and so would require a new 3D print, something that at this point was not possible. Removing some of the hook eye bolts and manually pulling the cables did show that the actuation system would work with stronger motors and no obstacles in the way of the cables. It is also possible that the holes for the cable routing system were too small and so were creating an unnecessary amount of friction on the cables, preventing free movement.

4.2 Electronics

The electronics system is made up of the microcontroller, motors and sensors. The microcontroller used for the prototype was the Teensy 4.0 [88]. It uses Arduino software and libraries but on a much smaller platform than any of the Arduino boards, with a footprint of only 18mm by 36mm. The micro metal motors were also chosen partly because they are compatible with the teensy board, in conjunction with the DRV8833 motor driver [89]. Each motor driver can drive a pair of motors, one for each direction of motion of the joint. An encoder was attached to each motor to ensure that the correct amount of cable is reeled in or let out to control the movement of each joint. The encoders used are magnetic encoders specifically designed to be used with the micro metal motors [90]. Figure 4.3 shows the circuit diagram for the electronics of BEAST. For simplicities sake it only shows one motor and encoder pair and their motor controller, and one sensor and the Inter-Integrated Circuit (I2C) expander that allows more than two sensors to be used. The sensors used for the active arm are IMU sensors, specifically the Sparkfun LSM9DS1 [91].

The IMU sensors worn on the active arm turn the exoskeleton from a unilateral system to a bilateral one. Using the I2C expander chip, up to eight IMU sensors can be added and controlled through the Teensy despite the Teensy only having two sets of I2C connections. Once the prototype was built, the system could be tested. Individually the sensors and motor systems had been built and tested to ensure they

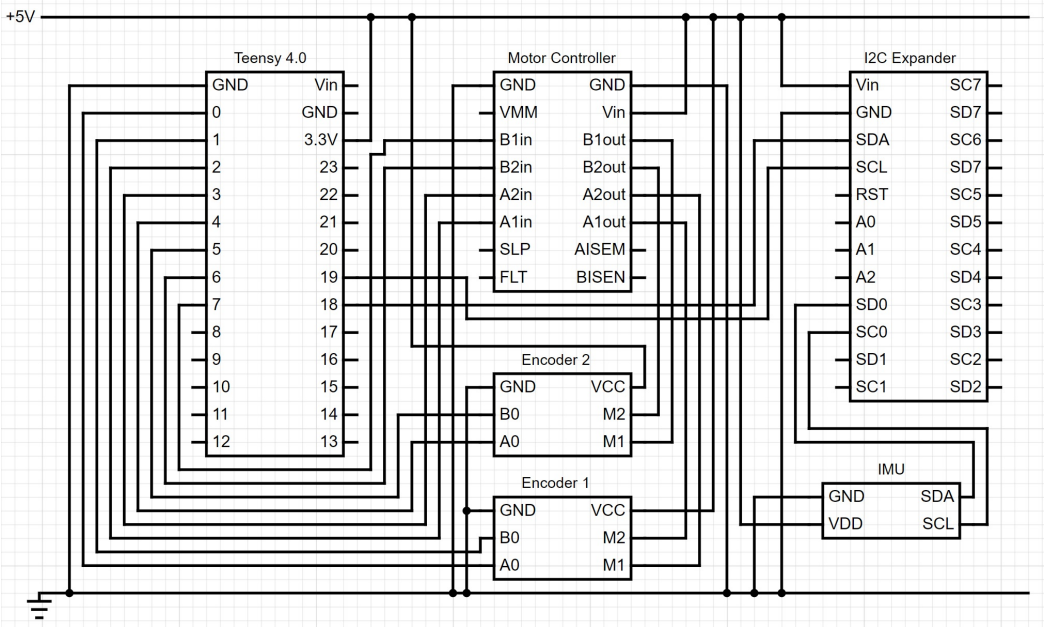


Figure 4.3: Circuit diagram for the electronics system of BEAST, showing one motor and encoder pair and their motor controller, and one IMU sensor and the I2C expander required for further sensors

worked as expected. Using pulse width modulation (PWM), the motor speed could be set to control how fast the cable reel was turned. The speed does not really need to be varied during normal exoskeleton operation so a single suitable speed just needed to be selected and used. The micro metal motors are capable of up to 310 RPM with no load when running off a 6V supply. The magnetic encoders were also tested. As the magnet on the end of the motor shaft rotates it pulls the digital signal to VCC or drives it low depending on which magnetic field has been applied. This creates a square wave on the output of each side of the encoder, where a full rotation of the motor is equal to one period of the square wave. Counting the number of times the signal goes high or low tracks the number of rotations the motor has done. This system however relies on the motor needing to rotate fully every time it runs, it does not allow for partial rotations. It also relies on the encoder magnet being in the same position every time it starts, otherwise it can count up before it's done a full rotation. The micro metals are therefore not the most accurate motors and ideally in a future prototype a different kind of motor would be used; potentially a stepper motor to improve accuracy.

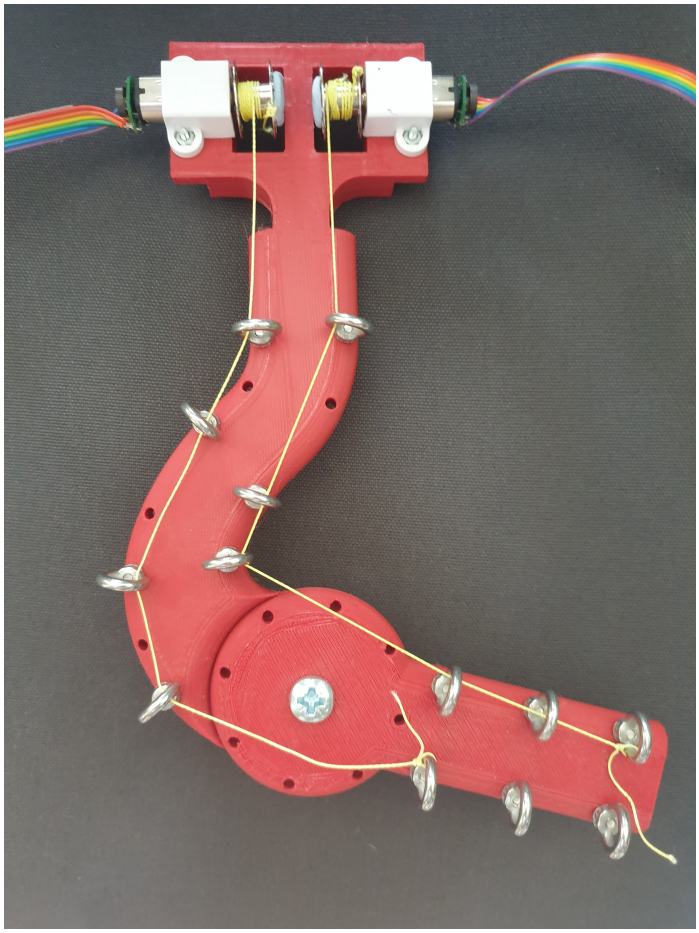


Figure 4.4: Cable actuation system test rig for the elbow joint

As part of the testing for the electronics systems, a stand alone version of the elbow joint was built, seen in Figure 4.4. This prototype was used to test the feasibility of the actuation system, but mainly that the electronics circuit would work as expected. Figure 4.5 shows the circuit used for the elbow joint prototype, taken from the circuit diagram in Figure 4.3. This circuit can then be very easily expanded to include the full number of motors, encoders and sensors. The IMU sensor circuit was built and tested to ensure that the position of the sensors could be read and correctly interpreted, but again due to the issues with the micro metals, no control system was created and so the sensor and motor systems were not fully integrated. Figures 4.6 and 4.7 show a close up of the motor and pulley system, and the final prototype.

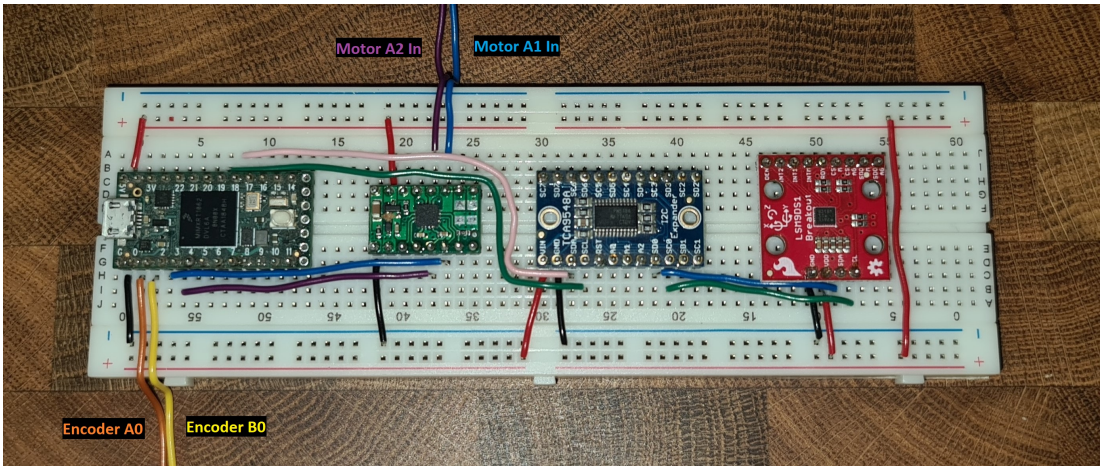


Figure 4.5: Circuit for the electronics system of BEAST, showing the teensy, one motor and encoder, the motor controller, one IMU sensor, and the I2C expander required for further sensors

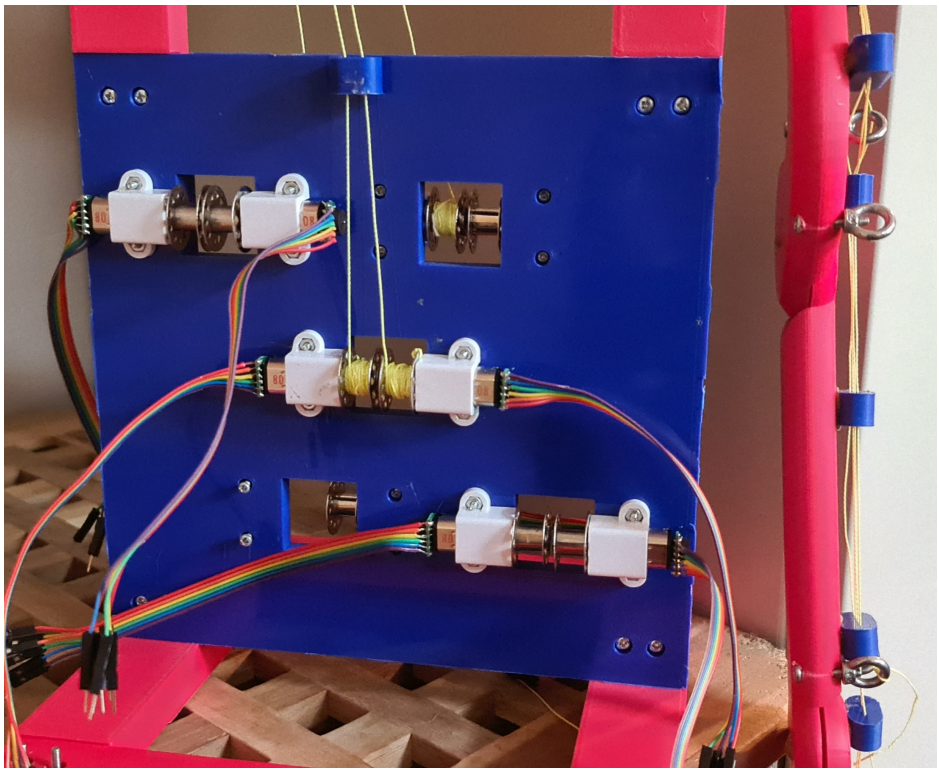


Figure 4.6: A close up of the motor and pulley system of BEAST

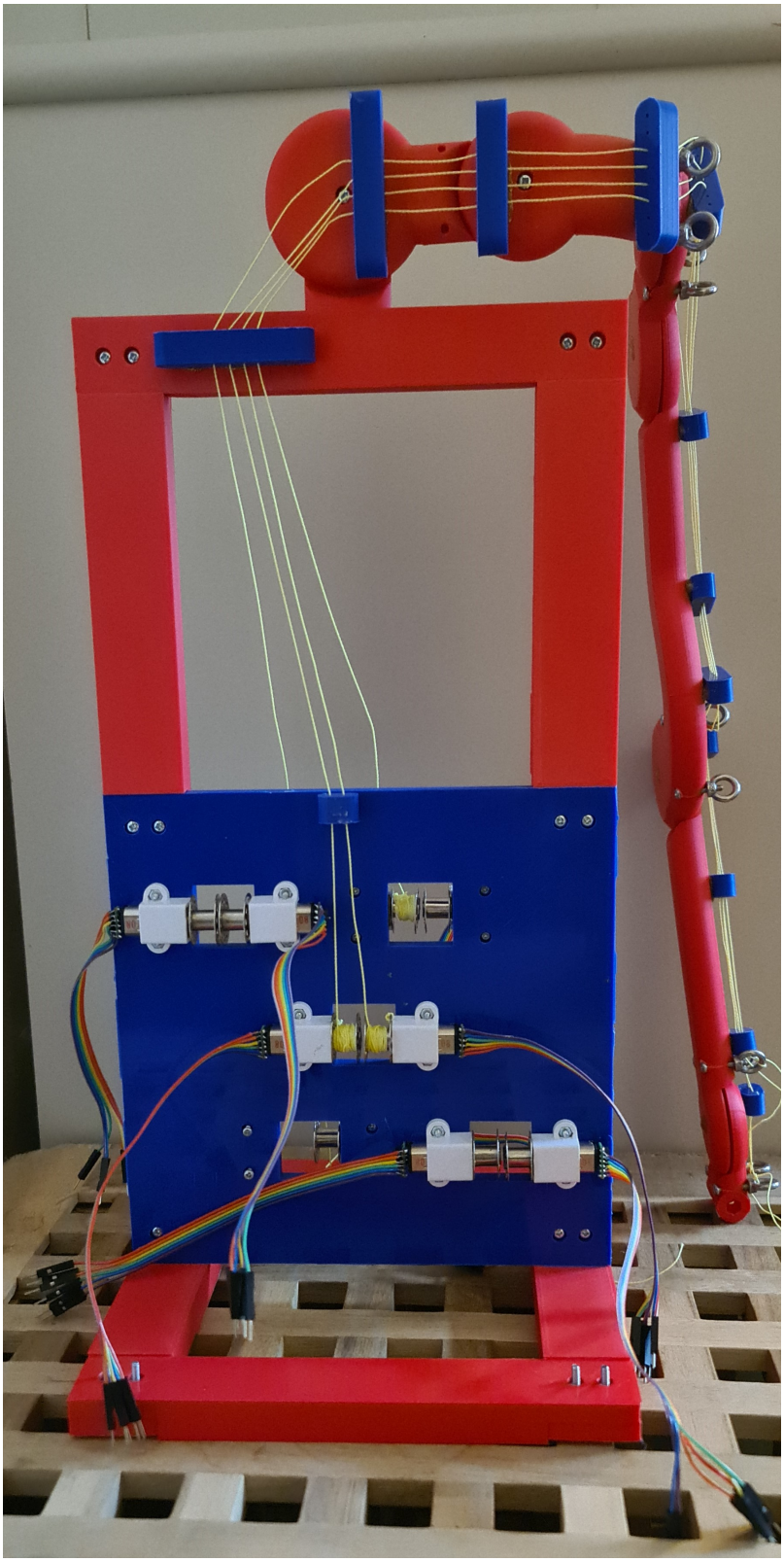
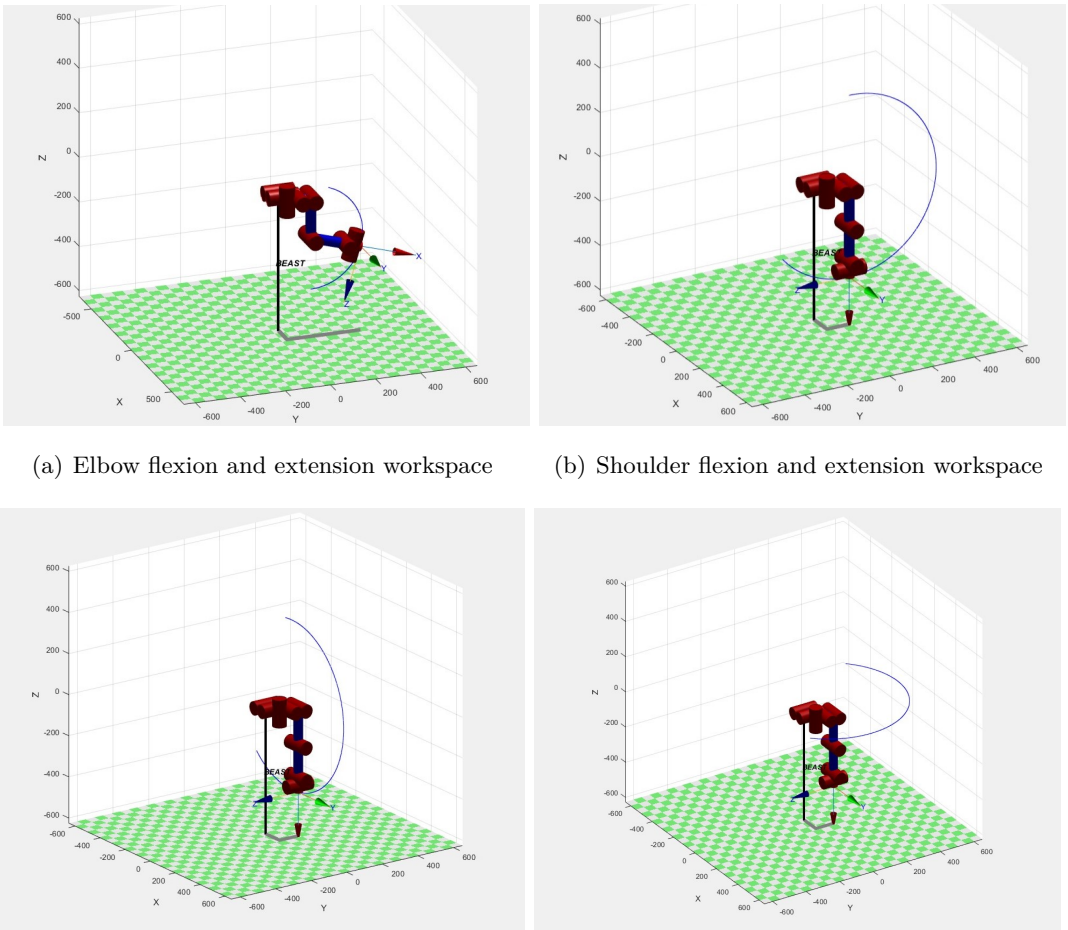


Figure 4.7: The final prototype of BEAST

4.3 Workspace Analysis

Using the Robotics Toolbox first used in Chapter 3 [86], the workspace of the exoskeleton can be determined. It does this by looping through the plotting function used for the kinematics plots, putting random values of θ in the T_9^1 matrix each time. The workspace of the exoskeleton needs to match the ROM of the human arm, or at least of the motions that are being rehabilitated. Figure 4.8 shows the trajectory workspace plots of flexion and extension in the elbow; flexion and extension, abduction and adduction, and horizontal abduction and adduction in the shoulder. The trajectory plots of each joint motion allow for verification of the exoskeleton and the joint ranges.



(a) Elbow flexion and extension workspace

(b) Shoulder flexion and extension workspace

(c) Shoulder abduction and adduction workspace

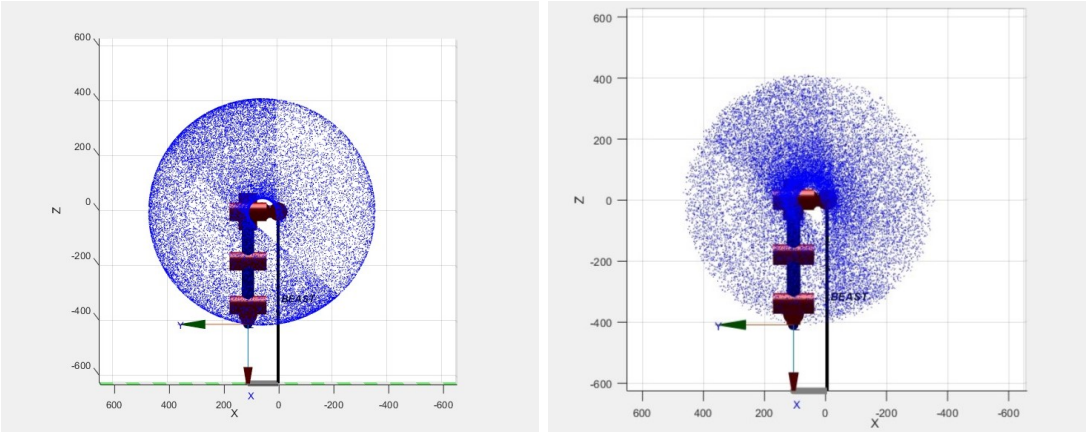
(d) Shoulder horizontal abduction and adduction workspace

Figure 4.8: Various trajectory plots of the elbow and shoulder joints

With the trajectories checked, the workspace of the exoskeleton could then be plotted. These were plotted in stages to ensure that the workspace shown was as expected. Any anomalies would have meant that the workspace was being plotted incorrectly and so adjustments would need to be made. Some of the initial plots that were created during the process had clear anomalies such as points that would have been inside the users head, or required the arm to move through the user's body, two things which are obviously impossible. First, the workspace of the elbow and shoulder flexion and extension movements were plotted, seen in Figure 4.10(a). This shows a clear workspace area with an outermost arc matching the trajectory plotted in Figure 4.8(b), which is to be expected. The rest of the points are various plots of positions the hand could be in within the range of shoulder and elbow flexion and extension. Then, the overall shoulder workspace was plotted, shown in the rest of Figure 4.10. This removed the movement of the elbow and focused on the three shoulder movements to check that the limits of movement were expected. Figure 4.10 shows a very clear vertical line in the middle of the workspace. This vertical line is the edge of the horizontal abduction movement when the arm is across the front of the body. When at the edge of this movement the shoulder is still able to continue with the flexion and abduction movements, creating the very firm vertical line shown in the plot. Finally, the full exoskeleton workspace was created, seen in Figure 4.11. The first iteration of the full exoskeleton had multiple anomalies that initially didn't make much sense. It showed an almost entirely spherical workspace plot, something that is again clearly impossible when taking into account the position of the human body. Upon further inspection it became clear that because the function used to create the plots simply took the upper and lower limits of each joint movement and plotted random points within those limits, there was an excess of movement when allowing all three shoulder movements to be fully actuated at the same time. This did not take into account situations where the body itself may impact movement. For example, when the human arm is raised vertically above the head, abduction is not possible due to the position of the head, however when the arm is almost vertical, abduction is possible across the front of the head. Therefore, plotting the workspace of the full exoskeleton is much more complicated than the initial plot that was created.

When creating the plots for the workspace of BEAST, the horizontal abduction and adduction movements were removed. This was because it was not possible to include

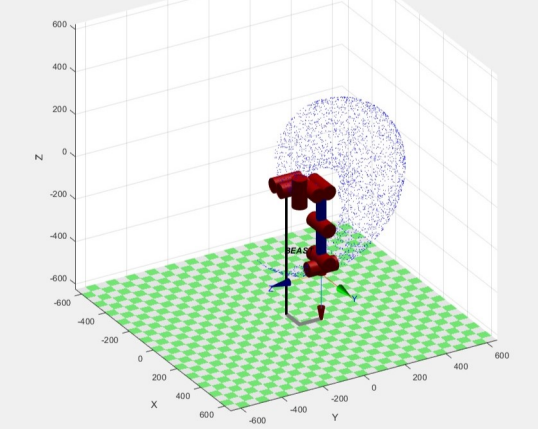
this in such a way that the horizontal abduction and adduction were not being carried out at the same time as the flexion and extension movements. As they are actuated using joints 4 and 5, they are technically separate movements, however they would never be fully actuated at the same time as the arm is simply not capable of this movement. The idea for these two joints is that one would be used when actuating the flexion and extension, and the other would be used when actuating the horizontal abduction and adduction. This may end up being done slightly differently in practice, for example using one of the joints for both movements and the other as a passive joint to allow for excess movement. Either way, if both of these full ranges of motion were to be used in the workspace analysis it would look like the exoskeleton was capable of a larger movement than in reality. The horizontal abduction and adduction movement was chosen to be removed when creating the workspace of BEAST as its range falls within the range of the flexion and extension movement, and is therefore incorporated within the workspace. This gives what can be seen as an almost entirely correct workspace except for the small gap shown in the very front of the workspace. This can be seen in Figure 4.9; which also shows the same gap in the workspace after adding the elbow and wrist joints into the workspace. It can be seen that this does make the gap smaller, improving the overall workspace.



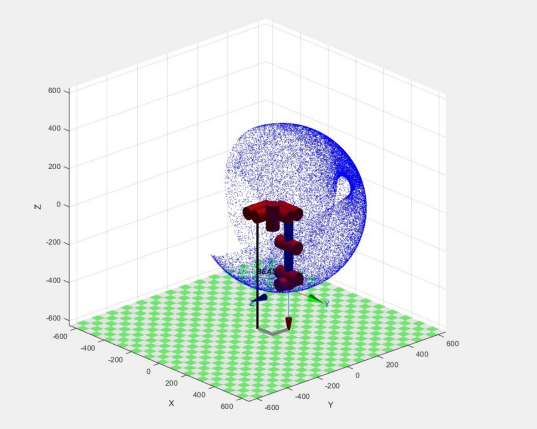
(a) Shoulder workspace front view

(b) Whole workspace front view

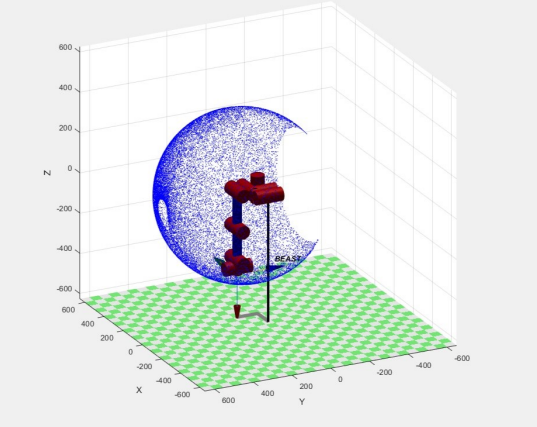
Figure 4.9: Workspace plots showing a gap in the workspace of BEAST V4



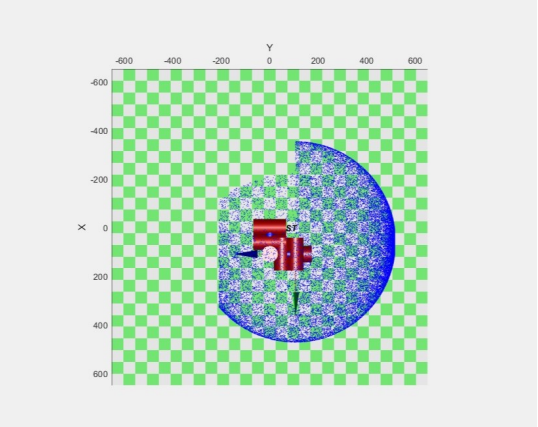
(a) Shoulder and elbow workspace



(b) Shoulder workspace viewed from behind the right shoulder

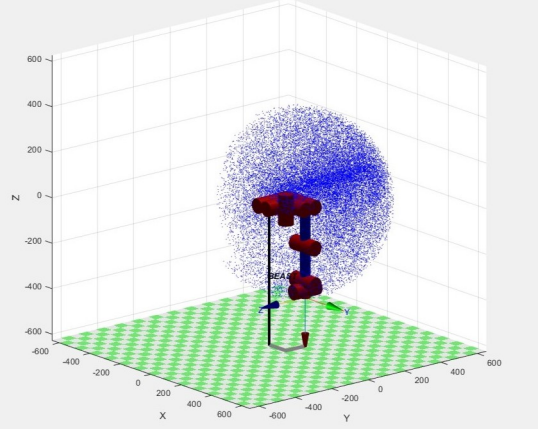


(c) Shoulder workspace viewed from in front of the body

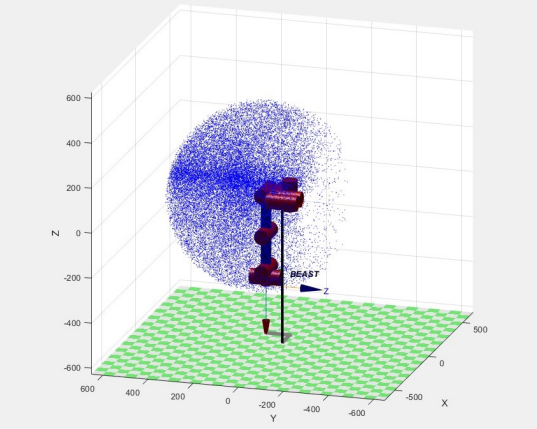


(d) Shoulder workspace viewed from directly above

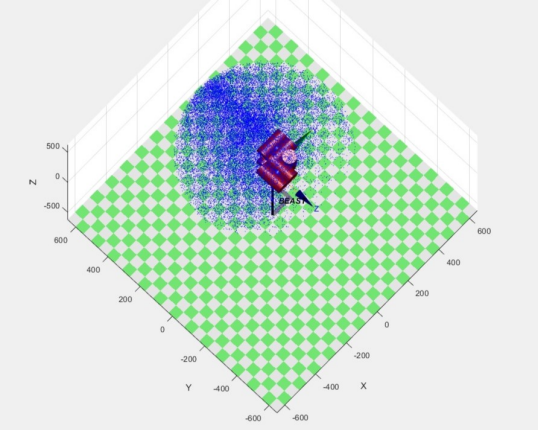
Figure 4.10: Various workspace plots of the elbow and shoulder joints



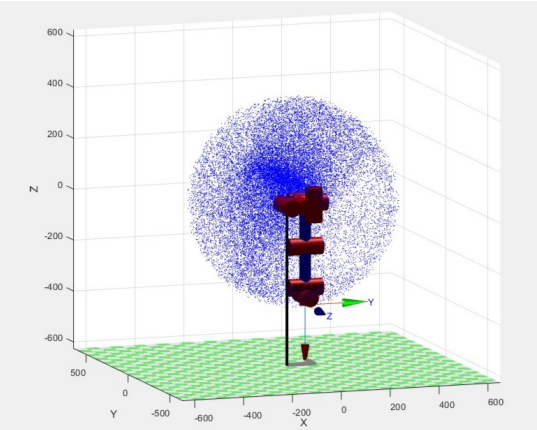
(a) Full workspace viewed from behind the right shoulder



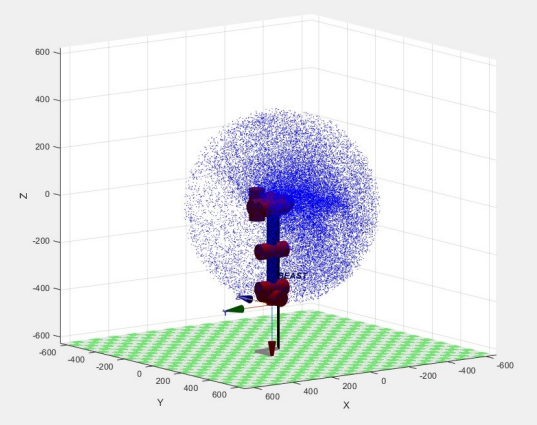
(b) Full workspace viewed from over the left shoulder



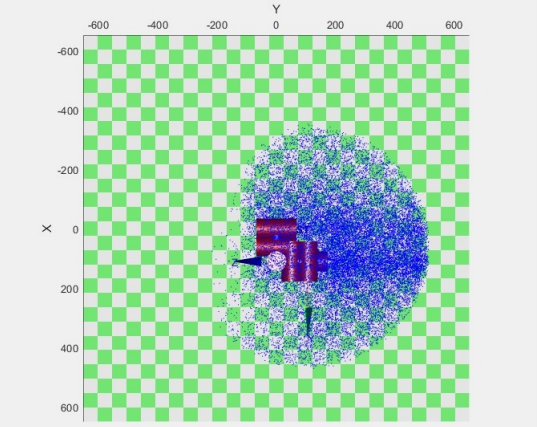
(c) Full workspace viewed from above the left shoulder



(d) Full workspace viewed from behind



(e) Full workspace viewed from the front



(f) Full workspace viewed from directly above

Figure 4.11: Various workspace plots of the whole BEAST V4 workspace

4.4 Conclusion

While the overall prototype was successfully constructed, and individual sections of it were successfully tested, there were some issues when testing the prototype as a whole. With the motors being too weak to withstand the building and testing of the prototype, no proper testing could be undertaken to fully validate the design. Although small areas of the prototype were manually validated, no results were gathered to collaborate this. Theoretically the design does work, the cable actuation system moves the exoskeleton as expected, and with a few small adjustments to the cable routing system to reduce friction and remove the hook eye bolts, it would be greatly improved. Generally, the prototype stage of the project did not go to plan, and there are several adjustments that would need to be made to create a fully working prototype.

The workspace analysis proved that the exoskeleton was capable of the full range of motion for each joint of the arm, as well as covering the majority of the workspace of the human arm. The workspace of both the shoulder joints and the full workspace did showcase a small area in front of the exoskeleton that was unable to be reached. Further work would ideally need to be carried out within the workspace calculations to really understand how this gap can be filled. The likelihood is that if full prototype testing could have been carried out this gap would be seen to be non-existent when including the horizontal abduction and adduction movement. If this was not to be the case then minor adjustments would likely to be needed for the overall shoulder joint to allow for further movement. This is something that could be done at the optimisation stage.

Chapter 5

Patient Needs in Stroke Rehabilitation

5.1 Introduction

A key aspect of any type of design work is to consider the end user of the product. The majority of current literature surrounding exoskeletons has a design process which is then turned into a prototype. The prototype then goes through several rounds of testing and design iterations before being considered for clinical trial. The clinical trial stage is usually the first stage that patients and medical professionals are given the chance to offer feedback on the exoskeleton. This often leads to further iterations of the design in order to make adjustments to aspects of the design that don't suit what the patient or medical professionals require from the device. These later adjustments could be avoided if the end users were included earlier in the design process. The surveys carried out in this thesis aim to do just that.

An upper limb exoskeleton can be designed from a purely mechanical point of view by creating a specification of engineering requirements. These requirements are mainly performance based, such as the types of joints that need actuating, the range of motion of those joints, the type of actuation and the type of sensing. These requirements were determined in Section 3.2, and a design was created that is able to carry out all the relevant movements for rehabilitation of the upper limb in Section 3.3. However, an exoskeleton that works from an engineering standpoint is not necessarily the best option from a patient's or a medical professional's point of view. An upper limb exoskeleton that is capable of the full range of motion of the human arm may not actually be the most useful when put in a clinical environment such as a hospital, something that does not seem to have been considered in existing literature. Considering both the engineering requirements and patient needs alongside each other would result in a more rounded design overall. This is where the survey of patient needs comes into play, allowing patient requirements to be considered during the design phase.

There are several papers within the existing literature that discuss patient needs after stroke [92–98]. These papers carry out interviews with anywhere from 4 patients [94], to 72 patients [96]. Most of the papers use in-depth interviews [92–95, 98], with one using focus groups [96], and one using medical testing [97]. Although all of these papers discuss very relevant information on patient needs, they focus on the medical, social and emotional needs of patients after stroke, rather than the needs of patients during rehabilitation. No papers were found that considered the specific needs of patients when using an exoskeleton during rehabilitation. Therefore, the following surveys have been

undertaken to gather data that can be specifically applied to rehabilitation with an exoskeleton, and how an exoskeleton can be used to improve the rehabilitation process. It is a different type of survey from existing literature due to it being approached from an engineering point of view in order to create a medically relevant device that considers patient needs.

Once the data from these surveys have been collected, it will be analysed so that the data that has been collected can be used to create relevant optimisation strategies for the existing design of BEAST. Although BEAST has been fully designed already, it was important that participants of the surveys could be shown an existing device to base their answers off. It is very possible that many of the participants have never seen an exoskeleton before. The aim here was not to use patient needs to design an exoskeleton, but instead to use patient needs to optimise an existing design so that the overall engineering requirements were properly considered before the patient needs were added. However, it was important that the patient requirements were added before a clinical trial phase was considered so that the initial design was patient focused. These surveys contribute a new area of patient needs considerations to the field of exoskeleton design.

5.2 Initial Survey

The first step that was taken to include end users in the design process was to meet with a group of physiotherapists for an informal chat. An initial survey design was taken to ask for their feedback. This initial survey featured the design of BEAST V2 on it and aimed to be distributed in person. During the discussion with the physiotherapists some good information was gathered, in particular that the handle of BEAST V2 would be a bad design for many stroke patients. This is due to the increased risk of the patient developing spasticity in the hand. The physiotherapists made it clear that patients are generally discouraged from carrying out too many gripping motions as this can increase the severity of spasticity if it already exists, or make the patient develop spasticity if it does not already exist. The general consensus of the feedback from the physiotherapists was that the survey asked many of the right questions, but needed some improvement on how to word some of the questions and response options. In particular, the ranking style question was recommended to be changed from ranking all of the design aspects in comparison to each other, to a question where each design

aspect is rated independently from each other. This change not only makes it easier for participants to answer the question but also for the results to be used in analysis at a later stage. Several other small changes were made to the wording of various questions, in both the physiotherapist and patient surveys; such as the types of exercises given as response options, and the factors that patients find difficult during rehabilitation.

After this initial meeting, the plan was to carry out more in person discussions through focus groups with both physiotherapists and patients. Surveys would also be distributed across both groups, and further focus groups would be carried out throughout the design process. With the COVID-19 lockdown in place, this became impossible and so a new arrangement needed to be made. Focus groups were no longer possible, and in person meetings were also off the table. Instead, an online survey was designed based off the initial survey shown to physiotherapists. This could be distributed online and although it would not be able to gather the same level of feedback throughout the design process, it would at least collect data about patient needs when using an exoskeleton for stroke rehabilitation.

5.3 Survey Design

Two different surveys were designed, one for medical professionals (seen in Appendix B), and one for patients (seen in Appendix C). They aimed to ask similar questions but were tailored to each specific group, particularly with the language that was used in each survey. The survey for medical professionals used medical terms that experts in the field would be familiar with, while the patient survey used simpler terms that anyone without a medical background would be able to understand. It was important that every person eligible to take the surveys was able to understand them without having to ask for clarification.

The surveys were designed on Qualtrics [99], a free survey design website that not only made designing the surveys easy, but also allowed a report of the results to be generated. Once the surveys had been designed on Qualtrics, they could then be uploaded onto another survey website, Prolific [100]. Prolific is a website that matches surveys from researchers with participants that are eligible for each survey based on the chosen criteria. Prolific allows participants to be filtered through various prescreening criteria that each participant has already filled in on their profile. This allows surveys to only be shown to participants that already fit the criteria, and prevents participants

from having to screen surveys themselves. Age, gender, nationality, employment domain, and a students field of study are just some of the options available through the prescreening criteria.

Unfortunately, there was no prescreening criteria that matched what was needed for the surveys carried out, and as such a prescreening survey was required (shown in Appendix A). This is because Prolific requires that all surveys shown to a participant are ones that they are eligible to take. The prescreening survey used consisted of two main questions; one that would identify patients that had suffered from a stroke and completed some amount of rehabilitation because of it; and one that would identify medical professionals that either currently worked in or had previously worked in some form of stroke or upper limb physiotherapy. It also gathered the participants Prolific ID. Each participant has their own unique ID that allows them to be added to a later study while also not giving the researcher any personal information, therefore making the data collected fully anonymous. This allows all of the data collected in these surveys to adhere to the data protection rules laid out in the ethical approval granted by the University of Leeds. Ethical approval was sought and granted for all three of the individual surveys, with the form being shown in Appendix D; ethical approval number MEEC 21-036.

The prescreening survey had three questions; the first simply gathered the participants ID number. The participant was then shown the main two questions; the first of which was aimed at identifying medical professionals that worked in the rehabilitation field; and the second that aimed to identify patients that had had a stroke. The survey was set up on Prolific to allow for 600 responses; with a payment of £10 an hour. Therefore, each participant would receive approximately £0.16 for taking part in the prescreening survey. Once participants started the survey, they could either complete the survey and receive a monetary award for their time, or they could return the survey if they decided not to complete it. Participants who started the survey and then did neither of these would time out after an amount of time set by Prolific based on the average time taken to complete the survey. As the prescreening survey was only three questions, the time to take the survey was only one minute; with Prolific setting the time limit for 13 minutes. During the collection of results, 42 participants returned their surveys, and 15 participants timed out. No results were collected from these participants. On Prolific, 600 participants are shown to have completed the survey, while

on Qualtrics, 603 responses were gathered. All the results that were gathered are full responses so the extra three responses appear to be from an error in Prolific allowing more than the allotted number of participants to access the survey.

Question two of the prescreening survey asked participants to select which category they were in out of the following;

1. I am a medical professional that works in stroke rehabilitation (10 responses)
2. I am a medical professional that works in upper limb rehabilitation (2 responses)
3. I am a medical professional that works in lower limb rehabilitation (2 responses)
4. I am (or have been) a medical professional that previously worked in stroke rehabilitation (10 responses)
5. I am (or have been) a medical professional that previously worked in upper limb rehabilitation (2 responses)
6. I am (or have been) a medical professional that previously worked in lower limb rehabilitation (5 responses)
7. I am a medical professional that works in the rehabilitation capacity specified below (2 responses)
8. I am (or have been) a medical professional that has previously worked in the rehabilitation field in another capacity specified below (2 responses)
9. I am a medical professional with no experience in rehabilitation (40 responses)
10. I am not a medical professional (528 responses)

Question three of the prescreening survey asked participants to select which category they were in out of the following;

1. I have previously had a stroke and undergone rehabilitation of the upper limb (8 responses)
2. I have previously had a stroke and undergone rehabilitation of the lower limb (7 responses)

3. I have previously had a stroke and undergone rehabilitation of both the upper and lower limbs (7 responses)
4. I have previously had a stroke and undergone rehabilitation but of neither the upper or lower limb (1 response)
5. I have previously had a stroke and am currently rehabilitation of the upper limb (1 response)
6. I have previously had a stroke am currently undergoing rehabilitation of the lower limb (1 response)
7. I have previously had a stroke and am currently undergoing rehabilitation of the upper and lower limbs (4 responses)
8. I have previously had a stroke but have not yet undergone rehabilitation, but I expect to start soon (4 responses)
9. I have previously had a stroke but have not and do not plan to have rehabilitation (12 responses)
10. I have never had a stroke (558 responses)

Once the results from the prescreening survey had been collected, the participants could be allocated to the main surveys. Participants that chose options 1-8 on question two were selected for the medical professional survey; while participants that chose options 1-8 on question three were selected for the patient survey. This resulted in 35 participants for the medical professional survey and 33 participants for the patient survey. Using the individual ID numbers collected in the prescreening survey, the participants could be allocated to the relevant survey on Prolific. This allowed the surveys to meet the requirement that Prolific has that specifies participants must only be shown surveys that they are eligible to take.

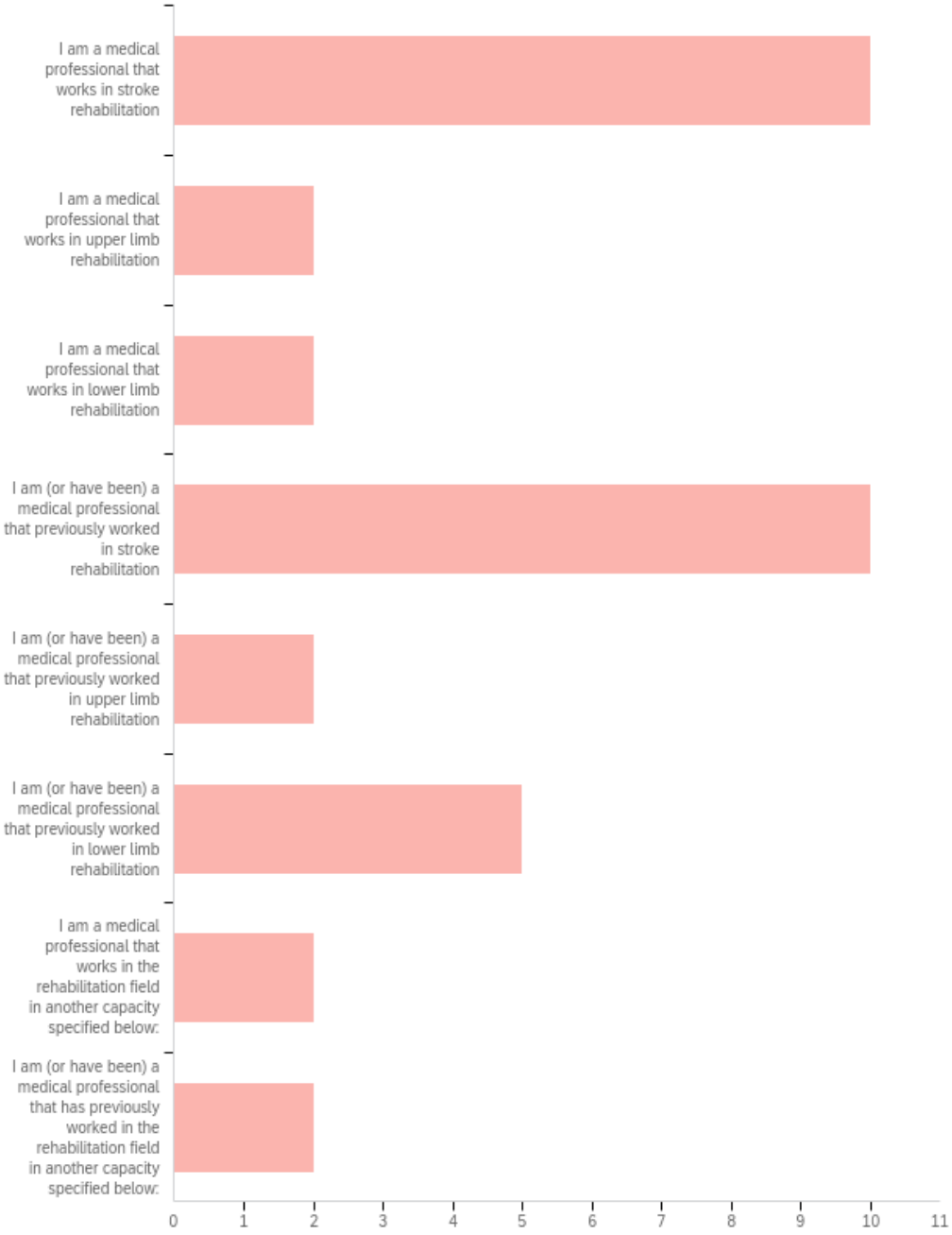


Figure 5.1: Results from question 2 of the prescreening survey: Please select which of these categories you fall into. Option 9: 'I am a medical professional with no experience in rehabilitation'; with 40 responses; and Option 10: 'I am not a medical professional'; with 528 responses; were removed to make the graph more readable.

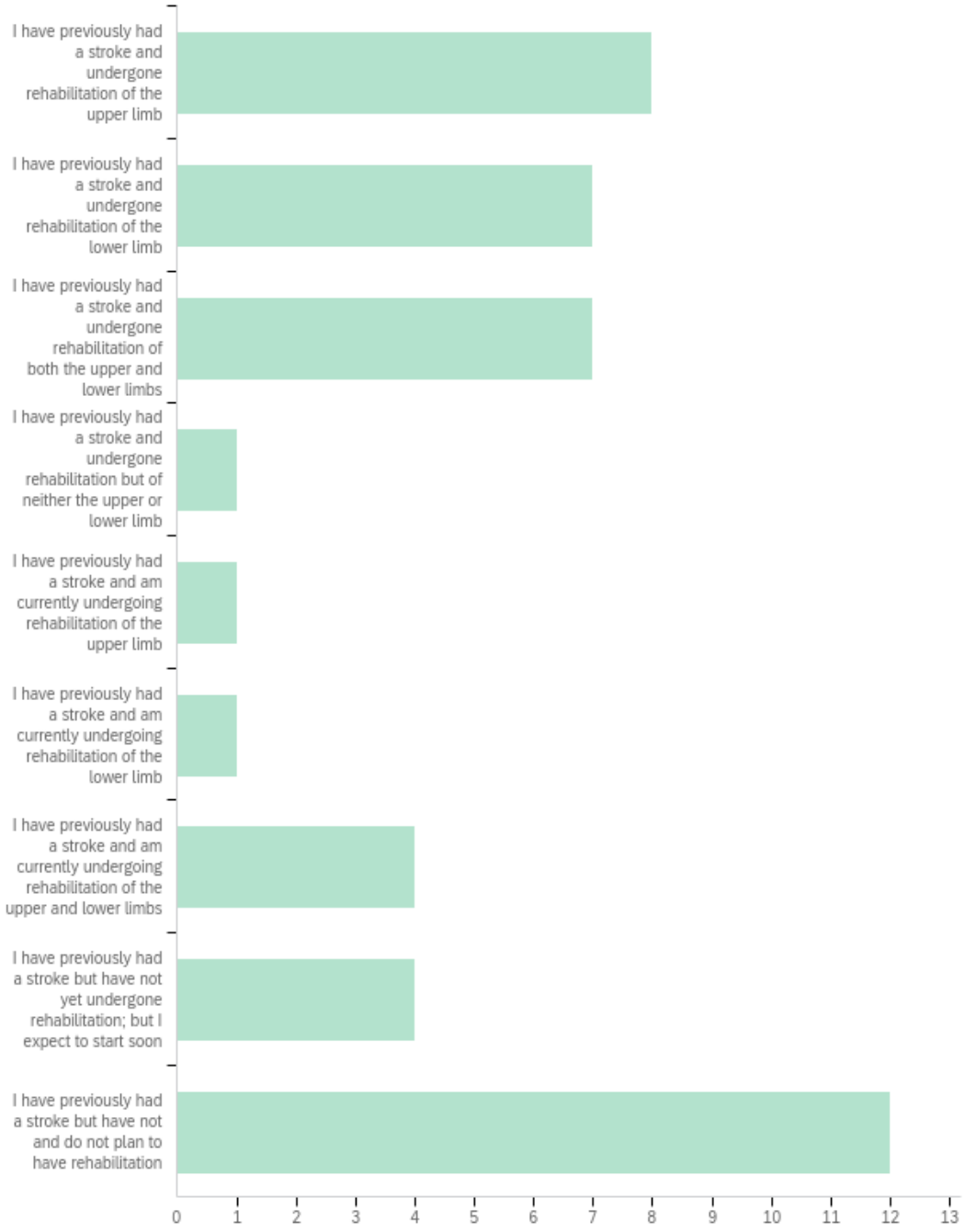


Figure 5.2: Results from question 3 of the prescreening survey: Please select which of these categories you fall into. Option 10: 'I have never had a stroke'; with 558 responses; was removed to make the graph more readable.

Participants were excluded from the medical professional survey if they were not medical professionals, for obvious reasons. Participants that were medical professionals with no experience in rehabilitation of any kind were also excluded as it was determined that they did not have the relevant knowledge to answer the survey correctly. Both of these options have been removed from the graph in Figure 5.1 as the high number of responses from each made it impossible to read the values of the rest of the bars. Participants were excluded from the patient survey if they had never had a stroke, but also if they had had a stroke but not undergone rehabilitation of any kind; as these people would not have any experience in stroke rehabilitation in a medical setting. The last option was removed from the graph in Figure 5.2 as the large number of responses again made the sizes of the rest of the bars on the graph impossible to determine.

The medical professional survey was originally estimated to take 8 minutes. After the surveys had been taken, Prolific identified that the median time taken to complete the survey was 9 minutes and 48 seconds; resulting in a request to increase the payments given to participants. Prolific prefers to keep payments to participants at a decent level and so request an increase when necessary. Participants in the medical professional survey therefore had a reward equal to £9.06 an hour; approximately £1.48 per survey. The patient survey was also originally estimated to take 8 minutes, with Prolific recording a median time of 8 minutes and 7 seconds, resulting in a payment of £8.07 an hour; approximately £1.09 per survey.

5.4 Results

With the prescreening survey complete and participants identified, the two main surveys were then run. Of the 35 participants that were eligible for the medical professional survey, 25 completed the survey, 5 returned the survey, 1 timed out before completing the survey, and 4 never started the survey. Of the 33 participants that were eligible for the patient survey, 25 completed the survey, 6 returned the survey, 1 timed out, and 1 never started the survey. Qualtrics gathered 30 responses from the medical professional survey and 29 responses from the patient survey; and as with the prescreening survey it was unclear why there were more responses gathered on Qualtrics than on Prolific. It is likely that Qualtrics collects results from any survey where a response is given even if the participant returns their survey or times out on Prolific. The results from both surveys were downloaded from Qualtrics in separate Excel worksheets which allowed

all of the results to be seen together. The worksheets were first checked for incomplete surveys so they could be removed from the overall results. Both of the surveys had 4 incomplete surveys. Filters were put in place on Qualtrics to remove the incomplete surveys using the Prolific ID collected at the beginning of each survey. With these surveys removed, the next step was checking that the participants had consented to have their data being collected and used for research purposes; which they all had. The last step was to check that all of the attention checks had been met. Two questions in each survey used matrix tables with a large number of rows. In order to make sure that participants were answering each row correctly and not just randomly selecting an answer, several attention check rows were added that asked participants to select a particular answer. If a participant failed any of the attention checks their results were removed from the overall results. One of the attention checks appeared to have some issues. It requested that participants select the 'disagree' option however, several participants got in contact through Prolific to say that the question asked them to select 'somewhat disagree', 'slightly disagree', or in one case even 'mostly agree'. It is unclear why some participants seemed to be shown different wording in this case and so it was decided that this attention check would be disregarded. With the results now initially checked, further analysis could be undertaken. Throughout the next sections, bar graphs depicting the data from the medical professional survey are red, while bar graphs depicting data from the patient survey are green; pie charts have the first element in the key as red or green respectively as well.

5.4.1 Background

The first few questions of the medical professional survey asked for more specific details of the participants job capacity, whether they specialised in stroke rehabilitation at all, and how much experience they had in each of those. These results are shown in Table 5.1. Some participants were removed at this stage of the analysis as the answers they gave were not suitable for the survey. One of the participants that was removed answered that they had no experience in rehabilitation at all; it's thought this participant may not have answered the initial survey correctly and only completed the survey in order to receive the monetary compensation. Another participant was a hospital pharmacist that worked with stroke patients throughout their rehabilitation but was not involved in the physiotherapy side and so their results were also removed

Table 5.1: Medical Professional Survey - Job Capacities

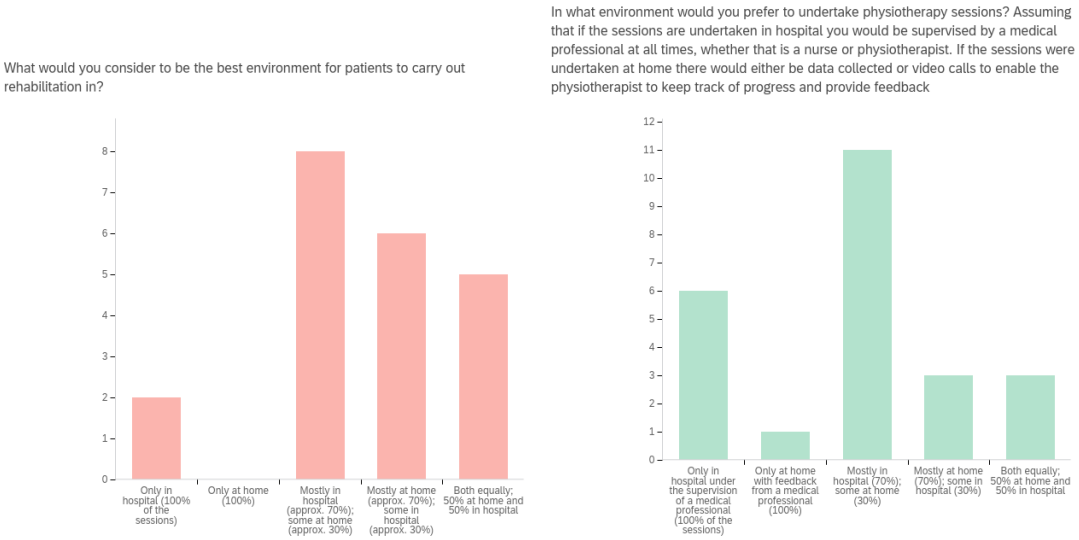
Participant	**Job Capacity**	**Years in Job**	**Rehabilitation Specialisation**	**Years Specialised**
A	Physiotherapist	10	Upper limb	10
B	Physiotherapist	30	No but carry out upper limb	-
C	Doctor	4	No but carry out upper limb	-
D	High Capacity?	1	Stroke and upper limb	1
E	Physiotherapist	1.5	Stroke and upper limb	1.5
F	Rehabilitation Doctor	6	Stroke	1
G	Primary Care Rehabilitation Clinic	1	Upper limb	0.5
H	Hemispheric stroke, upper limb rehab, quality of life support	3 + 8 Months	No but carry out upper limb	-
I	Physiotherapist	25	Stroke	20
J	Restorative Rehabilitation	5	Stroke	-
K	Rehabilitation Nurse	1	Stroke and upper limb	1
L	Stroke Rehabilitation	-	Upper limb	-
M	Physiotherapy Student	-	No but carry out upper limb	-
N	Mobility Training	2	No but carry out upper limb	-
O	Counseling	4	Stroke	Few months
P	Home Assessment Reablement Team	1	Stroke and upper limb	3 months
Q	Osteopathy	2	No but carry out upper limb	-
R	Nurse - Neurological Rehabilitation Clinic	5	Stroke	5
S	Intern	1	No but carry out upper limb	-
T	Neuropsychologist	1	None	-
U	Physiotherapist	2	No but carry out upper limb	-

Table 5.2: Patient Survey - Stroke Details

Participant	Time since stroke	Length of physiotherapy
A	8 Years	2 Months
B	3 Years	1 Year
C	1 Year	7 Months
D	1 Year	7 Months
E	3 Years	8 Months
F	5 Years	5 Months
G	1 Year	5 Months
H	3 Years	2.5 Years
I	6 Months	2 Months
J	2 Years	1 Year
K	3 Years	1 Year
L	10 Years	8 Months
M	3 Months	2.5 Months
N	10 Years	1 Year
O	1 Year	6 Months
P	5 Years	3 Years
Q	16 Years	2 Years
R	2 Years	6 Months
S	1 Year	6 Months
T	2 Years	1 Year
U	5 Years	10 Months
V	3 Years	6 Months
W	2 Years	7 Months
X	6 Years	4 Years

from the overall set. Once the incomplete, unsuitable and data sets that failed the attention checks were removed, there were 21 data sets left to be analysed.

The first few questions of the patient survey asked for more specific details of the patients stroke and rehabilitation journey; in particular how long ago they had their stroke and the length of time they were in rehabilitation for. These results can be seen in Table 5.2. Only one data set was required to be removed from the patient survey as the participant had given answers that implied they had been undergoing rehabilitation for their stroke since before their stroke had occurred. Due to the discrepancy in the answers it was decided that it would be better to remove the whole set of results just in case rather than assume it was an accidental error. After removing this set of results there were 24 participants left in the overall data set to be analysed.



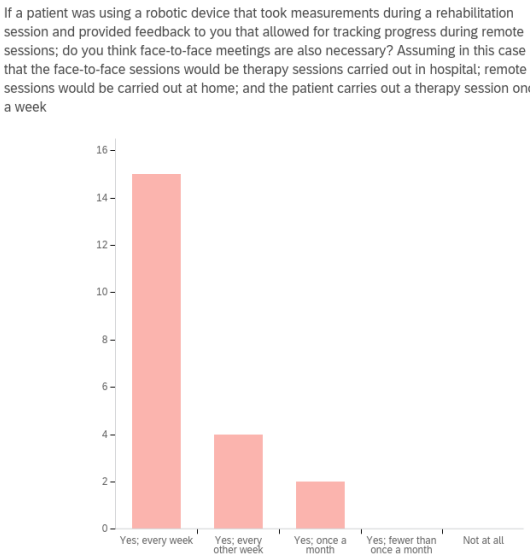
(a) Medical professional environment

(b) Patient environment

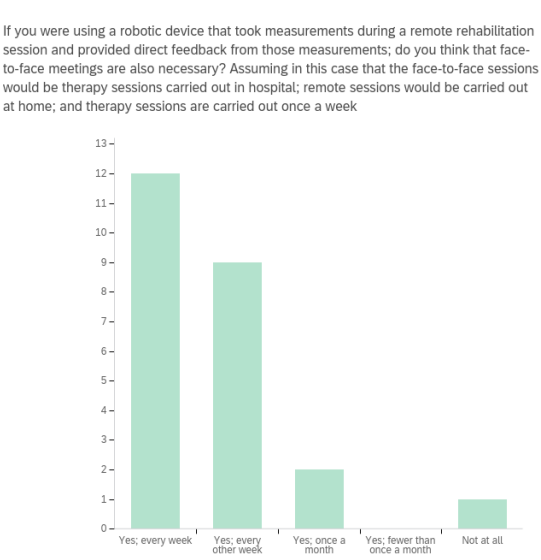
Figure 5.3: Graph showing the number of responses from participants when asked what environment would be best to carry out rehabilitation in.

Figure 5.3 shows two graphs of responses when asked about the best environment for carrying out rehabilitation, with 5.3(a) showing the response of medical professionals and 5.3(b) the response of patients. Each group was given the same overall question with slightly different wording to ensure a full understanding. They were also given the exact same answers to choose from; 'only in hospital', 'mostly in hospital', 'both equally', 'mostly at home', and 'only at home'. Both groups appear to agree that the

best environment would be 'mostly in hospital', with 38% of medical professionals and 46% of patients choosing this option. Interestingly, a higher percentage of patients than medical professionals chose the 'only in hospital' option; 25% versus 10%. It could be that patients feel more comfortable carrying out rehabilitation under direct supervision, while medical professionals are aware of the ever-increasing demand on services and feel that with patients carrying out at least some rehabilitation at home it could free up critical resources to see more patients. More available resources mean patients can be seen sooner after the onset of stroke. This reasoning is backed up by a higher percentage of medical professionals selecting the 'mostly at home'; 29% versus 13%; and 'both equally'; 24% versus 13%; options than patients. These responses make it clear that there is room in the market for exoskeletons designed to be used in the home environment in certain situations, most likely in conjunction with hospital-based rehabilitation.



(a) Medical professional face-to-face



(b) Patient face-to-face

Figure 5.4: Graph showing the number of responses from participants when asked whether face-to-face meetings were necessary; and how often.

Figure 5.4 shows the graphs of responses when participants were asked about the need for face-to-face meetings during rehabilitation. The question was asked with the assumption that patients would be using a robotic device at home that could track measurements and provide feedback to the physiotherapist. 71% of medical profes-

sionals said that weekly face-to-face sessions would still be necessary; 19% said every other week, and 10% said once a month. Patients had a fairly similar response, with 50% saying weekly face-to-face meetings would be necessary. However, a larger percent of patients said that every other week would be enough; 38% compared to only 19% of medical professionals. 8% of patients said that meetings once a month would be enough, a very similar percentage to the medical professionals. 4% of patients said that no face-to-face meetings would be necessary with the provided remote robotic device. Overall, it seems clear that both medical professionals and patients find the face-to-face aspect of rehabilitation to be important, meaning the overall concept of at-home rehabilitation needs a bit more work to find the most suitable method for everyone involved. It's important that patients feel supported throughout their rehabilitation, and it seems that they are likely to be more confident in this with more face-to-face meetings with medical professionals.

Figures 5.5 and 5.6 show the responses from participants when asked about the particular joints that are used in rehabilitation sessions. Medical professionals were asked which joint motions they believe are essential, while patients were asked which joint motions were included during their rehabilitation. Both groups could choose as many responses as were relevant. Medical professionals clearly favoured movement of the shoulder above any other joint, with the elbow following closely behind. The least important overall seemed to be ulnar and radial deviation of the wrist, and individual finger motions. Patients reported that a combination of wrist, elbow and shoulder movements were the most often carried out during their rehabilitation, with hand and finger movements a close second. Table-top exercises were rare, and wrist movements were used the least often of all the joints.

The data collected in these two questions can be used to make some reasonable assumptions on the type of exoskeleton that might be useful in rehabilitation settings. From the patients point of view, the wrist, elbow and shoulder together are most often used; followed by the hand/finger and then the elbow. From the point of view of the medical professionals, the various shoulder joints are seen to be the most important, followed by the elbow and hand gripping motions. These results show that an exoskeleton capable of a selection of shoulder, elbow and wrist movements could be the most useful for both patients and medical professionals. As patients reported that they rarely did table-top exercises, an exoskeleton would be more appropriate than a table-top device;

and as both groups suggested that the wrist is one of the least used/one of the least important joint motions, it makes sense that only the flexion/extension motion may be necessary. The hand/finger movements, and the hand gripping and individual finger motions are also shown to be important and often used, however due to the engineering complexity required for their inclusion in an exoskeleton it makes sense to keep these as a separate system.

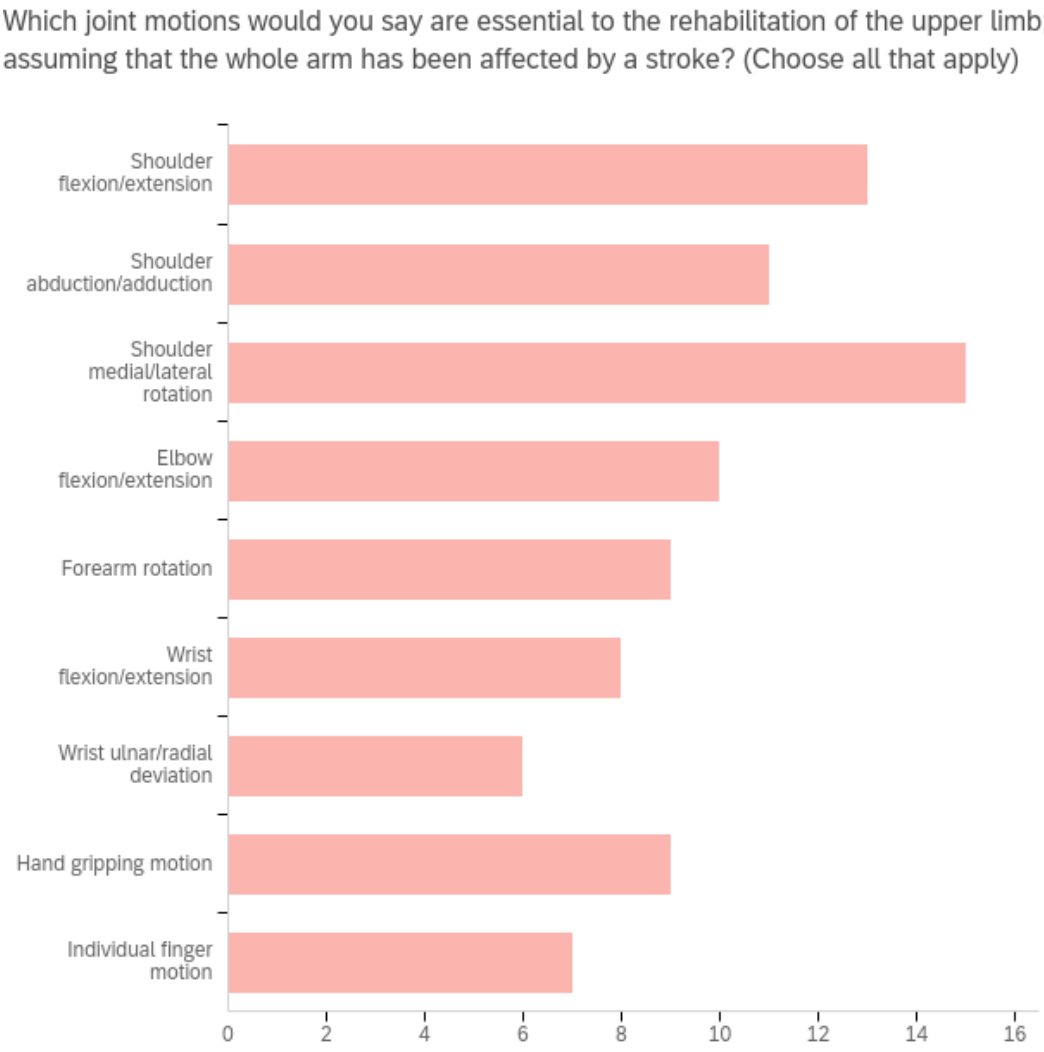


Figure 5.5: Graph showing the number of responses from medical professionals when asked which joint movements were essential to rehabilitation of the upper limb. Participants were able to choose multiple answers.

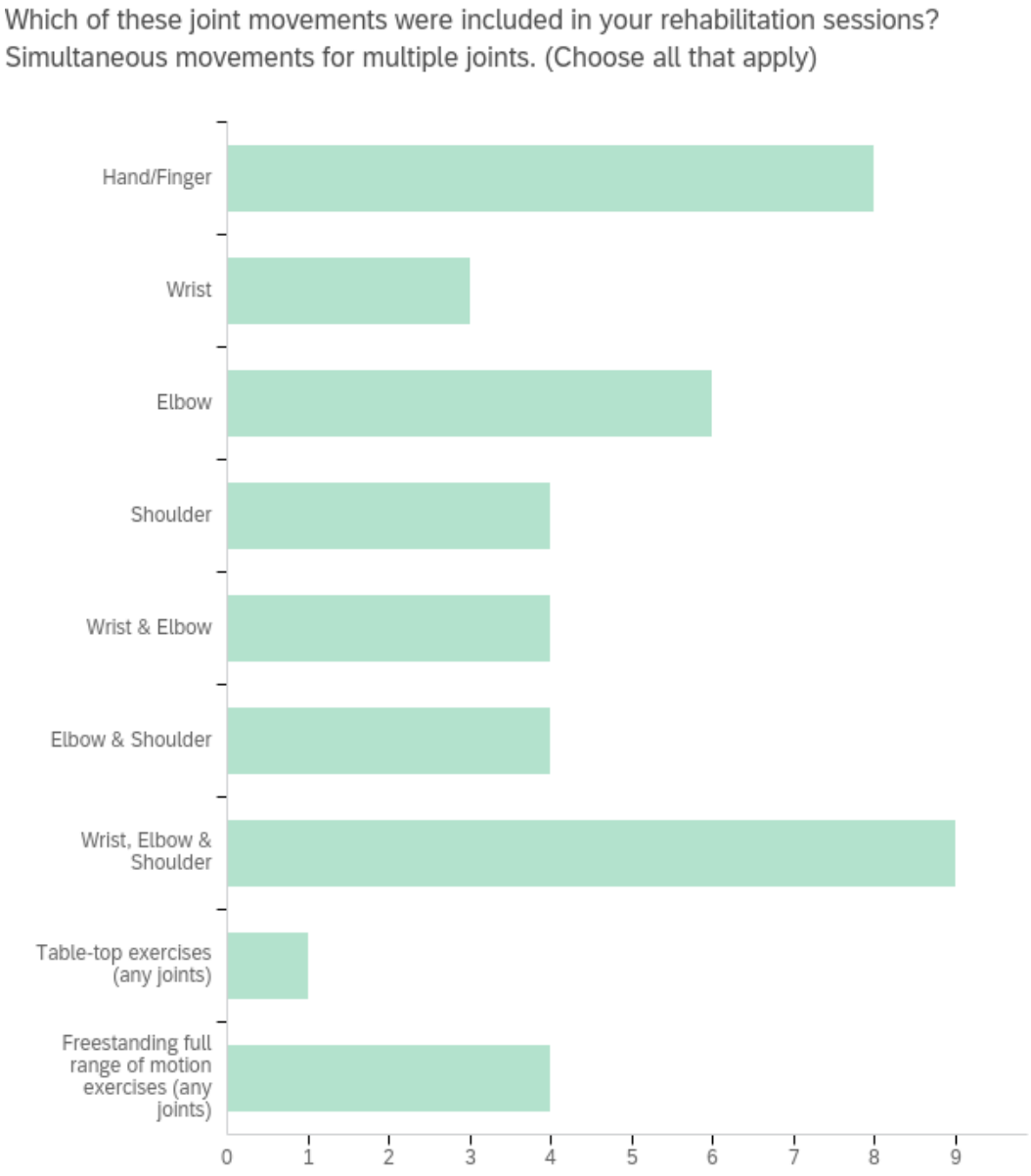
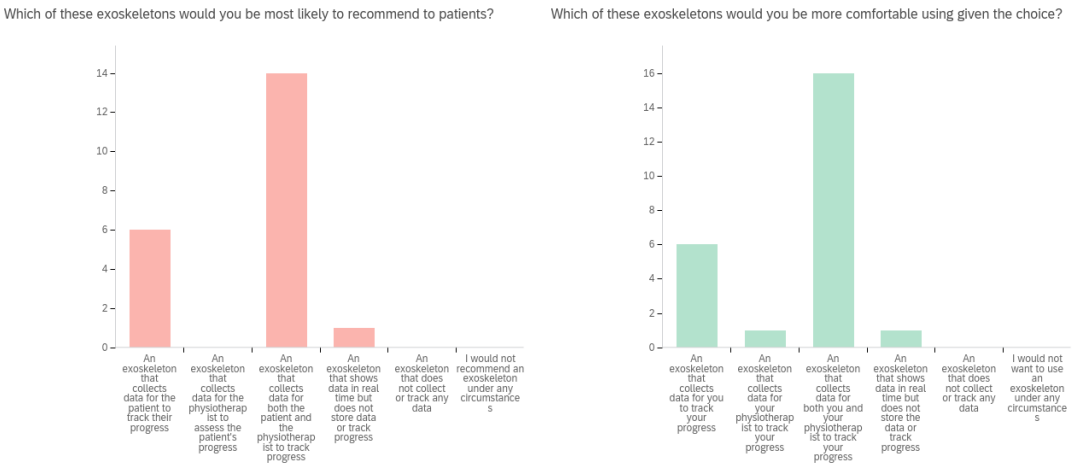


Figure 5.6: Graph showing the number of responses from patients when asked what joint movements they rehabilitated during their sessions. Participants were able to choose multiple answers.

Both groups of participants were asked a very similar question about types of exoskeletons. Medical professionals were asked what type of exoskeleton they would recommend to patients, and patients were asked which type of exoskeleton they would rather use. Having been given the exact same answers to the questions, there was an overwhelmingly obvious answer with two thirds of each group deciding that the best type of exoskeleton would be one that collects data for both the patient and the physiotherapist in order to track progress. An exoskeleton that could show data in real time but not store data had a single response from each group, and one that could collect data for just the physiotherapist to track progress has one vote from the patient group. With six votes from each group, an exoskeleton that can collect data for the patient to track their own progress is the only other option that received any responses.



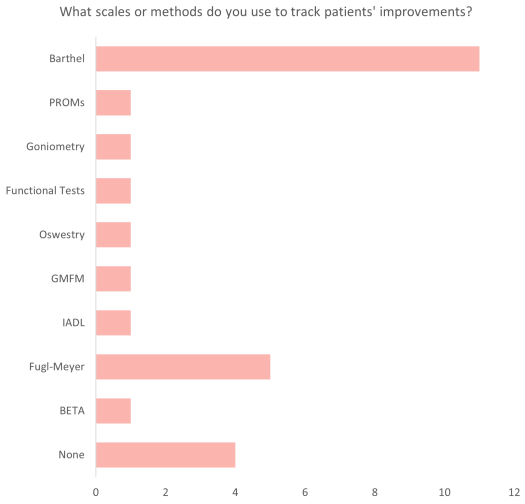
(a) Medical professional responses

(b) Patient responses

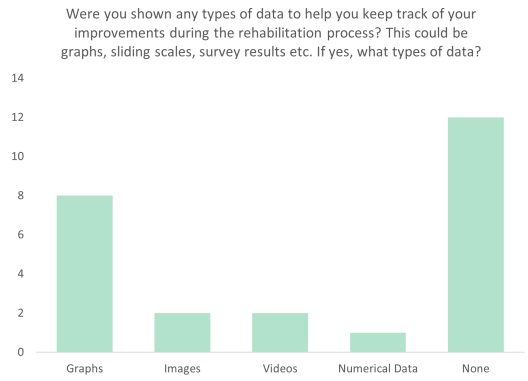
Figure 5.7: Graph showing the number of responses from participants when asked what type of exoskeleton they would recommend to patients; or what exoskeleton patients would be more comfortable using.

The last few questions of the survey that gathered background information on the participants are shown in Figure 5.8. Medical professionals were asked one final question about the methods they use to track patients improvements. The favourite of which was the Barthel Index with 11 responses. The majority of the options only received a single response, however the Fugl-Meyer Assessment had 5 responses, and surprisingly there were 4 responses for the 'none' option. It seems that the two most well known options

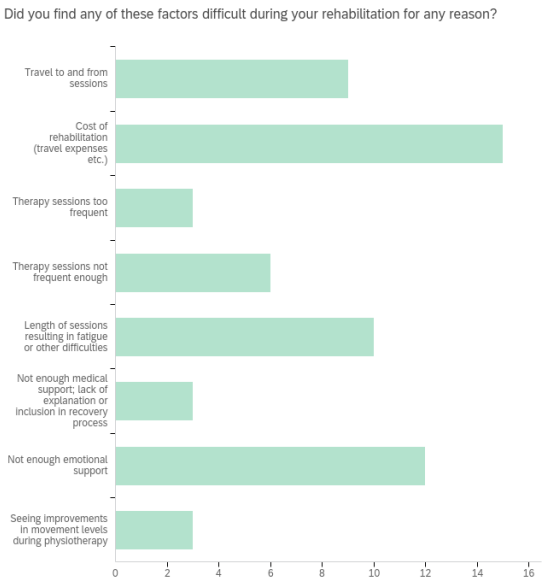
are also clearly the most widely used, but it is interesting that there are some medical professionals seemingly not measuring any form of progress in patients rehabilitation at all. It could be that there are other ways of showing the patient that they are improving without these types of data.



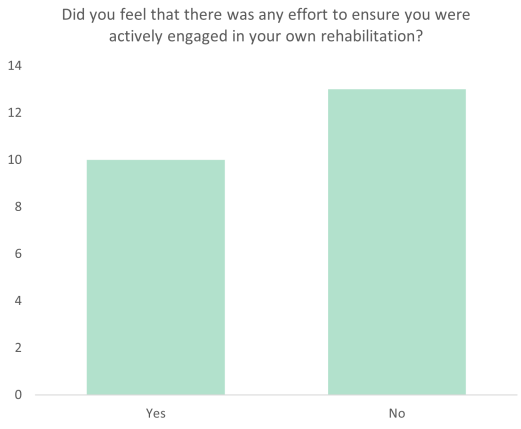
(a) Medical professional tracking types



(b) Patient tracking types



(c) Patient difficulties



(d) Patient active engagement

Figure 5.8: Graphs showing the number of responses to the last few questions of the survey regarding the background of participants

This does lead into the next question that patients were asked, which was what types of data are they shown to keep track of their improvements. The highest number of responses here was for the 'none' option, showing patients were not necessarily kept in the loop with the improvements they were making in any tangible way. Graphs was the most popular option for those that were shown data, with 8 responses. Images and videos both received two votes, and numerical data received one. Patients were asked two further questions. The first of which asked patients to highlight any difficulties that they had during their rehabilitation. The biggest difficulty was the cost of rehabilitation, including travel and any other expenses throughout. Not receiving enough emotional support was next, followed by fatigue from the length of sessions and the ability to actually travel to and from rehabilitation sessions. The smallest difficulties were identified as therapy sessions being too frequent; with therapy sessions not being frequent enough receiving twice as many responses; not receiving enough medical support and seeing improvements during their physiotherapy. The last question simply asked patients if they had felt like effort was made to ensure they were actively engaged in their own rehabilitation. The answers were fairly similar, with 43% of participants saying they did feel actively engaged, and 57% saying they did not.

There's nothing overly surprising from the data gathered from the background questions. Most of the results back up what is already known from the literature. It confirms that the most widely mentioned stroke assessments are also the most common ones used in practice. It confirms that patients don't always feel included or supported during their rehabilitation as well as several other difficulties that they face such as costs and travel. Although it has not necessarily confirmed the need for an exoskeleton purely for home use, it does show that both groups think an amount of rehabilitation carried out at home is still a good option. Medical professionals even seem to think that carrying out rehabilitation mostly at home is almost as good of an option as mostly in hospital. Patients however have chosen rehabilitation in hospital only as their second choice, which is likely to be more about their confidence in medical professionals and being more comfortable knowing they have support there if they need it. It could be that at home rehabilitation is just not suitable for every patient, and using an exoskeleton in a home environment could be used as an option for those that are comfortable or that have an existing support system at home. Despite the responses to the question about the best environment, the responses from the question about face-to-face sessions seems

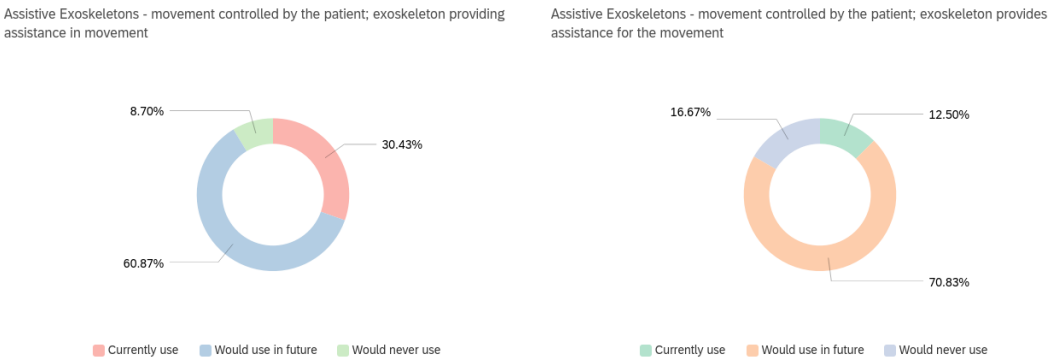
to contradict these results. Both patients and medical professionals said that meeting face-to-face every week when using an exoskeleton at home would still be necessary. Considering that patients said that some of the main difficulties in their rehabilitation was the cost and travel, it seems odd that they would want to travel to the hospital specially for a face-to-face meeting if they were able to carry out their rehabilitation at home. Overall the data collected showed the trends that were expected, with only a few interesting results. This could be put down to the questions not being asked in the right way, or it could be that the participants that took part in the survey have different views on certain aspects than previous surveys.

5.4.2 Technology Use

The next set of questions that were asked during the survey are based on the use of technology with exoskeletons during rehabilitation. Both groups of participants were generally asked the same questions, starting with what types of exoskeletons they use. Participants were asked about assistive exoskeletons, where the patient is the one controlling the movement and the exoskeleton is providing assistance. They were also asked about active exoskeletons, where the movement is instead controlled by the exoskeleton with the patient being passive to the movement. All of the questions in this section had the same three answers; 'currently use', 'would use in future', and 'would never use'.

Figure 5.9 shows the responses from both groups of participants. 30% of medical professionals said that they currently use assistive exoskeletons; 61% said they would use an assistive exoskeleton in the future; and 9% said they would never use one. Patients on the other hand only had 12.5% of participants say they currently use an assistive exoskeleton, with 71% saying they would use one in the future, and 16.5% saying they would never use one. Interestingly, almost double the percentage of patients than medical professionals voted to never use an assistive exoskeleton, though the majority of both groups said they would use one in the future. When looking at Figure 5.10 showing the responses when asked about an active exoskeleton, the results have changed quite a lot. Now, 23% of medical professionals say that they currently use active exoskeletons. 59% say they would use them in the future, and 18% say they would never use them. So active exoskeletons appear to be being used less often, and more than double the percentage of participants would never use one. A similar percentage

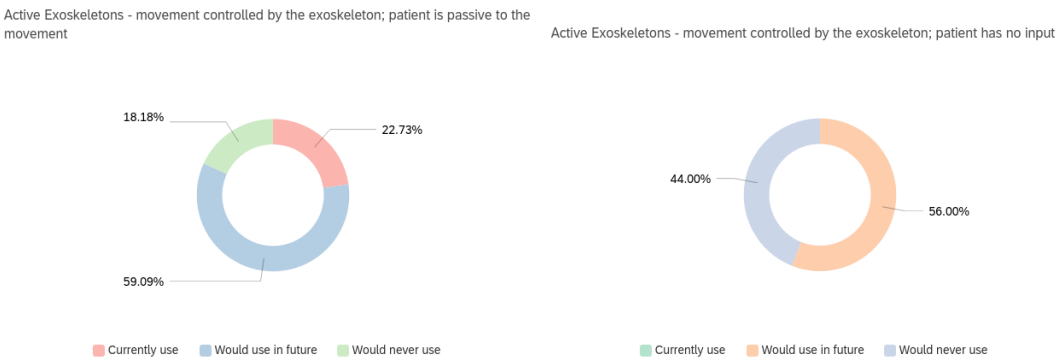
of responses were collected for participants that would use an active exoskeleton in the future. No patients said that they currently use an active exoskeleton, though 56% said they would use one in the future. A massive 44% of participants said that they would never use an active exoskeleton. This clearly shows that many patients want to be actively involved in their rehabilitation. They do not want to just put an exoskeleton on and let it do all the work, they want to actually be involved in the process. Some however, may see an active exoskeleton as a good option that would be able to carry out their rehabilitation without them having to participate.



(a) Medical professional responses

(b) Patient responses

Figure 5.9: Pie charts showing the responses from participants when asked about their use of assistive exoskeletons.

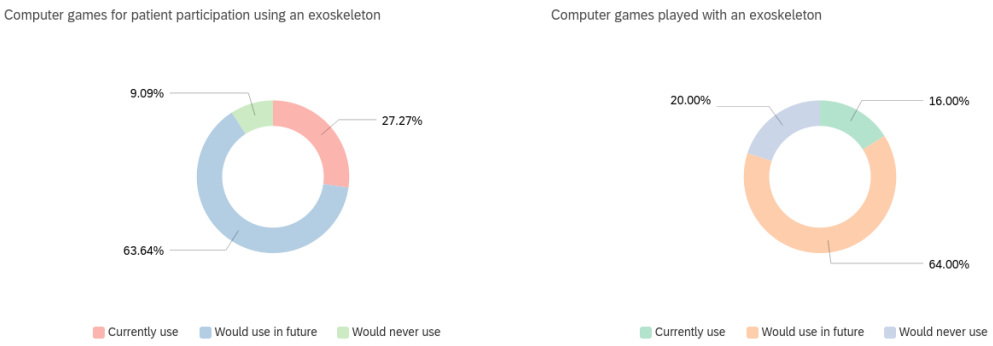


(a) Medical professional responses

(b) Patient responses

Figure 5.10: Pie charts showing the responses from participants when asked about their use of active exoskeletons.

Figure 5.11 shows the responses from participants when asked if they use computer games as a means of participation when using an exoskeleton. 27% of medical professionals say they currently use them, 64% say they would use them in the future, and 9% say they would never use them. Patients responses are fairly similar, with 16% saying they currently use computer games with an exoskeleton, 64% saying they would in the future, and 20% saying they would never use them. It would be interesting to see if the participants that select 'would never use' are the same for every question and they just do not like the use of exoskeletons at all, or whether participants are really invested in the different ways of using exoskeletons. It is likely that there is a mixture of the two within the results. Despite there being a lot of current literature to support the use of exoskeletons there are always bound to be some medical professionals and patients who do not agree with the use of them or do not feel comfortable using them for various reasons. There are also bound to be those that can not use them for various reasons, be that cost limitations, size limitations, or even limitations on what type of patient can use a certain exoskeleton.



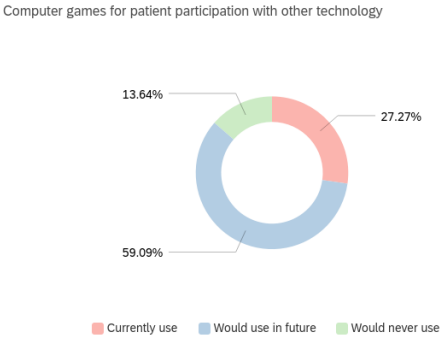
(a) Medical professional responses

(b) Patient responses

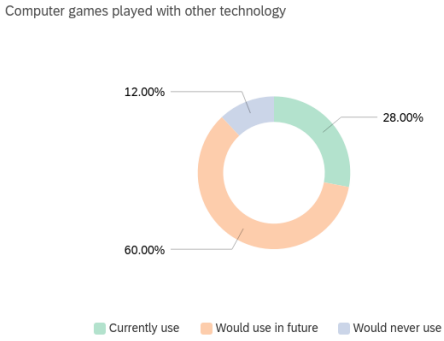
Figure 5.11: Pie charts showing the responses from participants when asked about their use of computer games with an exoskeleton.

Participants were also asked about the use of computer games with other forms of technology, other than an exoskeleton. They were also asked about using computer games without any form of technology. This was mainly to gauge whether computer games are used as a form of encouraging active participation with patients in any form. 27% of medical professionals and 28% of patients say that they currently use computer games with other technology, while 24% and 17% respectively say they currently use

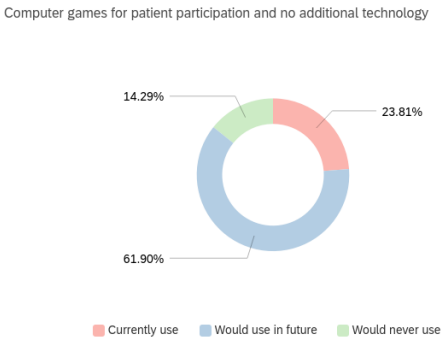
computer games without technology. Generally these responses are all fairly similar, with slightly fewer patients using computer games without technology. 59% of medical professionals and 60% of patients would use computer games with another form of technology in the future; 14% and 12% respectively would never use them. 62% of medical professionals would use computer games without additional technology, however only 46% of patients would. 37.5% of patients would also never use computer games without technology compared to only 14% of medical professionals. Medical professionals don't seem to favour either option, while patients are much more likely to choose to use computer games when there is a form of technology involved, and even more so when that technology is an exoskeleton. Overall however, both medical professionals and patients would use computer games in the future under any circumstances and would be a good option for increasing patient participation.



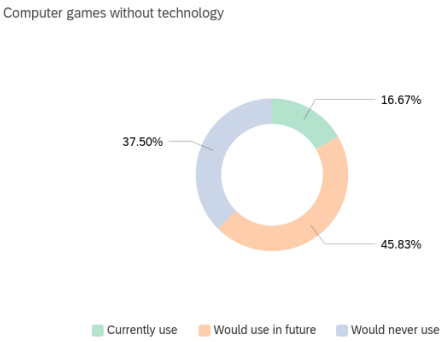
(a) Medical professional responses - other technology



(b) Patient responses - other technology



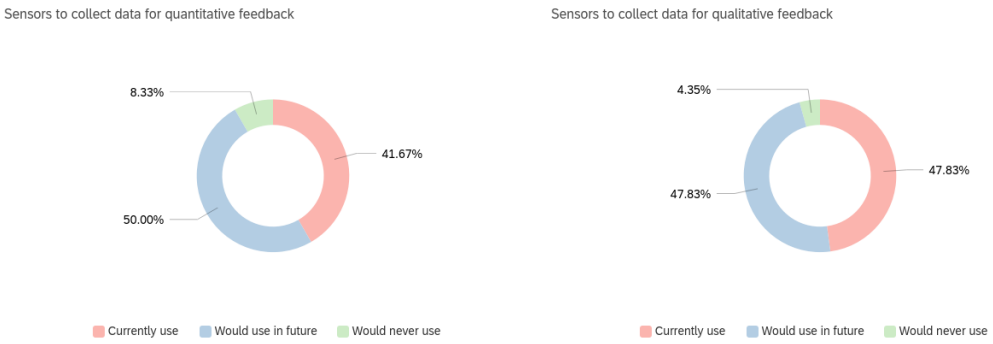
(c) Medical professional responses - no technology



(d) Patient responses - no technology

Figure 5.12: Pie charts showing the responses from participants when asked about their use of computer games with other technology and no technology.

The last few questions in this section of the survey were about the use of sensors for collecting data during rehabilitation sessions. Medical professionals were asked about the use of sensors for both quantitative and qualitative feedback. 41% of medical professionals say that they currently use sensors for quantitative feedback; 50% would use them in the future, and 8% would never use them. For qualitative feedback, 48% currently use them, 48% would use in the future, and 4% would never use them. The responses to each are fairly similar, with qualitative feedback being slightly more popular as there is a lower percentage of responses for 'would never use'. From the responses given there is obviously a need for both quantitative and qualitative feedback when using an exoskeleton.

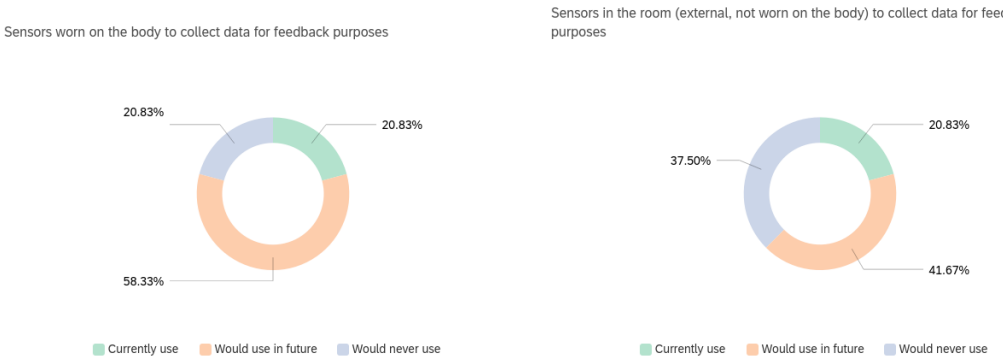


(a) Sensors for quantitative feedback

(b) Sensors for qualitative feedback

Figure 5.13: Pie charts showing the responses from medical professionals when asked about using sensors to collect data for different types of feedback.

Patients were asked about the use of both wearable and external sensors for collecting data for feedback purposes. 21% of patients said they already use both wearable and external sensors. 58% said they would use wearable sensors in the future, but only 42% said they would use external sensors. This left 21% that would never use wearable sensors and 37% that would never use external sensors. Patients appear to want wearable sensors over external sensors when using an exoskeleton. This makes sense as wearable sensors are smaller, don't require a separate system, and are unintrusive. Patients are going to want all of these things in an exoskeleton system, especially as an external sensing system would also limit the area of movement, and potentially create a more complicated system that patients may interpret as being more difficult to use. Patients want an accessible system that makes their rehabilitation experience easy.



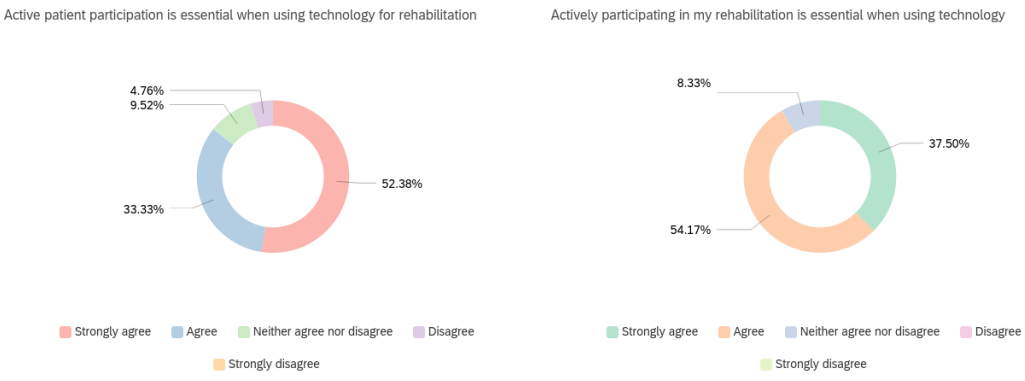
(a) Wearable sensors

(b) External sensors

Figure 5.14: Pie charts showing the responses from patients when asked about using different sensors to collect data for feedback purposes.

5.4.3 Statements

This next set of questions were statements, with the participants having to select how strongly they agreed or disagreed with said statement. Medical professionals and patients were given the same overall questions with slightly different wording. Participants were first asked how essential active participation is when using technology in rehabilitation sessions. Medical professionals strongly agreed with this statement with a higher percentage than patients, with patients opting for 'agree' as their highest response. Medical professionals were the only group to disagree at all with 5% of the responses.

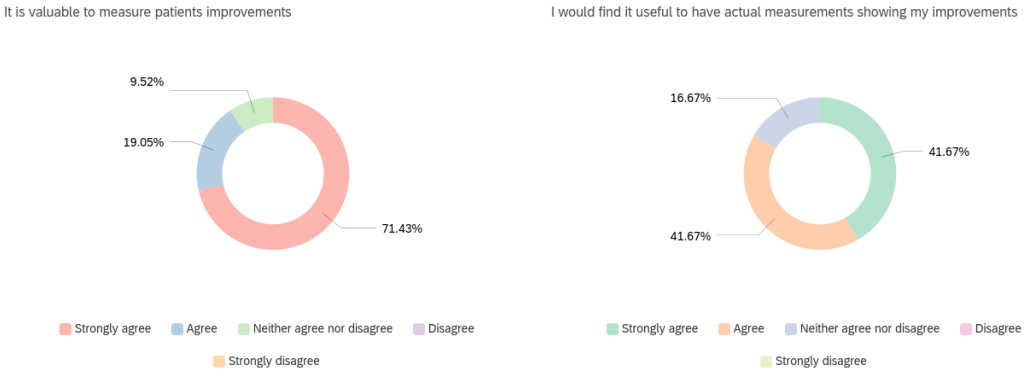


(a) Medical professional responses

(b) Patient responses

Figure 5.15: Pie charts showing the responses from participants when asked their opinion on active participation during rehabilitation.

A massive 72% of medical professionals strongly agreed when asked if it was valuable to measure patients improvements, with none disagreeing in any way. Patients were less sure, with 42% strongly agreeing and 42% agreeing. No patients disagreed with this either, however they were more specifically asked whether it would be useful to have specific measurements to show the improvements so this could have had something to do with it. Patients may agree that they need to be able to see their improvements but may not be bothered with specific measurements.

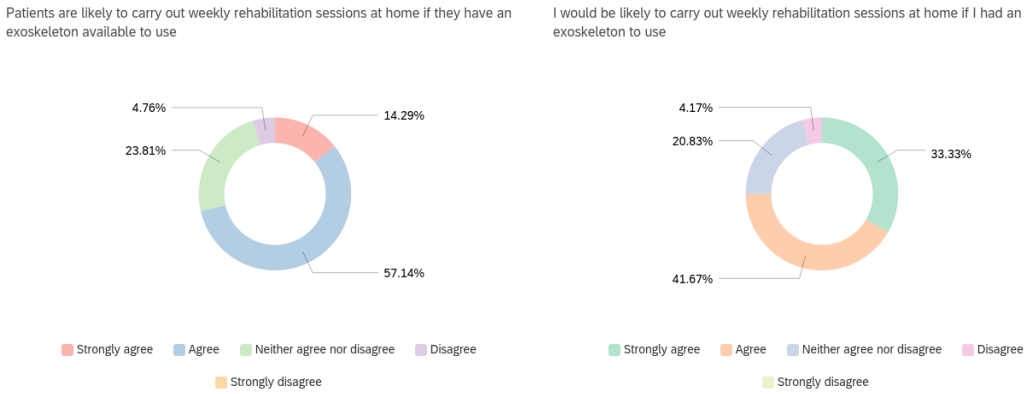


(a) Medical professional responses

(b) Patient responses

Figure 5.16: Pie charts showing the responses from participants when asked their opinion on measurements for seeing improvements.

When asked whether patients are more likely to carry out at-home rehabilitation if they have an exoskeleton available to use, only 14% of medical professionals strongly agreed, while 33% of patients strongly agreed. This could be down to medical professionals already being aware of how well patients carry out tasks that have been set for patients to complete at home, i.e. not very well at all. The patients asked in this survey could obviously have every intention of carrying out rehabilitation at home which is why there is a much higher percentage of responses. Still, 57% of medical professionals do agree with this statement, so there must still be some confidence that patients may carry out rehabilitation at home with an exoskeleton. 42% of patients also agree with the statement. Interestingly, 5% of medical professionals and 4% of patients actually disagree with this statement meaning that they don't believe patients would carry out rehabilitation at home with an exoskeleton.



(a) Medical professional responses

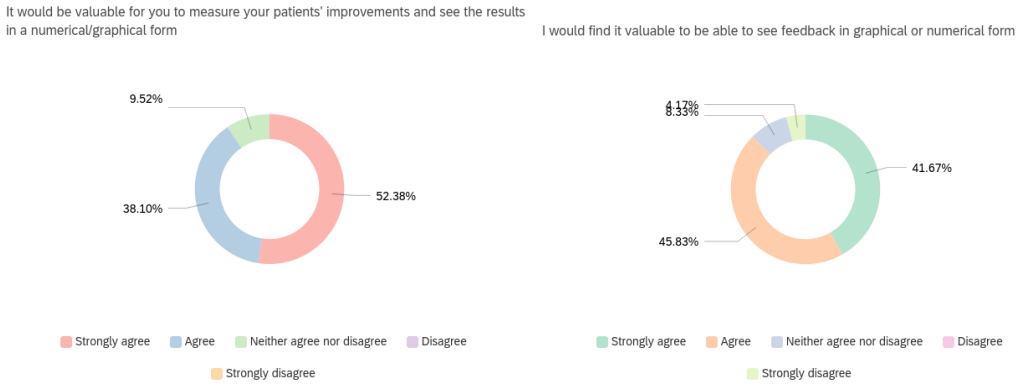
(b) Patient responses

Figure 5.17: Pie charts showing the responses from participants when asked their opinion on the likelihood of patients carrying out weekly rehabilitation at home when using an exoskeleton.

Measuring patients improvements and showing them their results in a graphical or numerical form seems like a good way for patients to be presented with their data, however 4% of patients actually strongly disagree with this. 42% strongly agree, and 46% agree so the majority certainly think it is a good idea. It would be interesting to know what other form of data that 4% would want to see, or if they would just rather not see any data at all. From the previous statement about measuring patients improvements, it would have been expected not to see any percentage of disagreement which leads to the belief that it is the form the data is in that the participants do not agree with. Medical professionals on the other side do not disagree at all, with 52% strongly agreeing and 38% agreeing with the statement.

Finally, participants were asked if they would be more likely to undertake rehabilitation with an exoskeleton if they were receiving feedback in numerical or graphical form that allowed them to track their improvements. 24% of medical professionals strongly agree, 43% agree, and 10% disagree. From the previous responses this disagreement seems to come from the likelihood of carrying out rehabilitation at home rather than from any other aspect of the statement. A fairly large percentage of responses in this case are for 'neither agree or disagree' which is interesting as in previous statements there was mainly only ever a small percentage of responses for this option. These middle ground responses also seem to come from the likelihood of carrying out rehabilitation

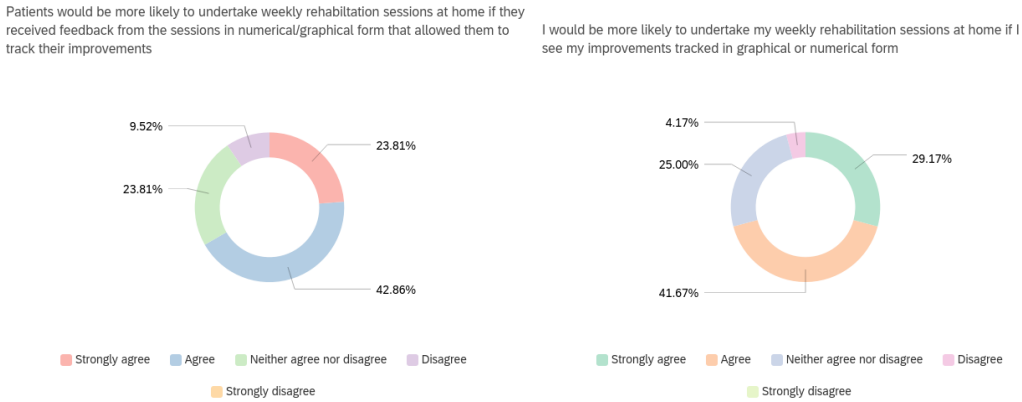
at home statement which had a similar percentage of responses for 'neither agree or disagree'. Patients have a slightly more positive response to this statement, with 29% strongly agreeing and 42% agreeing. There is also 4% of responses that disagree, which can be traced back to both the likelihood of weekly rehabilitation with an exoskeleton but also the graphical/numerical form of feedback statements. There is also a decent percentage of responses for 'neither agree or disagree' at 25%, which yet again can be traced back to the weekly rehabilitation statement.



(a) Medical professional responses

(b) Patient responses

Figure 5.18: Pie charts showing the responses from participants when asked their opinion on using graphical or numerical forms to show patient feedback.



(a) Medical professional responses

(b) Patient responses

Figure 5.19: Pie charts showing the responses from participants when asked their opinion on how likely patients are to carry out rehabilitation at home when provided with data for tracking improvements.

The statements in this section built on the previous ones; first with simple statements about active participation and the value of measuring data for tracking improvements; and finally with a statement that included several other statements all together, and in particular when using an exoskeleton. Generally the responses to each of the statements was positive, with the main negativity and indecisiveness coming from the lack of confidence in patients carrying out weekly rehabilitation at home.

5.4.4 Ratings

The final question in the surveys was the ratings question, where participants were asked to rate a selection of engineering requirements for the design of an exoskeleton. Participants were asked to rate each requirement on a scale of 1-5; with 5 being the most important; as to how important each requirement was to them. They were asked to rate these independently, not by comparing them against each other. The responses for both surveys are shown below in pie chart form, showing the number of responses for each rating level. These results are fully analysed in Section 6.2, where they are used as part of an optimisation algorithm, so they are only briefly discussed here.

In general, medical professionals and patients had fairly similar responses for the level of importance they would apply to each requirement. When rating the importance of an exoskeleton being lightweight, 38% of medical professionals rated it as a 5, and 33% rated it as a 4. On the other hand, 33% of patients rated it as an importance of 5, and 42% at a 4. Medical professionals thought it was more important that the exoskeleton be lightweight. Following on the same trend when rating the wearable requirement, 38% of medical professionals rated the wearability with an importance factor of 5, and 29% with a factor of 4. Patients had a 33% response rate for an importance of 5, and a 50% response rate for an importance of 4. So a higher percentage of medical professionals rated the wearability with a higher importance than patients. When rating the comfort requirement, both groups agreed that this was of a high importance, with 81% of medical professionals and 79% of patients rating this at the highest importance.

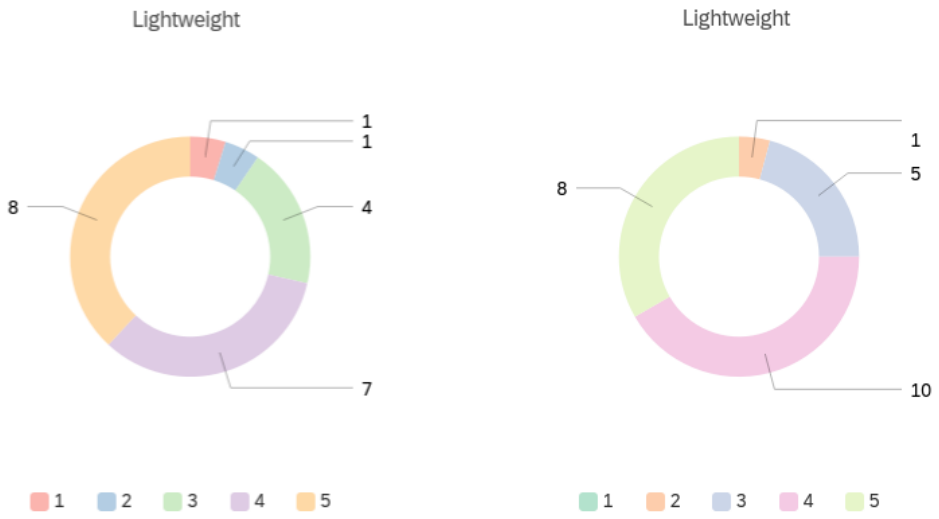
Looking at the next two requirements, independent use and home use, patients had a higher percentage rating them as an importance of 5, with 58% and 54% respectively. 29% and 17% respectively rated these requirements a 4 in importance. only 43% and 38% of medical professionals rated independent use and home use as a 5; with 29% and 38% rated them at a 4. Clinical relevance has more of a split across the ratings. While

43% of medical professionals rated the importance as a 5, only 14% rated it as 4, 24% at a 3, and 14% at a 2. Patients had a more even split across the ratings, with 33% rating it a 5, 29% a 4, 17% a 3, and 21% a 2. This shows that medical professionals with their medical knowledge have a better understanding of the importance of a device being clinically relevant than patients who are potentially happy with a device that is capable of rehabilitation even if it is not the best device on the market.

The adjustable, durable, and safety requirements all fairly predictably have high percentages of responses for the highest rating, with 57%, 48% and 76% of medical professionals and 46%, 67% and 79% of patients voting for it respectively. Maintenance seems to be much more important to patients, with 63% rating it with an importance of 5, and 25% a 4. 43% of medical professionals rated the maintenance as a 5, and 29% with a 4. When it comes to the active participation requirement, there is more disagreement across the participants, with 33% of medical professionals rating it as a 5, 24% as a 4, 24% as a 3, 14% as a 2, and 5% as a 1. The importance ratings from patients had a lower distribution, with only 21% rating it as a 5, 33% as a 4, 38% as a 3, and 8% as a 2. Patients seem to think that active participation is less important than medical professionals, possibly because they do not understand the significance, or maybe because they just do not think it is that important for them to actively participate.

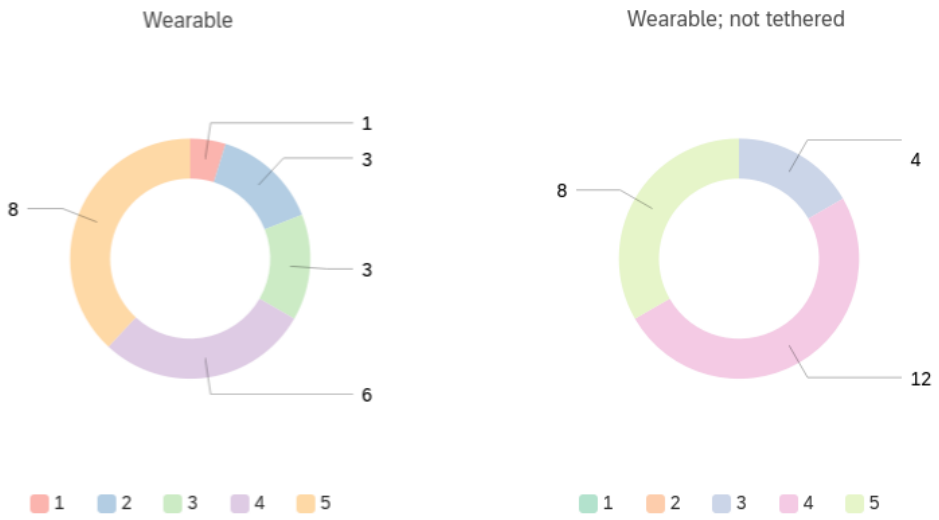
Feedback has a similar importance to both groups, with 33% of medical professionals and 38% of patients rating it as a 5; 24% and 25% respectively rating it as a 4; and 24% and 33% rating it as a 3. Patients have put more importance on the exoskeleton being rechargeable, with 63% rating it a 5 and 21% rating it a 4. 43% and 29% of medical professionals rated it a 5 and a 4 respectively. With cost being one of the biggest factors when it comes to designing an exoskeleton as to its quality, it is a requirement that can have a big effect on the end product. Medical professionals were asked to rate two different types of cost requirements; cost to the hospital, and cost to the patient. The first option was given a lower overall importance, with 19% of medical professionals rating it a 5, 29% rating it a 4, and 33% rating it a 3. The second option; the cost to the patient; was given a higher overall importance, with 43% rating it a 5, 10% a 4, and 24% a 3. When patients were asked about cost, they were asked to rate the importance of the cost to themselves, either in order to rent the device, or to own it. There was only a very small differentiation between the two, with 63% rating renting

as a 5, and 67% rating owning as a 5. 25% rated renting as a 4, and 21% rated owning as a 5. Patients therefore did not seem bothered as to whether they rented or bought the exoskeleton, as long as either option was low cost.



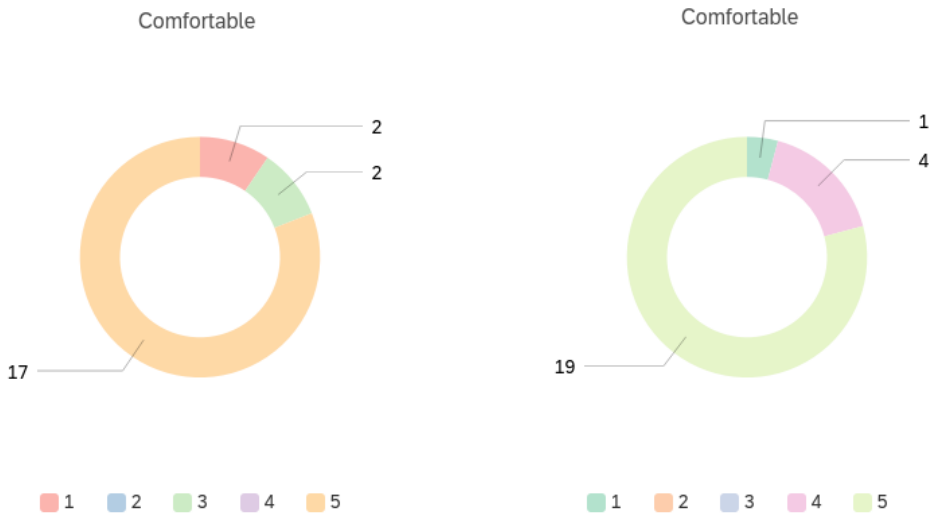
(a) Medical professional responses (b) Patient responses

Figure 5.20: Pie charts showing the responses for 'Lightweight'



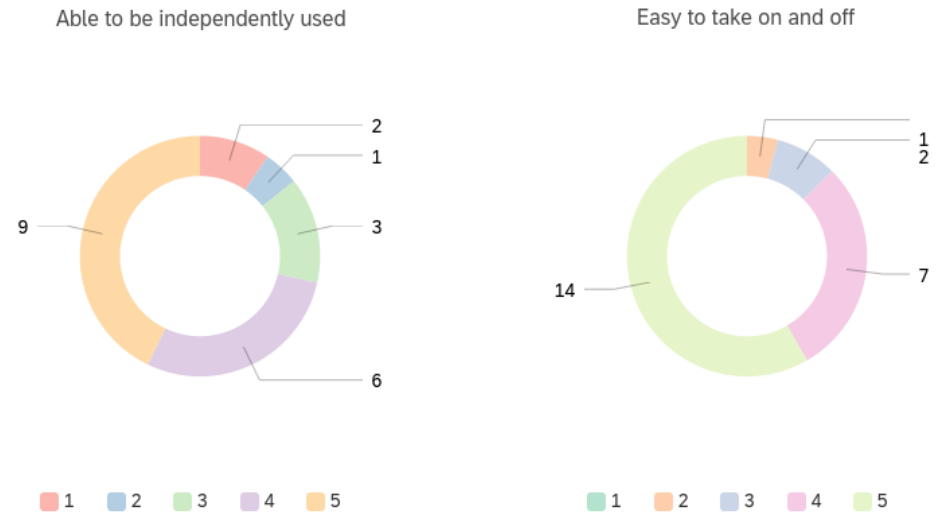
(a) Medical professional responses (b) Patient responses

Figure 5.21: Pie charts showing the responses for 'Wearable'



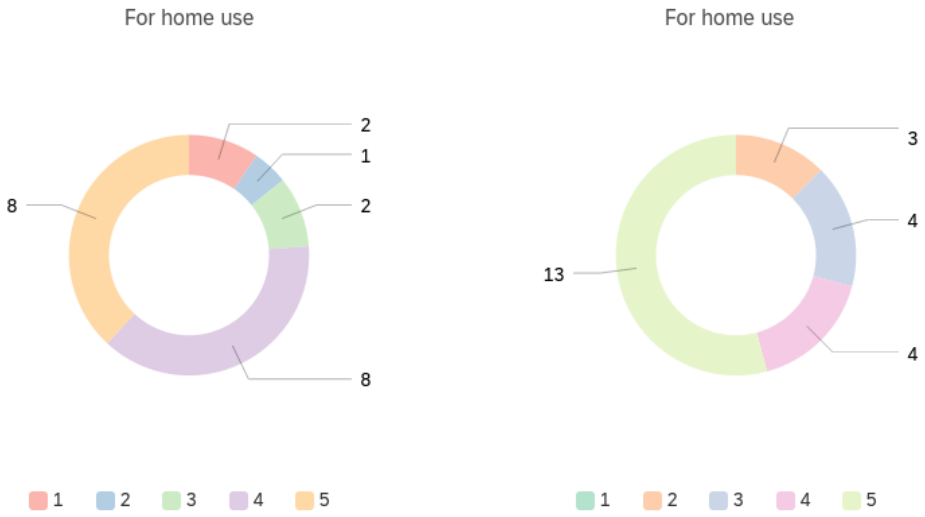
(a) Medical professional responses (b) Patient responses

Figure 5.22: Pie charts showing the responses for 'Comfortable'



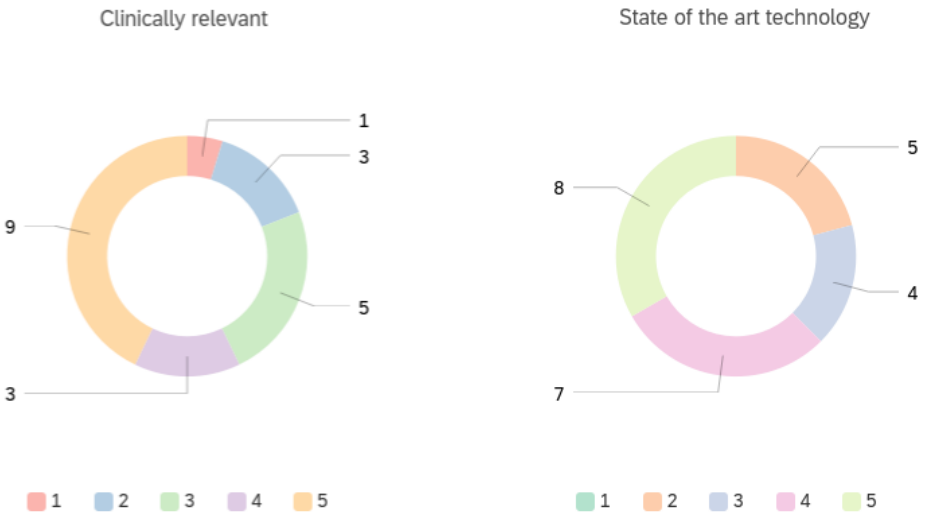
(a) Medical professional responses (b) Patient responses

Figure 5.23: Pie charts showing the responses for 'Independent Use'



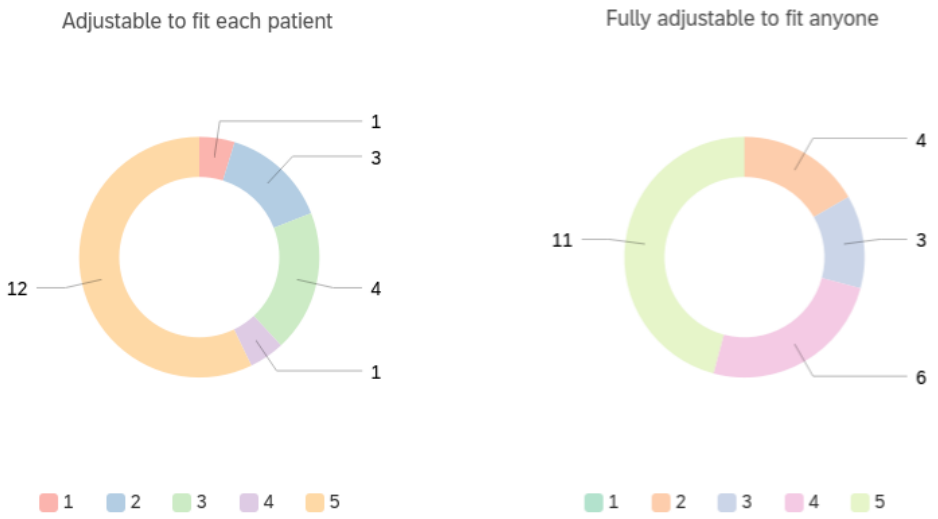
(a) Medical professional responses (b) Patient responses

Figure 5.24: Pie charts showing the responses for 'Home Use'



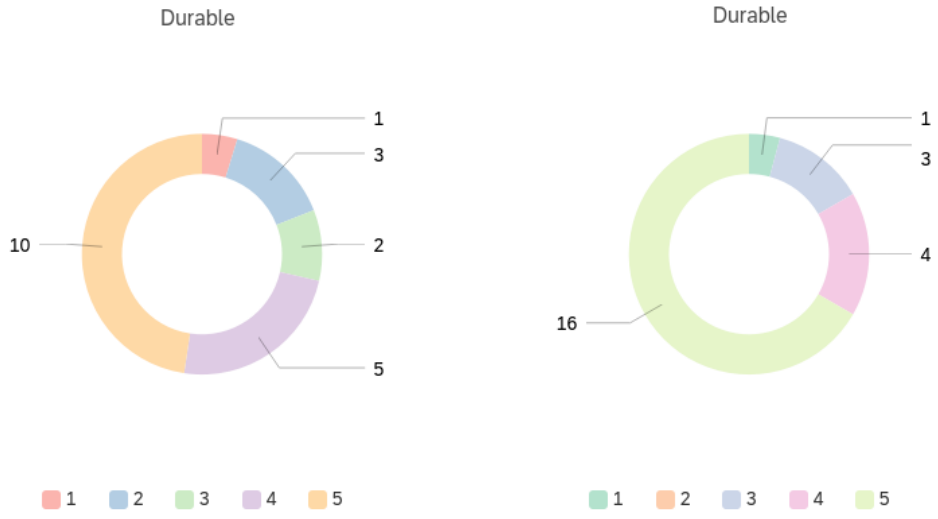
(a) Medical professional responses (b) Patient responses

Figure 5.25: Pie charts showing the responses for 'Clinical Relevance'



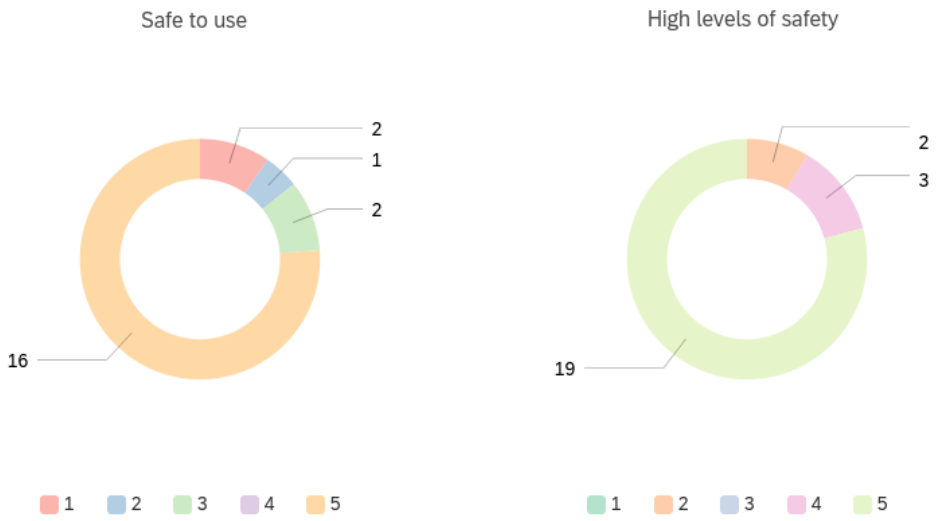
(a) Medical professional responses (b) Patient responses

Figure 5.26: Pie charts showing the responses for 'Adjustable'



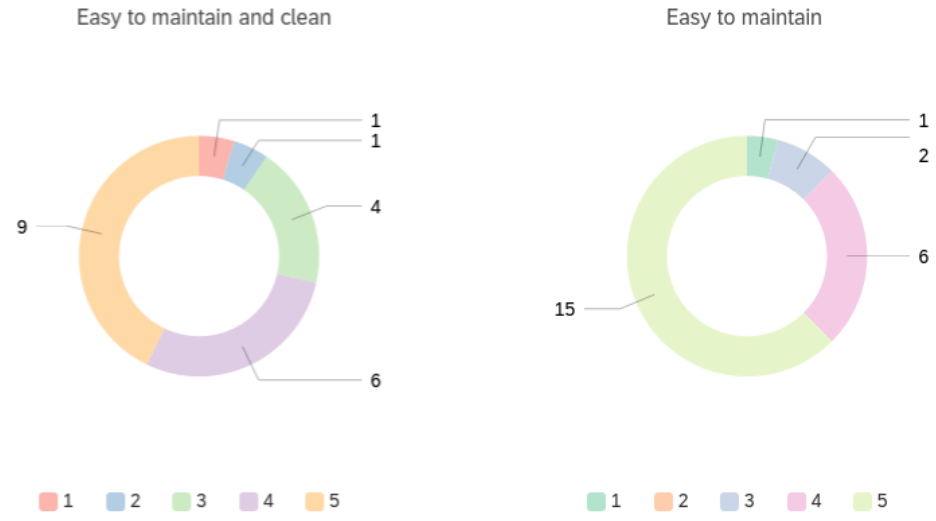
(a) Medical professional responses (b) Patient responses

Figure 5.27: Pie charts showing the responses for 'Durable'



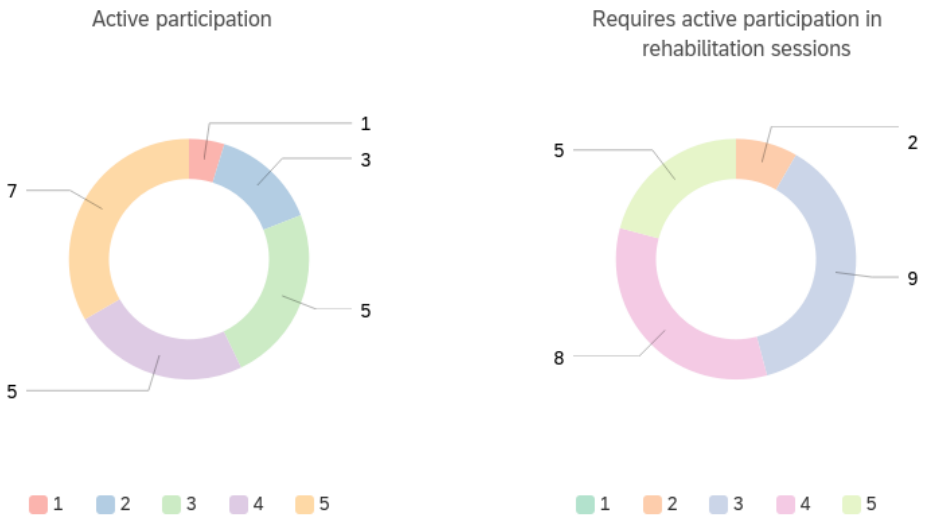
(a) Medical professional responses (b) Patient responses

Figure 5.28: Pie charts showing the responses for 'Safety'



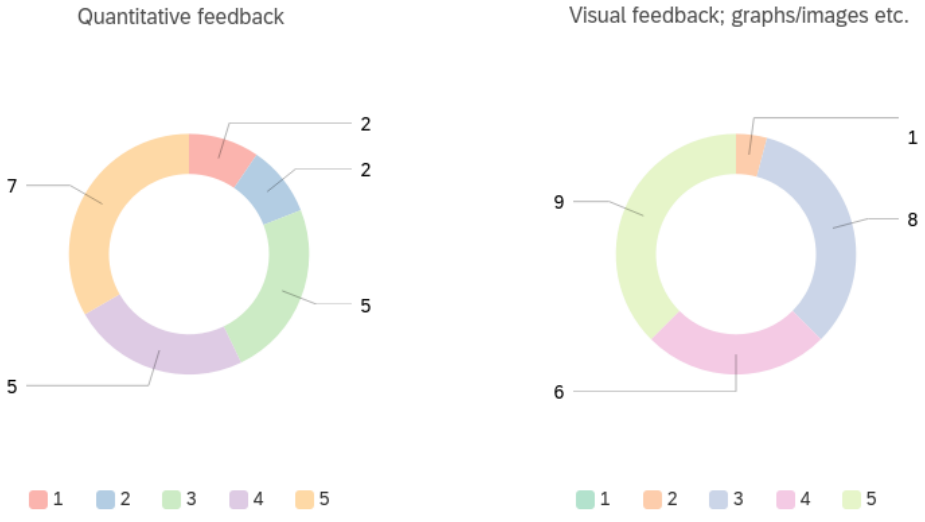
(a) Medical professional responses (b) Patient responses

Figure 5.29: Pie charts showing the responses for 'Maintenance'



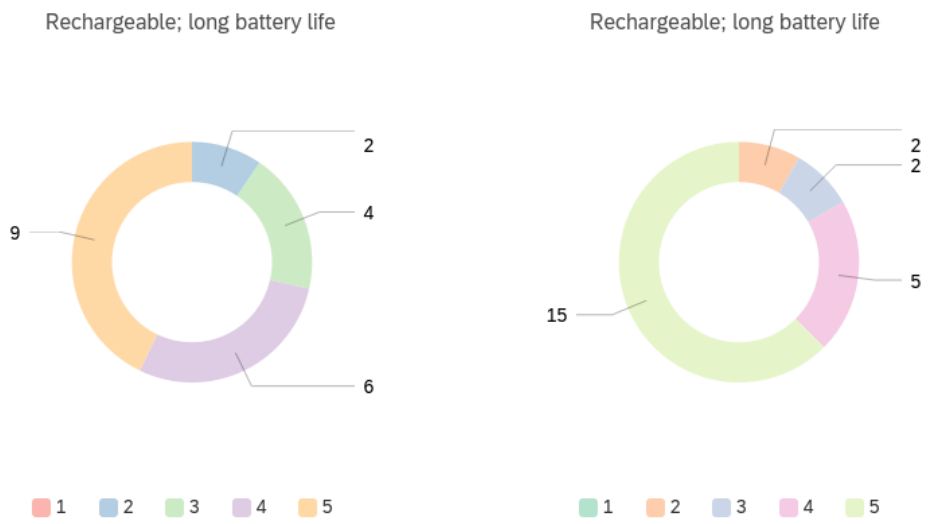
(a) Medical professional responses (b) Patient responses

Figure 5.30: Pie charts showing the responses for 'Active Participation'



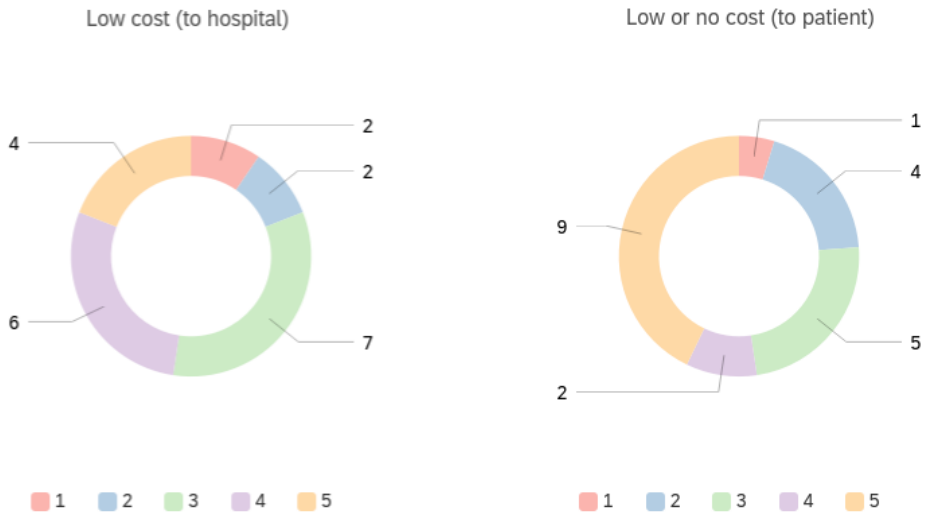
(a) Medical professional responses (b) Patient responses

Figure 5.31: Pie charts showing the responses for 'Feedback'



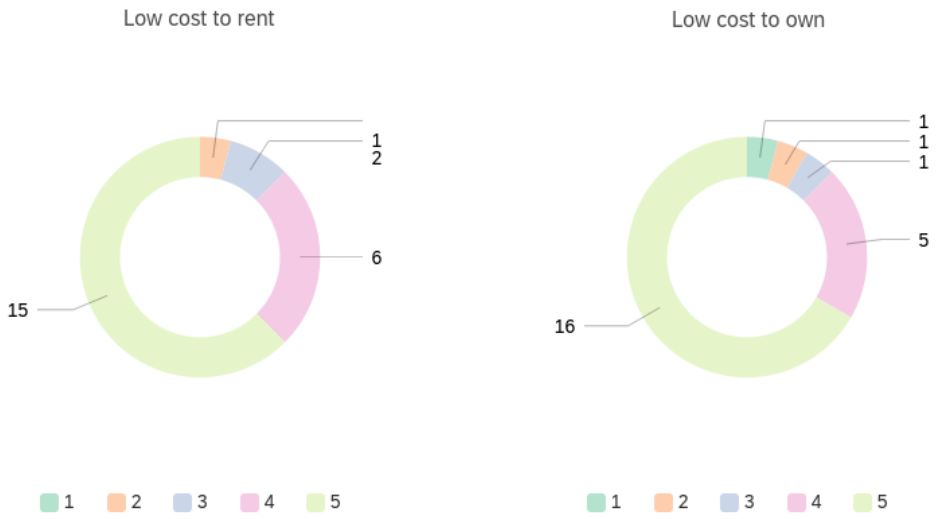
(a) Medical professional responses (b) Patient responses

Figure 5.32: Pie charts showing the responses for 'Rechargeable'



(a) Cost to the hospital (b) Cost to the patient

Figure 5.33: Pie charts showing the responses from medical professionals



(a) Cost for the patient to rent

(b) Cost for the patient to own

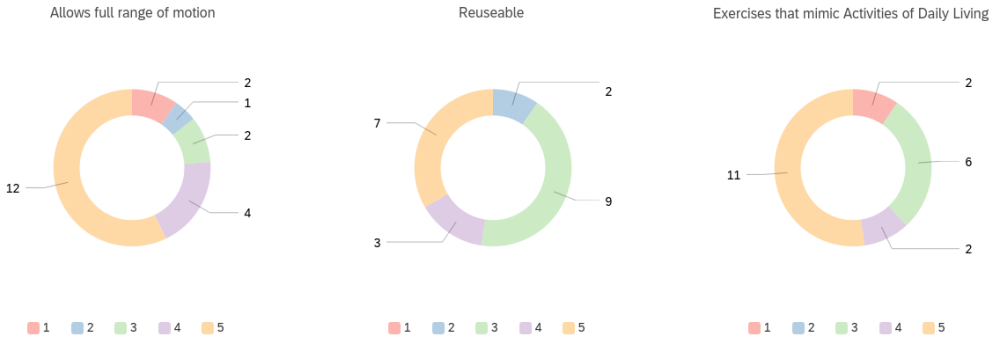
Figure 5.34: Pie charts showing the responses from patients

The final three sets of ratings for each group of participants can not be directly compared against each other, but were instead more suitable to be asked to only one or other of the groups. Medical professionals were asked to rate the importance of the range of motion of the exoskeleton, the reusability of it, and whether the exercises it uses mimic ADLs. 57% of participants rated the full range of motion as being an importance of 5, 19% an importance 4, and 10% an importance of 4. Generally a very important factor in the view of medical professionals. 33% rated the reusability as an importance of 5, 14% an importance of 4, and 43% an importance of 3. Medical professionals saw this as one of the least important factors that they were asked to rate. When it came to the importance of rehabilitation exercises mimicking ADLs, 52% rated it as a 5, 10% rated it as a 4, and 29% rated it as a 3.

Patients were asked about the aesthetics of the exoskeleton, the importance of the exoskeleton being made to specifically fit them (in conjunction with the previously asked rating about the exoskeleton being adjustable), and the storage capabilities of the exoskeleton. Patients did not see the aesthetics of the exoskeleton as very important, with only 13% of participants rating it as a 5, 24% rating it a 4, 4% rating it a 3, 46% rating it a 2, and 13% rating it as a 1. This was the lowest overall rating for any of the requirements that were rated in the patient survey. The exoskeleton being a specific fit

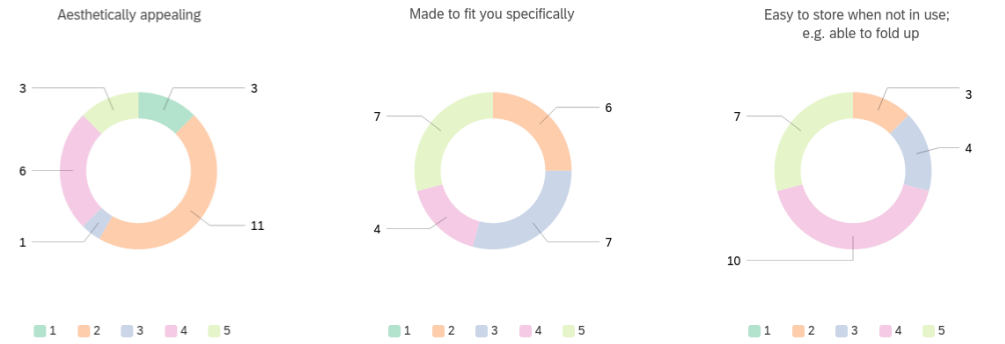
for the patient was rated lower than the adjustable requirement, with 29% rating it a 5, 17% rating it a 4, 29% rating it a 3 and 25% rating it a 2. Easy storage of the device was also not seen as overly important, with 29% rating it a 5, 42% rating it a 4, and 17% rating it a 3.

The ratings discussed above tend to only discuss the top 3 importance ratings as the lower ratings had very few responses and it was the higher ratings that gave a more detailed overview of how participants viewed each requirement. The lower ratings across all of the requirements tended to have only 1 or 2 responses each.



(a) Range of motion (b) Reuseable (c) Activities of daily living

Figure 5.35: Pie charts showing the responses from medical professionals



(a) Aesthetics (b) Specific Fit (c) Storage

Figure 5.36: Pie charts showing the responses from patients

5.5 Conclusion

The surveys in this chapter aimed to gather as much information as possible about the needs of patients when using an exoskeleton for stroke rehabilitation. They successfully covered both the general background information such as the difficulties that patients face, and the background of medical professionals in the field; as well as the more in depth data on exoskeletons in particular. The initial survey that was carried out gathered some very interesting feedback on the design of BEAST V2 which was taken into the later designs of BEAST. Ideally, there would have been more in-person focus groups and interviews carried out to gather the data required, as aspects that had not been considered when coming from a background in engineering were brought up and discussed by medical professionals in the rehabilitation field. The lack of direct contact with participants will definitely have resulted in the loss of some good data that could have been useful, however the data that was gathered through the online surveys was still very informative. The inability to carry out in-person meetings also meant that follow up meetings were not possible to continue to gather feedback throughout the design process, and instead the data had to be gathered at a particular point in the design process and applied to the design that existed at that time.

The online surveys that were designed included most of the relevant information that was needed for the patient needs considerations. In hindsight, it could have been beneficial to be more specific in some particular questions, for example asking patients how much time passed between the onset of stroke and the beginning of their physiotherapy; giving medical professionals more open-ended questions when considering tracking improvements; being more explicit with some of the engineering information, including more detailed explanations of sensors and exoskeletons; and including a question at the end for any further comments to cover aspects that may not have been considered but that either group would want to mention. One particular pro that came from carrying out the online surveys was that participants came from all sorts of backgrounds in many different countries and were not necessarily from the same facility/ background that they would have been from if in-person focus groups and interviews had been carried out.

Lots of the data gathered through the surveys helped to strengthen the motivations behind this thesis, such as both groups of participants considering the home environment to be at least partially ideal or preferred as seen in Figure 5.3. The results gathered

in Section 5.4.2 show that although not many participants currently use exoskeletons in rehabilitation, a large percentage of them would be open to using them in the future in various ways, especially assistive exoskeletons. Many participants would also use computer games alongside exoskeletons, something that could be developed in the future to work alongside BEAST. Section 5.4.3 highlights some good preferences that both medical professionals and patients have, such as the type of feedback they would find valuable (numerical and graphical formats), ways in which they would feel more likely to carry out rehabilitation at home (by being able to track their improvements), and being more likely to carry out rehabilitation at home if they had an exoskeleton to use.

Finally, Section 5.4.4 gathers some very interesting data on the importance of actual engineering requirements, which is the most novel section of this chapter in terms of the type of information gathered. Previous patient needs studies focus on the medical needs of patients after stroke [92–98]. However, this does not always help to create assistive devices that have the potential to improve the rehabilitation experience for both medical professionals and patients. The biggest contribution to the research is the data that can be used to create an optimisation strategy in the next chapter that allows for a more patient-orientated exoskeleton design to be created.

Chapter 6

Exoskeleton Design Optimisation

6.1 Introduction

This chapter investigates two different types of optimisation; quality function deployment (QFD), and kinematic optimisation. QFD uses the results of the surveys in Chapter 5 to build an optimisation strategy that can be used on BEAST V4 to build a more patient orientated design. The kinematic optimisation can be used to improve the mechanical aspects of the design.

6.2 Quality Function Deployment

QFD considers the importance of the customers requirements versus the functional requirements of a product. The information is gathered and then analysed in order to see which of the functional requirements are most important from the customers point of view. Using some of the data gathered from the survey detailed in the previous chapter, a QFD analysis has been carried out using a House of Quality (HOQ) of several sets of data. Both the patient and medical professional responses have been analysed individually, followed by a combination of the two.

The first step of building a HOQ is to determine the customer requirements. During the survey, participants were asked to rate a number of design aspects on a scale of 1-5, with 1 being the least important and 5 being the most important. The design aspects highlighted in this survey question were used as the basis of the customer requirements for the HOQ. Figures 6.1 and 6.2 show the graphs of the summarised responses given by the participants of the medical professional and patient survey respectively, with the mean of these responses plotted on top. The mean of the responses is used as a factor of importance, which is then used to determine the relative weight of each requirement. With the customer requirements fully defined, the next step is to determine the functional requirements. These are the engineering requirements necessary to actually create the exoskeleton. These requirements have been determined simply from the design of the existing version of BEAST, with a few additions. The functional requirements need to be able to be measured in some way in order to be useful in the HOQ. As they can be measured, they also have an aim tied to them. The aim for each functional requirement is either to minimise the requirement, maximise it, or aim for a specific target value. The functional requirement ‘Weight’ needs to be minimised, while the requirement for ‘Motor Torque’ needs to be minimised.

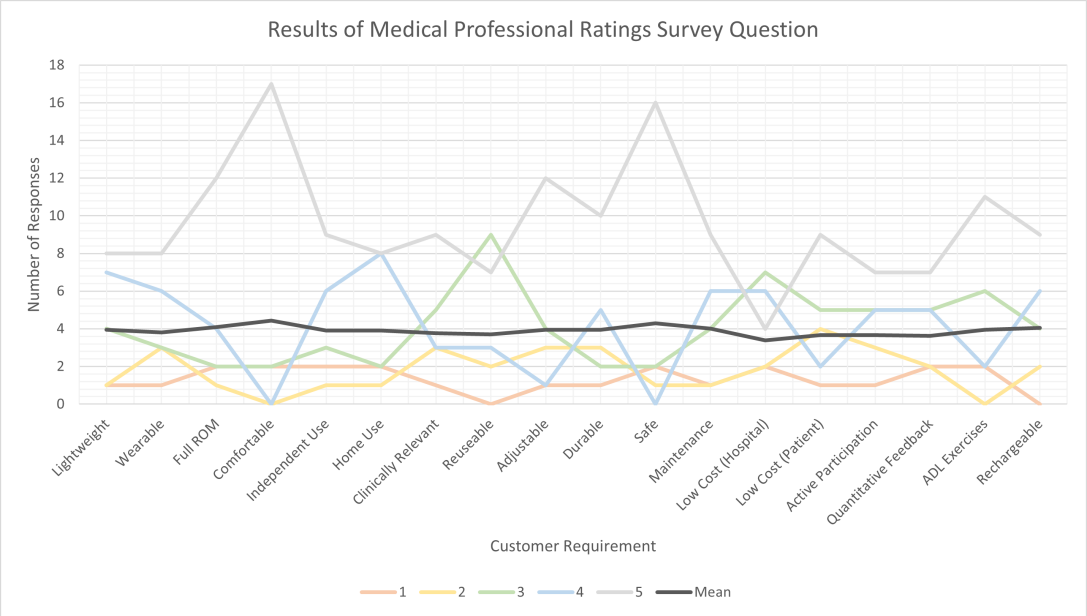


Figure 6.1: Graph showing the survey results of the rating question for medical professionals, including the mean

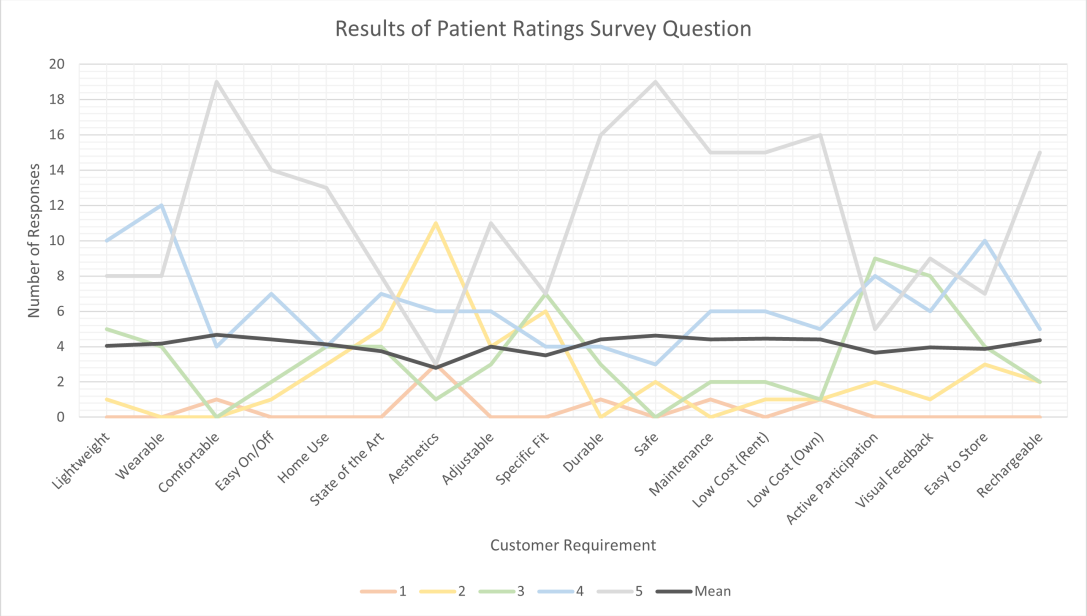


Figure 6.2: Graph showing the survey results of the rating question for patients, including the mean

The HOQ built from the medical professional and patient responses can be seen in Figures 6.3 and 6.4. They show the functional requirements and their targets, as well as the relationships between the customer requirements and functional requirements. This relationship is given a value of 0, 1, 3, or 9 depending on how strong the relationship between the two factors is. For example, the relationship between the customer requirement 'Lightweight' and the functional requirement 'Weight' is given a 9; they have a very strong relationship. This is because making the exoskeleton lightweight directly impacts the weight of it. The relationship between 'Comfortable' and 'Size of Exoskeleton' has a relationship of 1. It is a weak relationship but it is still there. Generally, an exoskeleton is likely to be more comfortable if it is smaller and less intrusive however, this is not necessarily the case. A large exoskeleton could also be considered comfortable depending on it's design and weight distribution. The requirements for 'Adjustable' and 'Strength of Material' have a relationship of 3; a moderate relationship. For the exoskeleton to be adjustable the material does not have to be strong, but it will make the adjustable parts last longer and will mean that adjusting the size of the exoskeleton is easier.

With the relationships between the customer and functional requirements set up, the last step is to complete the 'roof' of the HOQ. This is where the relationships between the functional requirements themselves are established. Some functional requirements will have a correlation between them. For example, as the size of the exoskeleton increases, the likelihood is that the weight of the exoskeleton will also increase. This means the two requirements have a positive correlation. Figure 6.5 shows the correlations that were identified between the functional requirements. The majority of the negative correlations are on the 'Cost of Materials' row. This is because generally when increasing other requirements it is likely to increase the cost. Increasing the motor torque for example would mean a more expensive motor as the majority of high torque motors are more specialist and therefore more expensive. This is also true for the tensile strength of the cable. The stronger the cable, the more expensive it is likely to be. As the target for both motor torque and tensile strength of the cable are to maximise them, while the target for the cost is to minimise, these correlations become negative despite both values increasing.

Relationship Between Requirements:
9 - Strong 3 - Moderate 1 - Weak

			Column Number	1	2	3	4	5	6	7	8	9	10
			Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9
			Requirement Weight	293.67	210.02	341.25	201.21	94.507	113.18	191.1	131.22	222.44	205.62
			Relative Weight	14.65	10.48	17.03	10.04	4.72	5.65	9.53	6.55	11.10	10.26
			Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)										
			Minimize (▼), Maximize (▲), or Target (x)	▼	x	x	▲	▲	▼	▼	▲	x	▼
			Target or Limit Value										
Row Number	Max Relationship Value in Row	Relative Weight	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Weight (g)	Adjustable Length of Links (mm)	Joint Angle Range (°)	Motor Torque (Nm)	Strength of Material (N/m^2)	Size of Components (mm)	Size of Exoskeleton (mm)	Tensile Strength of Cable (N/m^2)	Backdriveable	Cost of Materials (£)
1	9	5.64	Lightweight	9			9			9			
2	9	5.44	Wearable	9	1	3		1	9	9			
3	9	5.85	Full ROM		3	9	9				9	9	
4	9	6.32	Comfortable	9	9	3			3	1			
5	9	5.56	Independent Use	9				1	1	3			
6	9	5.56	Home Use	3					3	9			
7	9	5.36	Clinically Relevant		3	9	9				3	9	3
8	9	5.29	Reuseable		9			3					9
9	9	5.64	Adjustable		9	1		3					
10	9	5.64	Durable					9			9		3
11	9	6.12	Safe	3		9	3			3	1	9	
12	3	5.71	Maintenance						1				3
13	9	4.82	Low Cost (Hospital)		1								9
14	9	5.24	Low Cost (Patient)		1								9
15	9	5.24	Active Participation			9	3					3	
16	9	5.16	Quantitative Feedback			9	3						
17	9	5.64	ADL Exercises		1	9					1	9	
18	9	5.78	Rechargeable	9					3				3

Figure 6.3: Medical Professional House of Quality

Relationship Between Requirements:
9 - Strong 3 - Moderate 1 - Weak

			Column Number	1	2	3	4	5	6	7	8	9	10
			Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9
			Requirement Weight	347.74	152.63	236.89	128.9	87.166	228.35	318.02	75.512	117.26	237.2
			Relative Weight	18.02	7.91	12.28	6.68	4.52	11.83	16.48	3.91	6.08	12.29
			Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)										
			Minimize (▼), Maximize (▲), or Target (x)	▼	x	x	▲	▲	▼	▼	▲	x	▼
			Target or Limit Value										
Row Number	Max Relationship Value in Row	Relative Weight	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Weight (g)	Adjustable Length of Links (mm)	Joint Angle Range (°)	Motor Torque (Nm)	Strength of Material (N/m^2)	Size of Components (mm)	Size of Exoskeleton (mm)	Tensile Strength of Cable (N/m^2)	Backdriveable	Cost of Materials (£)
1	9	5.48	Lightweight	9			9			9			
2	9	5.66	Wearable	9	1	3		1	9	9			
3	9	6.34	Comfortable	9	9	3			3	1			
4	9	6.00	Easy On/Off	9				1	1	3			
5	9	5.60	Home Use	3					3	9			
6	9	5.09	State of the Art		3	9	9				3	9	3
7	9	3.79	Aesthetics		1				9	9			3
8	9	5.43	Adjustable		9	1		3					
9	9	4.75	Specific Fit		1				3	9			
10	9	6.00	Durable					9			9		3
11	9	6.28	Safe	3		9	3			3	1	9	
12	3	6.00	Maintenance						1				3
13	9	6.05	Low Cost (Rent)		1								9
14	9	6.00	Low Cost (Own)		1								9
15	9	4.98	Active Participation			9	3					3	
16	9	5.37	Visual Feedback			9			3				9
17	9	5.26	Easy to Store	9	1			1	9	9			
18	9	5.94	Rechargeable	9					3				3

Figure 6.4: Patient House of Quality

Row Number	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	1 Weight (g)	2 Adjustable Length of Links (mm)	3 Joint Angle Range (°)	4 Motor Torque (Nm)	5 Strength of Material (N/m^2)	6 Size of Components (mm)	7 Size of Exoskeleton (mm)	8 Tensile Strength of Cable (N/m^2)	9 Backdriveable	10 Cost of Materials (£)
1	Weight (g)										
2	Adjustable Length of Links (mm)										
3	Joint Angle Range (°)										
4	Motor Torque (Nm)										
5	Strength of Material (N/m^2)	-	+		+						
6	Size of Components (mm)	+			+	-					
7	Size of Exoskeleton (mm)	+					+				
8	Tensile Strength of Cable (N/m^2)			+		+					
9	Backdriveable			+					+		
10	Cost of Materials (£)	+	-		-		-		-		

Figure 6.5: House of Quality roof

Having carried out the HOQ analysis, the relative importance of the functional requirements is the data that can be used to optimise the existing design of BEAST. With the current set of results, two separate optimisations can be done, one that takes into account the requirements of the medical professionals, and one that takes into account the requirements of the patients. The next step is to combine the two into a third HOQ. To do this, the customer requirements first needed to be adjusted. Many of the requirements were the same for both groups of participants, however some were not. The requirements that could not be combined were removed. From the medical professional requirements, 'full ROM', 'reuseable', 'quantitative feedback', and 'ADL exercises were removed. From the patient requirements, 'aesthetics', 'specific fit', 'visual feedback', and 'easy to store' were removed. None of these results could be combined across the two groups and had the potential to skew the importance of the requirement if used with less responses than other requirements. A further set of requirements were combined despite having slightly different wording in the original survey question. Where patients were asked to rate 'state of the art', medical

professionals were asked to rate 'clinically relevant'. These could easily be argued to mean the same thing and so the responses were combined. Figure 6.6 shows the full set of combined ratings with the mean of each requirement plotted on top. The new set of customer requirements and their relative importance is input in the new HOQ with the same functional requirements as before. The relationships between the two sets of requirements and the correlations between the functional requirements are also kept the same.

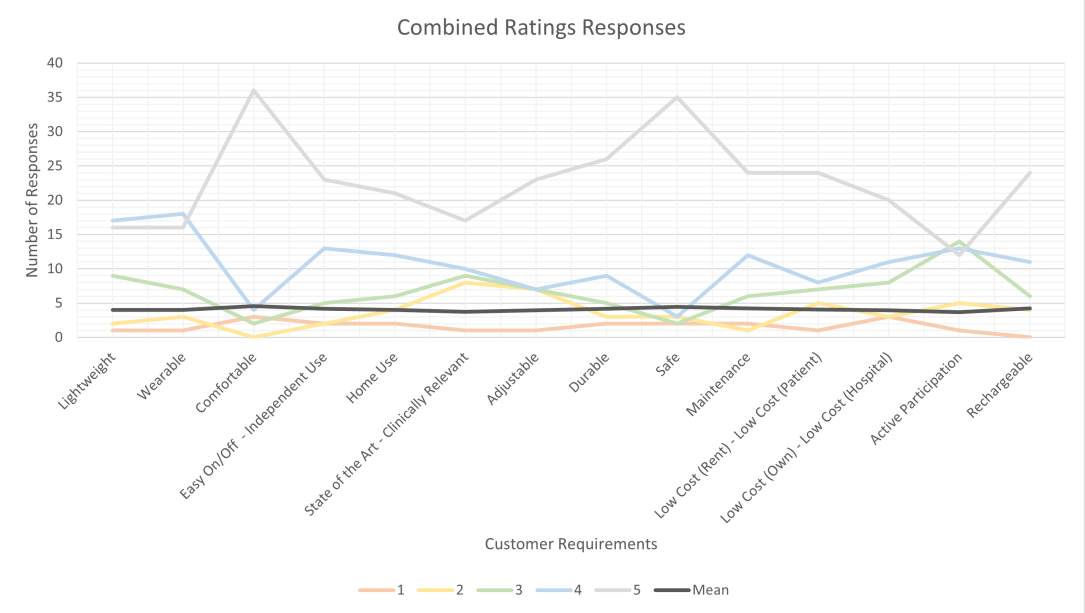


Figure 6.6: Graph showing the combined responses to the ratings survey question, including the mean

Once all 3 HOQ have been built, the data collected from each can then be analysed. The simplest way to do this is to compare the relative importance of the functional requirements in each case, as this is what has been determined through the QFD process. Figure 6.7 shows this information on a graph. The results are very interesting, as there is no one set of responses that has a higher importance percentage than the others. Each requirement has a very different amount of importance depending on which group of end users are asked. the importance is a percentage of the full 100% for each functional requirement. Overall, medical professionals ended up with the most important requirement being the joint angle at about 17%. This is not particularly

surprising as this is such a key medical aspect of rehabilitation with an exoskeleton. When looking back at Figure 6.1, 'full ROM' does not receive the highest number of responses for an importance of 5, showing that the relationships between the customer requirements and the functional requirements are clearly an important aspect; with 'joint angle range' having the most strong relationships with the customer requirements. Weight was the second most important requirement at about 14.5%, and backdriveable was third with about 11% of the importance. The least important requirement is the strength of the material (4.5%), followed closely by the size of the components (5.5%), and the tensile strength of the cable (6.5%). These are all aspects that although important from an engineering point of view, may not seem notably important from a medical point of view.

When looking at how the importance turns out for the patients, the most important is weight at 18%, followed by size of the exoskeleton (16.5%), and finally cost of materials (12%). From the patients point of view it absolutely makes sense that these would be most important. Patients need to be able to pick up and manoeuvre the exoskeleton around on their own (if using in a home environment); they need to be able to be able to lift and wear the exoskeleton, and have somewhere large enough to store it. They are also more likely to consider the cost of the device if they may be expected to fund it themselves. The least important aspects are again the tensile strength of the cable with less than 4% of the importance; the strength of the material (4.5%), and the ability for the motors to be backdriveable (6%). As with the analysis of the medical professional HOQ, it's also not surprising that these engineering aspects are not important to patients as they are more bothered about comfort and useability. They would be under the assumption that the exoskeleton they are given to use would be fully functioning and the engineering aspects already dealt with.

When combining the responses of both groups, the importance changes a bit. The most important overwhelmingly becomes weight at almost 20%, with size of exoskeleton and joint angle range next at around 12.5%, much lower on the graph. The least important from the combined responses is unsurprisingly the tensile strength of the cable and the strength of the material, both with around 5% of the importance, with the size of the components coming in next in the 7% range.

Overall, there are fairly different importances given to most of the functional requirements based on the responses from each group of participants. Patients deemed

aspects that would affect their ability to use the device comfortably on their own as the most important, while medical professionals deemed aspects that would affect the quality of the actual rehabilitation that is being undertaken as the most important. This can also be seen for some of the functional requirements in the middle of the importance scale. Motor torque for example is just over 3% more important to medical professionals than patients; which can be traced back to the initial responses where lightweight and state of the art were both ranked fairly highly. These are the two customer requirements that have a strong relationship to the motor torque requirement. Backdriveable is just over 5% more important to medical professionals; this however could be linked back to the difference in customer requirements between the two groups. During the HOQ analysis, medical professionals had four customer requirements that had a strong relationship with backdriveability, and one that had a moderate relationship. Patients on the other hand only had two strong relationships and one moderate relationship between backdriveability and the customer requirements. This leads to it being much less important in the patient's overall HOQ than the medical professional's HOQ.

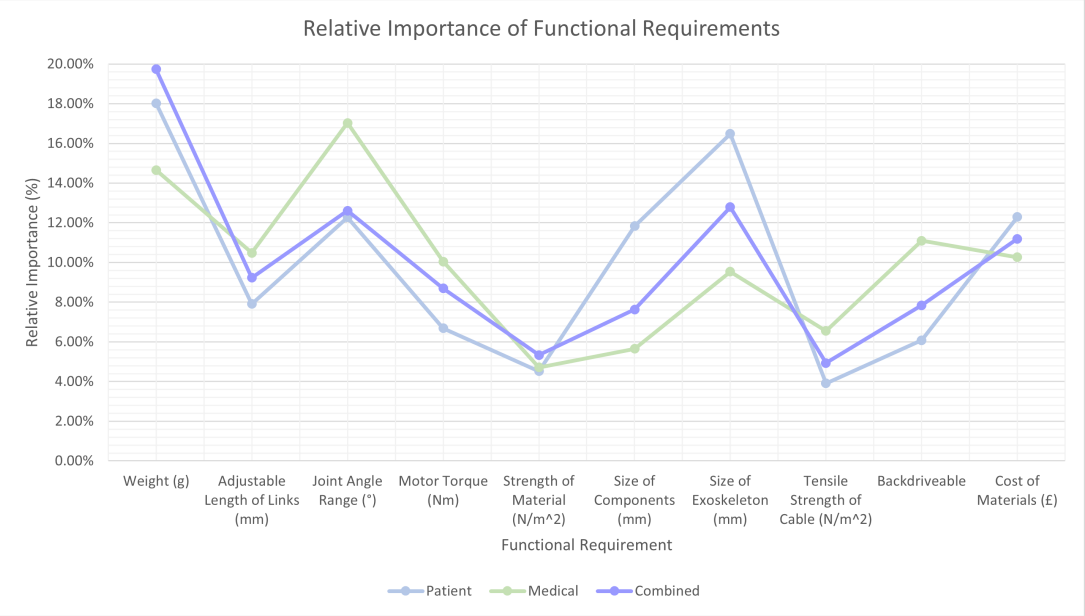


Figure 6.7: Graph of relative importance of the functional requirements of the House of Quality

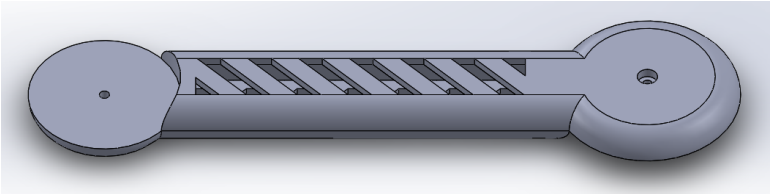
While the data in Figure 6.7 has been taken directly from the initial versions of the HOQ analysis, one thing to note is that the importance of each group is now missing a section as they have both had customer requirements removed after the analysis has been carried out. This means the overall importance no longer adds up to 100%. If we were to look at only the requirements that are the same across the groups from the beginning, the graph comparing the relative importance would show three very similar lines, rather than the three different lines seen in the existing figure, where the biggest difference in percentage across the three lines would have been about 1%. Taking the customer requirements out from the beginning would have created a skewed look at the importance given to each requirement by the participants of the survey which is why the requirements have been removed after the initial HOQ analysis rather than before.

6.2.1 Optimisation

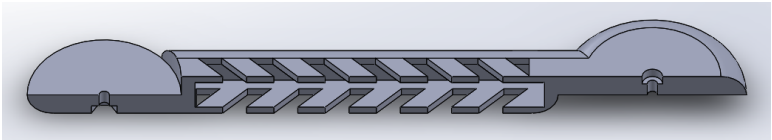
From the QFD analysis completed above, there are several options for optimisation. A single optimisation could be done that takes into account the combined QFD analysis, or an individual optimisation can be done using either the patient or medical professional QFD analysis. Instead of fully creating an optimised design based on just one of the options, all three options were instead considered to see how the optimised design might look based on each users thoughts. The three most important requirements as determined through the QFD analysis, shown in Figure 6.7, were taken as a starting point for the optimisation process.

Starting with a patient orientated optimisation, the three most important requirements are the weight, size of exoskeleton, and cost of materials. Reducing the weight of the exoskeleton can be done in several ways, one of which is to reduce the amount of material required for the frame itself. Figure 6.8 shows a very simple way this could be done. Not only would this reduce the weight of the exoskeleton, it could also add to the aesthetics if the cutouts were designed in an artistic way. This type of redesign would need extensive testing to ensure that it was still strong enough to withstand the stresses put on it during use. The size of the exoskeleton is something that is likely to change depending on the person wearing it, however could be improved by creating a cable system that runs through the centre of the links instead of over the top. Although much more complicated, it could reduce the overall size of the exoskeleton significantly. Optimising the cost of the materials is a much more difficult task. Reducing the weight

would reduce the amount of material and therefore reduce the cost. However, reducing the size of the exoskeleton would add complexity which is likely to add cost. The main cost in the design of BEAST is the cost of the motors, as small high torque motors are very specialist and therefore fairly costly. The cost is something that may never be fully optimised due to the rest of the constraints on the exoskeleton. It could be optimised for the patient through subsidies from the hospital, or a rental or deposit scheme instead of the patient having to buy the exoskeleton outright.



(a) Full view



(b) Section View

Figure 6.8: Possible redesign of the elbow-wrist link of the exoskeleton to reduce weight.

For medical professionals, the three most important requirements are the joint angle range, weight, and backdriveability. The joint angle range can be optimised through a kinematics analysis, detailed in the next section. The weight can be optimised in a similar method to in the patient-orientated optimisation above. Optimising the backdriveability is a little difficult, mainly because a motor is either backdriveable or it's not. However, when looking at the actuation system as a whole, the cable system could be optimised to use a single motor to control each joint. Instead of having two motors, one for say flexion and one for extension, with each motor controlling the cable on either side of the joint; one motor could be used instead that has two cables attached. This way as the motor turns one cable is unravelled and one is wrapped around the pulley. This would require either the cables to change length at the same rate, or for there to be two different size pulleys that account for the difference in length. This could add a much larger level of complexity to the system but would certainly optimise the backdriveability of the system.

In the combined analysis, the three most important requirements are the weight, size of exoskeleton, and joint angle range. Optimising these three requirements would give an exoskeleton that has reduced the amount of material required for each link, relocated the cable system inside the links, and optimised the joint angle range through further optimisation. It is likely to be a much more complicated system that is not necessarily as cheap as patients would like, or have a backdriveable that is as good as medical professionals would like, but it would reach an in-between that hopefully both users would find acceptable.

6.3 Kinematic Optimisation

Kinematic optimisation is used to create the highest dexterity with the smallest volume of workspace used [101].

6.3.1 Kinematics Analysis

The Jacobian matrix is used to convert angular velocities of the joints into the velocity of the end effector of the exoskeleton. This matrix can be used alongside an optimisation strategy to optimise the movement of the exoskeleton from one end effector position to the next. The mathematics for calculating the Jacobian matrix follow on from the initial equations in Section 3.4, where the D-H parameters and homogenous transformation matrices (HTM) were specified. The joint velocities of an exoskeleton that moves in three dimensions are transformed into end effector velocities using the Jacobian matrix as shown in Equation 6.1 below. The matrix on the left represents the velocities of the end effector in both linear and angular directions; while the matrix on the right represents the joint velocities.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}_{6\times1} = J_{6\times n} \begin{bmatrix} \dot{q_1} \\ \dot{q_2} \\ \dots \\ \dot{q_n} \end{bmatrix}_{n\times1} \tag{6.1}$$

The Jacobian matrix can be calculated using Equation 6.2 below, where $n = 8$ for the number of revolute joints in BEAST. It uses values calculated from the homogenous

transformation matrix found in Equation 3.4, and the D-H parameters found in Table 3.5. Equation 6.3 shows how the HTM breaks down in order to be used to calculate J, with R being the rotation section of the matrix and d being the displacement section.

$$J = \begin{bmatrix} J_v \\ J_w \end{bmatrix} = \begin{bmatrix} R^0_{i-1} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \times (d^0_n - d^0_{i-1}) \\ R^0_{i-1} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \end{bmatrix} \tag{6.2}$$

$$A^{i-1}_i = \left[\begin{array}{ccc|c} cos\theta_i & -sin\theta_i cos\alpha_i & sin\theta_i sin\alpha_i & a_i cos\theta_i \\ sin\theta_i & cos\theta_i cos\alpha_i & -cos\theta_i sin\alpha_i & a_i sin\theta_i \\ 0 & sin\alpha_i & cos\alpha_i & d_i \\ \hline 0 & 0 & 0 & 1 \end{array}\right] = \left[\begin{array}{ccc|c} & R & & d \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \tag{6.3}$$

In order to start the calculation of the Jacobian matrix, several more individual HTMs need to be found following on from Equations 3.2 - 3.9; A^0_1 - A^0_8.

$$A^0_2 = A^0_1 \times A^1_2;\ A^0_3 = A^0_2 \times A^2_3\ etc. \tag{6.4}$$

At this point, the displacement section of the HTM for each joint can be used to plot the trajectories of each joint. This is a quick check to make sure that the HTMs are correct. Due to the values of θ_i being ranges rather than set values, the calculations were set up to run in MATLAB in order to simplify them. Each range of θ_i could then be run for each individual value of i, with all other values of i being set to 0. Trying to run all of the ranges of θ_i at once resulted in ever increasing sizes of matrices that didn't seem to work in the for loops within the MATLAB code, therefore running them each separately seemed to be the best option. The ranges for i for each value of θ_i can be seen in Table 6.1. Using these joint ranges, a plot of each of the trajectories for BEAST can be created, shown in Figure 6.9. For θ_5 it also included setting θ_2 to 90° to bring the exoskeleton to a position where the horizontal abduction and adduction could be carried out. The links of BEAST have also been plotted to try and show which joint each trajectory matches in the space that the link would move in; each trajectory line is the same colour as the link that is rotating to create the movement.

Table 6.1: Joint Ranges for θ_i

	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8
Lower Bound	0°	-140°	-90°	-90°	-135°	-160°	-70°	-65°
Upper Bound	0°	90°	-90°	140°	45°	0°	90°	25°

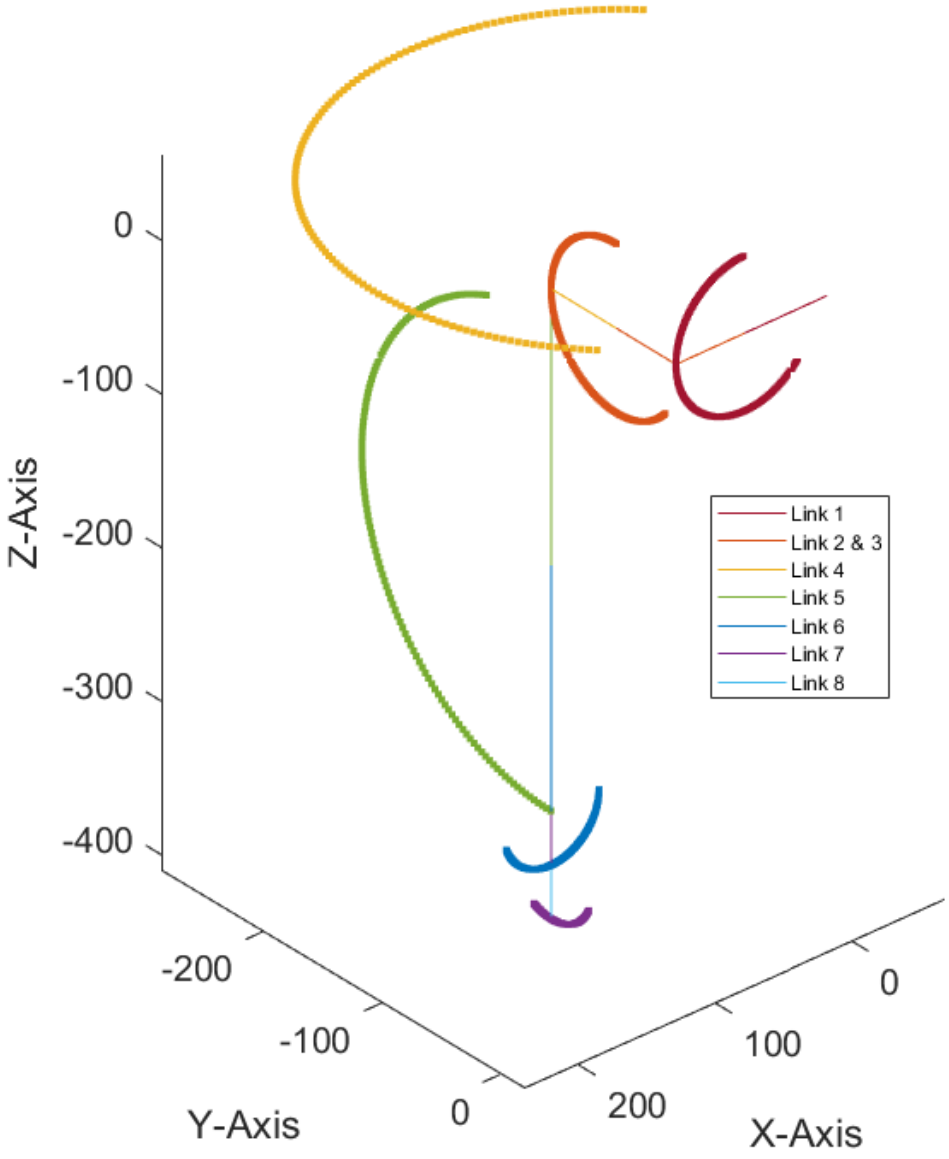


Figure 6.9: The arcs of joint motion plotted in a 3D space with the links of BEAST shown in corresponding colours. The plot is shown as if BEAST was worn on the left arm, looking at the exoskeleton from behind the left shoulder.

The trajectories are plotted using the displacement part of the HTM for each joint. Each point plotted in the trajectory line uses this displacement as the coordinates, d_x for the x-coordinate, d_y for the y-coordinate, and d_z for the z-coordinate. As the value of θ_i increments through the given range, a new point is plotted with the new value of d, developing the curve of the trajectory as it goes.

The Jacobian matrix from Equation 6.2 can be expanded into the full matrix using all of the HTMs that have been found, shown in Equation 6.5. This matrix has not been fully expanded due to its complex nature. It is instead calculated in a MATLAB programme in the next section as part of the forward kinematics for the full optimisation strategy.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} R_0^0 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \times (d_8^0 - d_0^0) & R_1^0 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \times (d_8^0 - d_1^0) & \dots & R_8^0 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \times (d_8^0 - d_8^0) \\ R_0^0 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} & R_1^0 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} & \dots & R_8^0 \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \\ \theta_6 \\ \theta_7 \\ \theta_8 \end{bmatrix} \tag{6.5}$$

6.3.2 Optimisation

The optimisation strategy that is being used here is the dynamic differential annealed optimisation (DDAO) strategy; a metaheuristic optimisation that has been designed for use in engineering applications [102]. DDAO mimics the annealing process of the production of steel. The mathematical model of the algorithm is shown in Equations 6.6-6.9, taken from [103].

$$S^k = (Sc_i - Sc_j) + Sr.f \tag{6.6}$$

$$f = \begin{cases} 1 & if\ rem(iteration, 2) = 1 \\ random[0, 1] & if\ rem(iteration, 2) = 0 \end{cases}, \tag{6.7}$$

where rem is the remainder after dividing by 2, the probability formula from the simulated annealing algorithm is then used [103].

$$P = e^{\frac{-\Delta E}{T}} \tag{6.8}$$

$$\Delta E = \frac{Cost(S^k) - Cost(S_L)}{Cost(S_L)}, \tag{6.9}$$

where S^k is the new solution for iteration $k = 1...n$, where n is the number of iterations, and Sc_i and Sc_j are randomly chosen solutions from within the population [103]. Sr is a randomly generated solution of the population within the search space [103]. P is the probability of accepting a new solution, ΔE is the difference between the objective value of the proposed solution, and the objective value of the solution S_L, with S_L being a solution of index L in the population $L = 1$, ..., population size [103]. T is the temperature variable that starts high and is updated each iteration to become smaller [103]. The new solution can be accepted if $P >$ random number $\in$ [0,1] [103]. According to Equation 6.8, P will be close to one to begin with as T is a high value. As there are a large number of random numbers that can be below one with the limits given, the new solution is likely to be selected. As the value of T decreases, P will tend towards zero. There will therefore be less random numbers that are less than P and the new solution is less likely to be selected. DDAO is independent of population size, a unique characteristic that many other algorithms do not share [103].

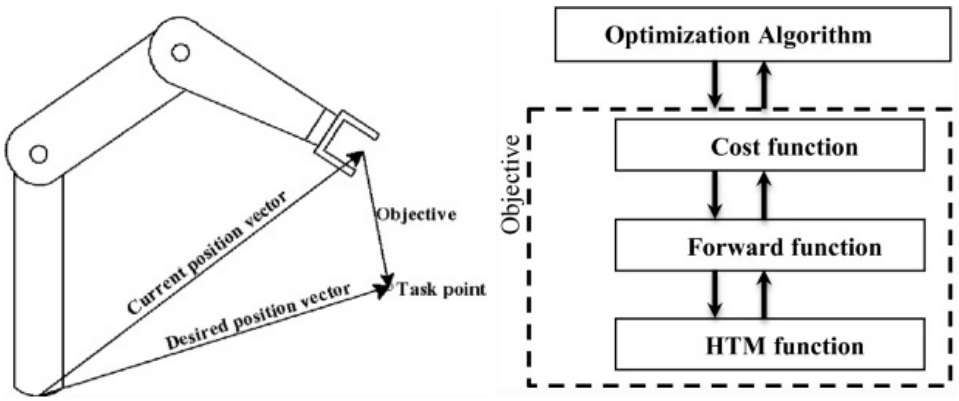
With the mathematical model set up, the cost function for the inverse kinematics is found. The inverse kinematics can be calculated using the Jacobian matrix from the previous section. Figure 6.10(a) shows the objective of the algorithm; the minimum 'cost' for moving to the task point within the exoskeleton workspace. The aim is for the cost to be zero, as this would mean that the end effector is in the correct position. The current position vector is measured from the base of the exoskeleton (for BEAST this would be at the top of the exoskeleton), to the current position of the end effector. The desired position vector is measured from the base to the task point. The objective function f is the vector between the two points and can be denoted as the magnitude of this vector.

$$f = ||Ci - De||, \tag{6.10}$$

where Ci is the instantaneous position vector and De is the desired position. This is the function that is being minimised, the distance between the end effector to the exoskeleton and the task point.

$$f = sqrt(x_c - x_t)^2 + (y_c - y_t)^2 + (z_c - z_t)^2, \tag{6.11}$$

where $[x_c, y_c, z_c]$ is the current position coordinates, and $[x_t, y_t, y_t]$ is the coordinates of the task point. The task point is given to the inverse kinematic problem.



(a) Objective cost shown as a vector (b) Algorithm methodology

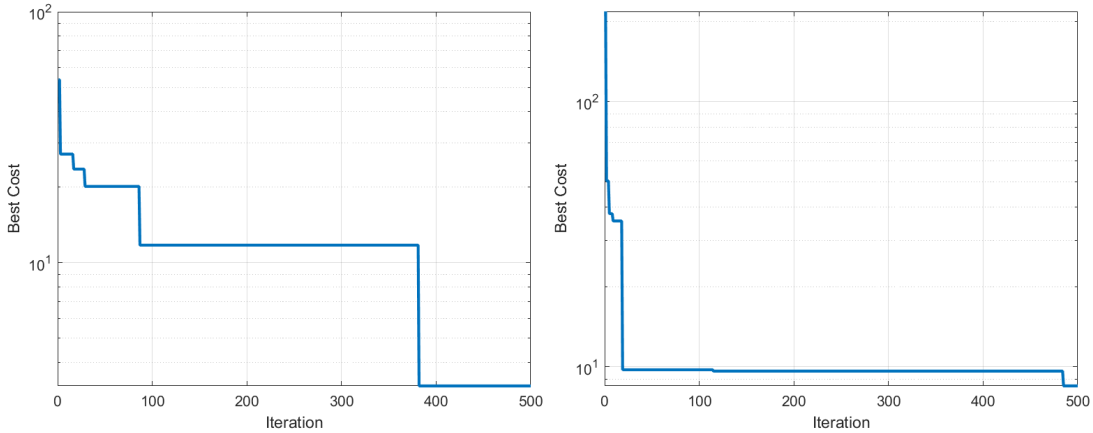
Figure 6.10: DDAO optimisation strategy [103]8

Figure 6.10(b) shows the procedure of the optimisation algorithm. An initial solution of joint angles is sent by the algorithm to the cost function. The cost function takes these ranges and sends them to the forward kinematics to determine the coordinates of the end effector of the exoskeleton. The forward kinematics calls the HTM function several times to calculate the overall HTM. This is then fed back into the forward kinematics function which finishes the calculation, sends the result to the cost function which uses Equation 6.11 to calculate the final cost which is sent back to the algorithm. The main optimisation algorithm then checks the cost against the cost it has saved, and uses Equation 6.8 to determine if this new cost should be saved as the best cost option. This is then repeated over the full number of iterations.

Applying this to BEAST is done fairly easily. The forward kinematics and HTM calculations have already been done in the previous section, and the upper and lower limits for each value of θ_i can be seen in Table 6.1. With the specific data for BEAST implemented in the algorithm, a task point was selected as random and the algorithm

was run. Each set of task point coordinates was run twice to try and show the randomness of the DDAO algorithm. The first task point was set as $[335.5, 0, 110.5]$. The first time the algorithm was run, the initial cost was 53.6038, reducing to 27.0936 at iteration 3, 23.6157 at iteration 17, 20.1455 at iteration 29, 11.7508 at iteration 87, and 3.2288 at iteration 382. As can be seen in Figure 6.11(a), there was a very obvious graduated descent to the final best cost. Compare that to the second time this task point was run in Figure 6.11(b) though and it shows a very different graph. This time, there is a lot of reduction in the cost within the first 20 iterations, going from 218.934 to 9.7598 by iteration 19, reducing minimally to 9.6457 at iteration 115, and finally to 8.4828 at iteration 485.

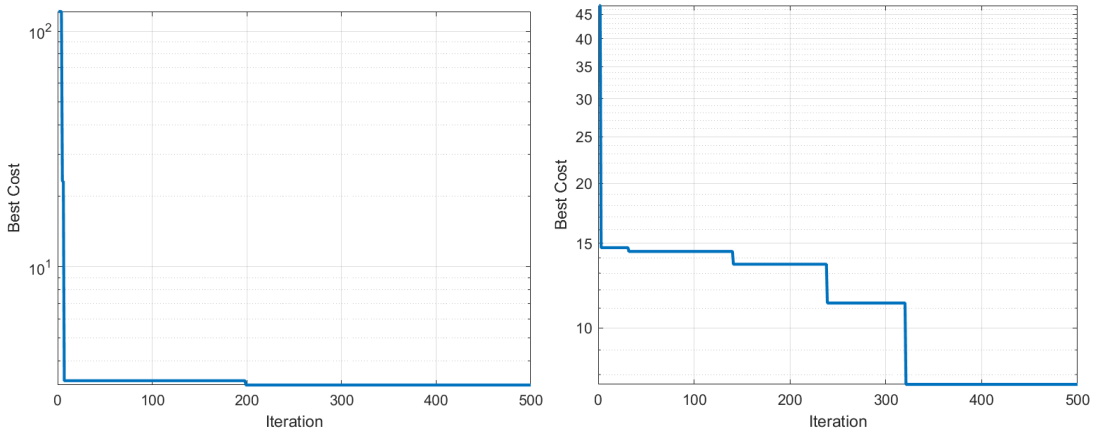
The next task point was set at $[200, 50, 110.5]$ and this time the first time the algorithm was run there was a lot of reduction within the first 10 iterations, going from 121.1099 to 3.2892 by iteration 7 with only 2 reductions, and then reducing once more to its final cost of 3.1535 at iteration 199. The second time this task point was run it reduced slower over more iterations, starting at 46.8829 and not reducing to its best cost of 7.6318 until iteration 321 after 5 reductions. The initial cost does not seem to have much of an effect on the number of reductions that happen over the iterations, however the first reduction does seem to. The lower the first drop in cost is, the less reductions it then takes over the iterations to reach its final cost. The number of iterations also does not seem to have an effect. There is either a lot of reduction in a short amount of iterations, or the same amount of reduction is spread more evenly over the iterations.



(a) Task=(335.5, 0, 110.5)

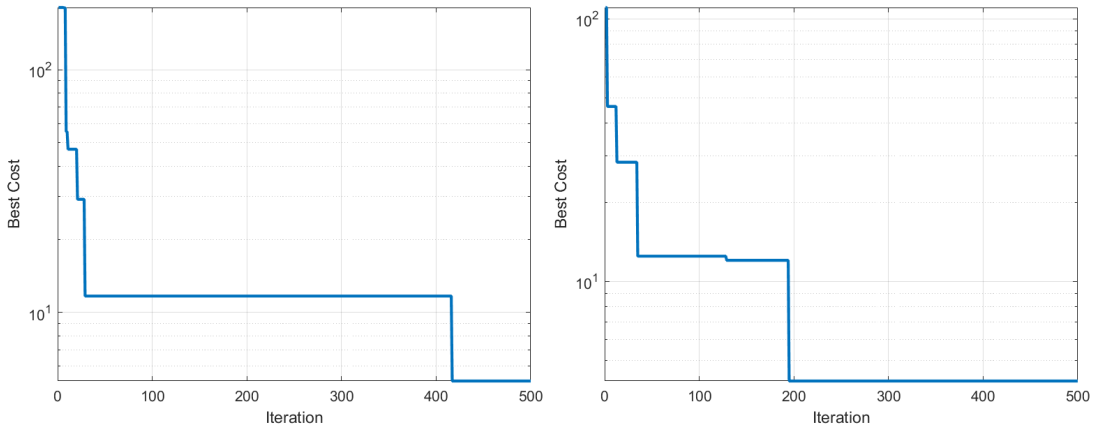
(b) Task=(335.5, 0, 110.5)

Figure 6.11: DDAO best cost graphs



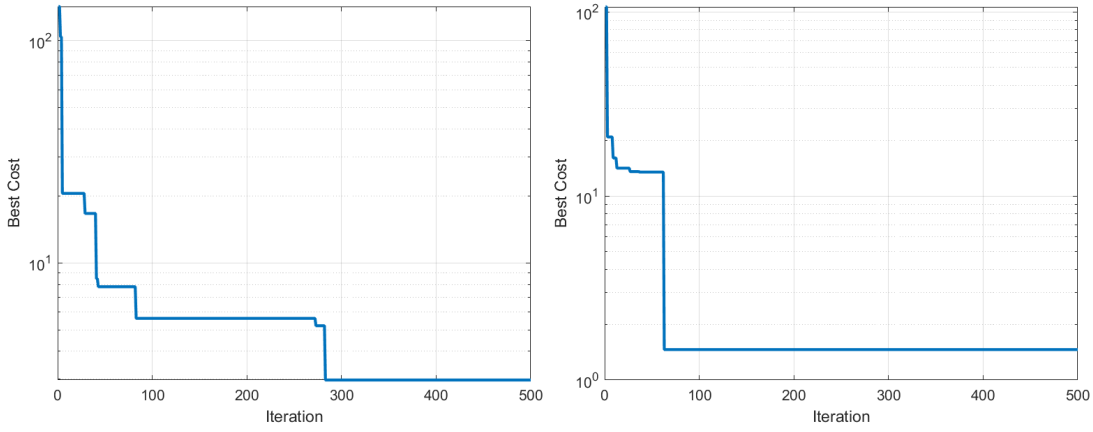
(a) Task=(200, 50, 110.5)

(b) Task=(200, 50, 110.5)



(c) Task=(150, 90, 110.5)

(d) Task=(150, 90, 110.5)



(e) Task=(90, 40, 130)

(f) Task=(90, 40, 130)

Figure 6.12: DDAO best cost graphs

Figures 6.12(c)-6.12(f) show another two sets of task points and show a very similar situation as the previous graphs. There is no obvious trend in the cost reductions shown, however the majority of the optimisations reach very close to zero. The only one that does not look like it reaches as close to zero as the others is the last graph. However, upon closer inspection of the cost values, this graph actually reaches the lowest cost of all of them, with a value of 1.4647 and it only seems to be the scaling of the graph that gives the impression that it is not as well optimised as the others. The scale of the graph was automatically generated through the MATLAB program and could not be changed. The MATLAB program used to run the DDAO algorithm was an existing piece of code written specifically for the DDAO algorithm that was adjusted to fit the kinematics of BEAST [104].

6.4 Conclusion

The two optimisation algorithms seen in this chapter both have very different effects on the design of the exoskeleton. The QFD analysis aims to bring the needs of the end users, the patients and the medical professionals, into the design process at an earlier stage than in previous literature. From the surveys that were undertaken, it takes the results from some of the questions asked in order to build a clearer picture of what is important to patients and medical professionals in the design of an exoskeleton. From the QFD analysis that was undertaken, the three most important design aspects from a patient's point of view were the weight, the size of the exoskeleton and the cost of materials. From a medical professional's point of view it was the joint angle range, the weight and the backdriveability. When combining the two sets of data, the three most important design aspects are the weight, size and joint angle range. Each set of results is slightly different and would leave to a slightly differently optimised design. The best option would most likely be to optimise it based on the combined results to reach a kind of best of both worlds situation, which could then be tested at a clinical trial phase to check that the most important design aspects on paper actually create a well optimised design in practicality. This optimisation strategy is novel in current research due to its inclusion of the patient needs survey that is itself a novel piece of work. Therefore, there is no comparison of results that can really be done with existing literature.

The kinematic analysis seen in this chapter is a more engineering based optimisation

strategy that is seen in literature fairly regularly. This optimisation strategy would be used at the control stage of the design, in order to create the most optimised movement trajectories for the rehabilitation exercises. It ensures that the movements that BEAST makes from one point to another are the most efficient. This optimisation strategy could be included in the control system to create the most efficient movements, however it would need to be streamlined as the current algorithm takes a minute or so to run and would slow down the movement of BEAST considerably.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

At the beginning of this thesis, three contributions were laid out to explain the work that would be carried out over each of the chapters. These have been considered below, with the work that was done for each contribution discussed.

1. Design of a novel cable-driven bilateral exoskeleton for the upper limb.

   Chapter 2 was a review of the existing literature of exoskeletons, from unilateral to bilateral exoskeletons and their actuation and sensing systems. It highlighted the gaps in research; wearable bilateral exoskeletons, home use exoskeletons, cable-actuated wearable exoskeletons, and patient needs considerations. These gaps in the literature were used to build the basis of the rest of the chapters, starting with the design of BEAST in Chapter 3, a wearable bilateral cable-actuated stroke rehabilitation exoskeleton for home use. The design of BEAST went through several iterations with some basic concept testing. The kinematics of the design were analysed, and the torque required for each joint was calculated. All of this information was published in a conference paper as part of this contribution [78]. Further to this, the design of BEAST used a patient needs approach, considering what patients and medical professionals would want from an exoskeleton design, through the use of several discussions with physiotherapists. This ensures the design is not only sound from an engineering perspective but also that it is being designed with patients in mind from the very beginning of the design process. In Chapter 4 a prototype of BEAST was built and a workspace analysis was completed to validate the design. The basic concept was proven, however full testing of the prototype could not be completed due to issues with the motors. All of the work completed in these chapters build up to complete this contribution to research.

2. Investigation into the needs of stroke patients during rehabilitation.

   Chapter 5 consisted of several surveys designed to gather data on patient needs from medical professionals and patients. It collected data from 21 medical professionals and 24 patients, across several different areas of patient needs. The results were analysed, and the data that was found could be used as part of an optimisation strategy. In particular, the analysis showed the importance of various engineering requirements, the views of patients and medical professionals on

the use of exoskeletons in rehabilitation, and the likelihood of each group using them in various rehabilitation scenarios. The work in Chapter 5 completes this contribution to research.

3. Optimise the exoskeleton design based on the patient needs data collected.

   Chapter 6 builds two optimisation strategies. The first of which is a quality function deployment algorithm that compares the engineering requirements against the user requirements to determine the most important ones. Medical professionals considered the most important engineering requirement to be the range of motion, while patients considered the most important requirement to be the weight of the exoskeleton. When combining the two groups, the three most important requirements were the weight, size and joint angle range, so this encompasses both of the groups independent choice for the most important requirement. A kinematic optimisation was also carried out to briefly consider the most efficient trajectory of movement from one position in the workspace of the exoskeleton to another. This contribution to research has been completed through the work in Chapter 6.

7.2 Future Work

- Full size working prototype of BEAST with improvements made from the issues found when creating the current prototype system. In particular, improving the motor selection and routing system.
- Further focus groups in-person with medical professionals and patients to consider patient needs in even more depth.
- A control system for BEAST that is based on the kinematic optimisation that was undertaken.
- A sensing system that allows for feedback for both patients and medical professionals based on the data gathered in the patient needs surveys.
- Further development of BEAST to take it to the point of a clinical trial and the potential for it reaching the general market.

Appendix A

Prescreening Survey

Pre-Screening Survey – to select participants for further surveys. Pay has been updated to £0.15, at £9.00 an hour.

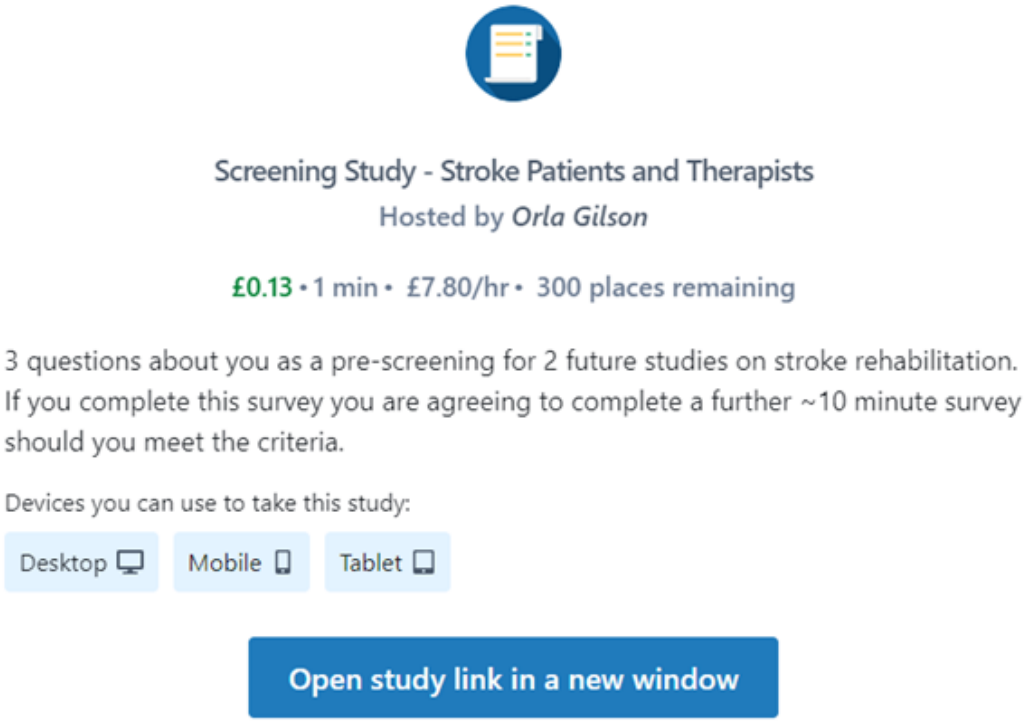


Figure A.1: Prolific introduction screen for the prescreening survey

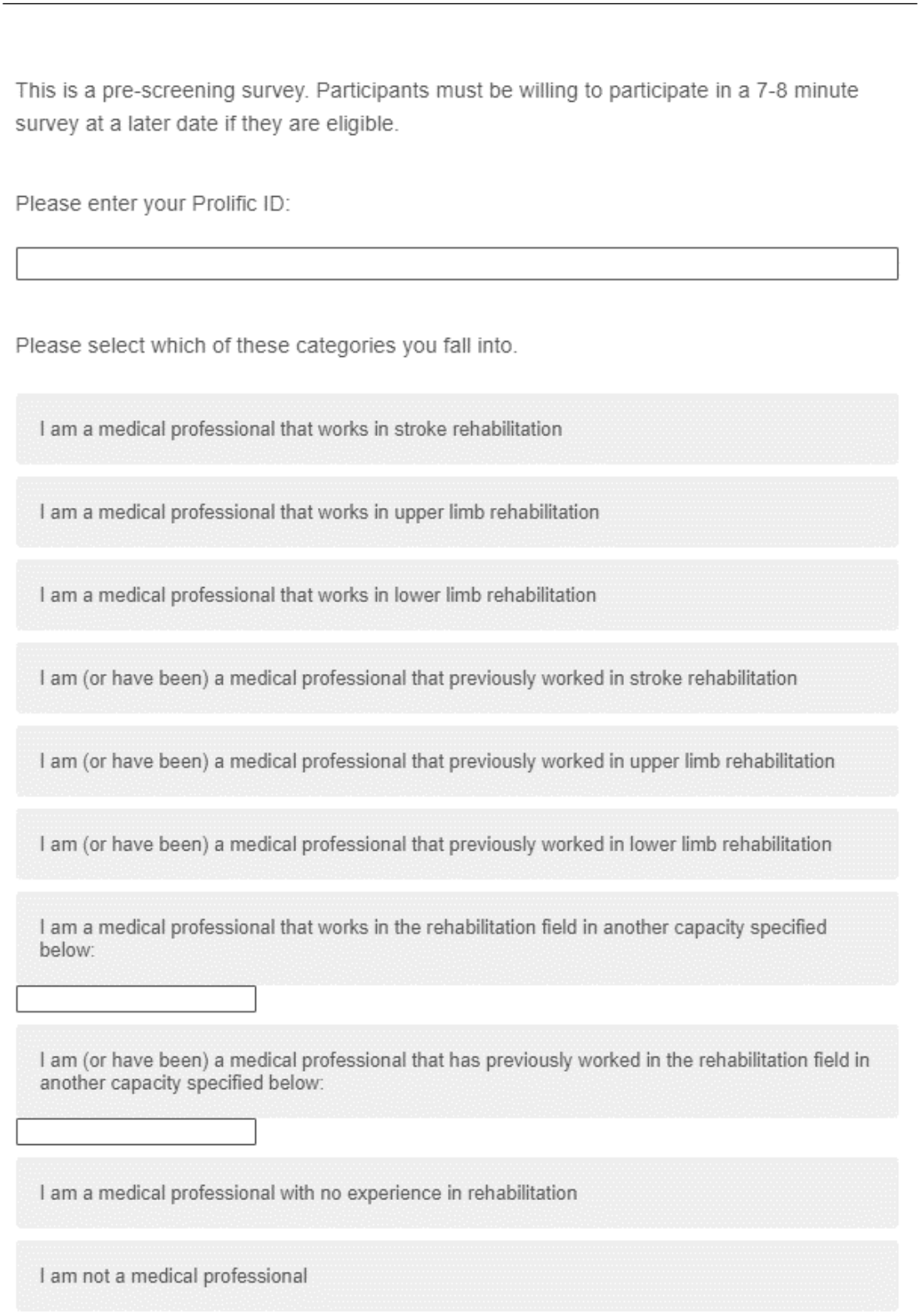


Figure A.2: Question 1 of the prescreening survey

Figure A.3: Question 2 of the prescreening survey

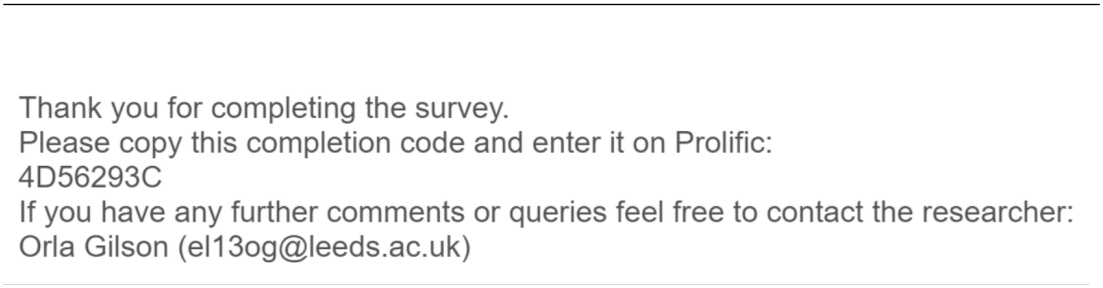


Figure A.4: Completion message for the prescreening survey

Appendix B

Medical Professional Survey

Medical Professional Survey – given to participants identified in pre-screening. Pay has been updated to be £1.20, at £9.00 an hour.

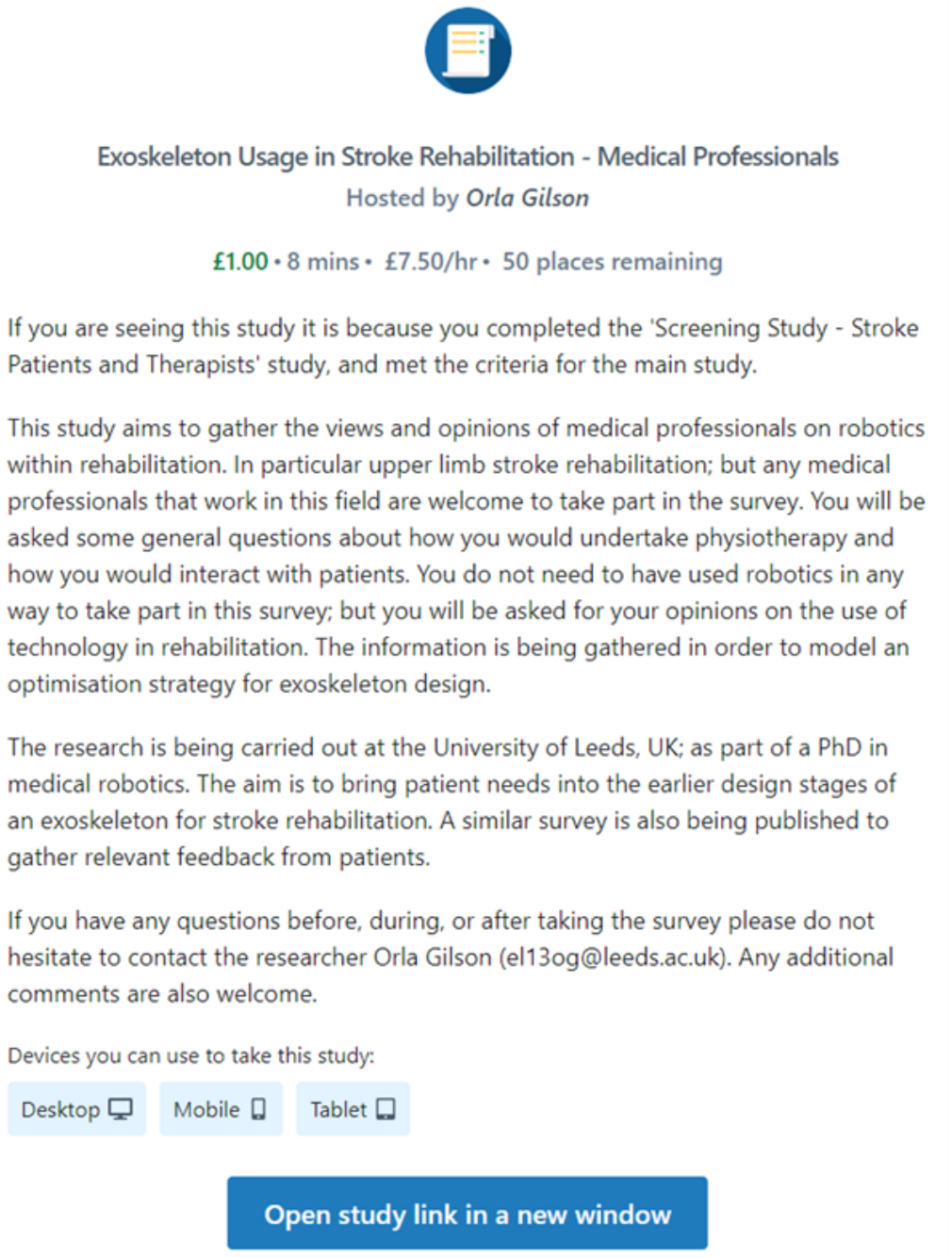


Figure B.1: Prolific introduction screen for the medical professional survey

This survey aims to gather information from medical professionals within the rehabilitation field. Experience in stroke rehabilitation is preferred but not strictly necessary. I would like to gather information on your opinions and experience of rehabilitation of the upper limb, as well as how you view the use of robotics within rehabilitation. You do not need to have used robotics in rehabilitation before.

The image below shows an exoskeleton that has been designed for use in stroke rehabilitation. This is the type of device the majority of the questions in this survey are about. An exoskeleton is a device worn on the body that can move the users body either with or without assistance from the user. The aim of using an exoskeleton within stroke rehabilitation would be to begin by moving the arm without assistance from the user to build up the range of motion of each of the joints in the arm. As the patient recovers and begins to gain more movement, the exoskeleton would give less assistance, and eventually would begin to apply resistance to movement to encourage the patient to build muscle strength. This way the exoskeleton could be used at all stages of rehabilitation no matter the severity of the disability in the arm.

Patients would start at whichever stage was most suitable and would then progress at the rate recommended by the physiotherapist overseeing the rehabilitation.

The research is being undertaken at The University of Leeds in the UK. If you have any questions about the information in this survey or have further information you would like to share, you can contact the researcher (Orla Gilson) by email: el13og@leeds.ac.uk

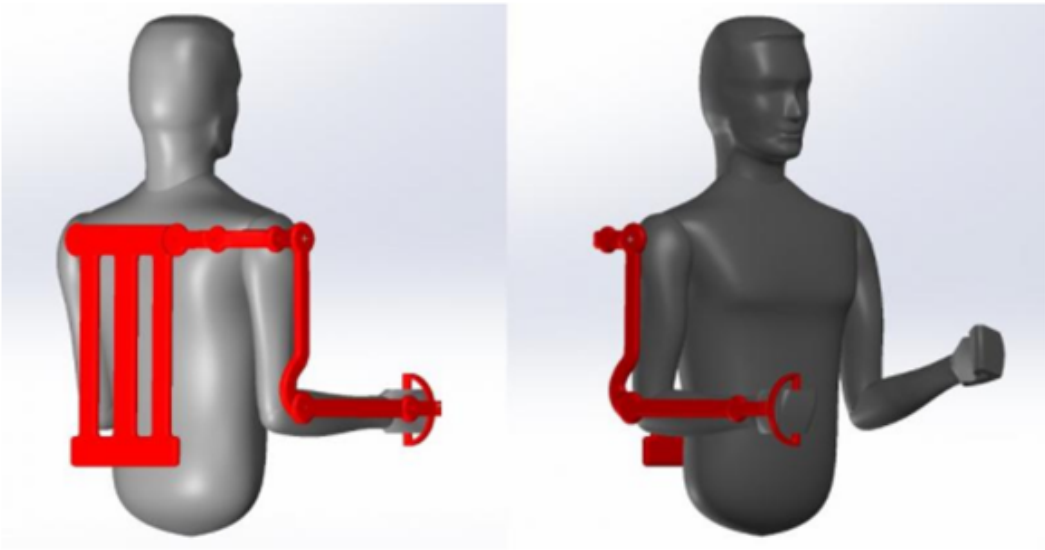


Figure B.2: Medical professional survey introduction

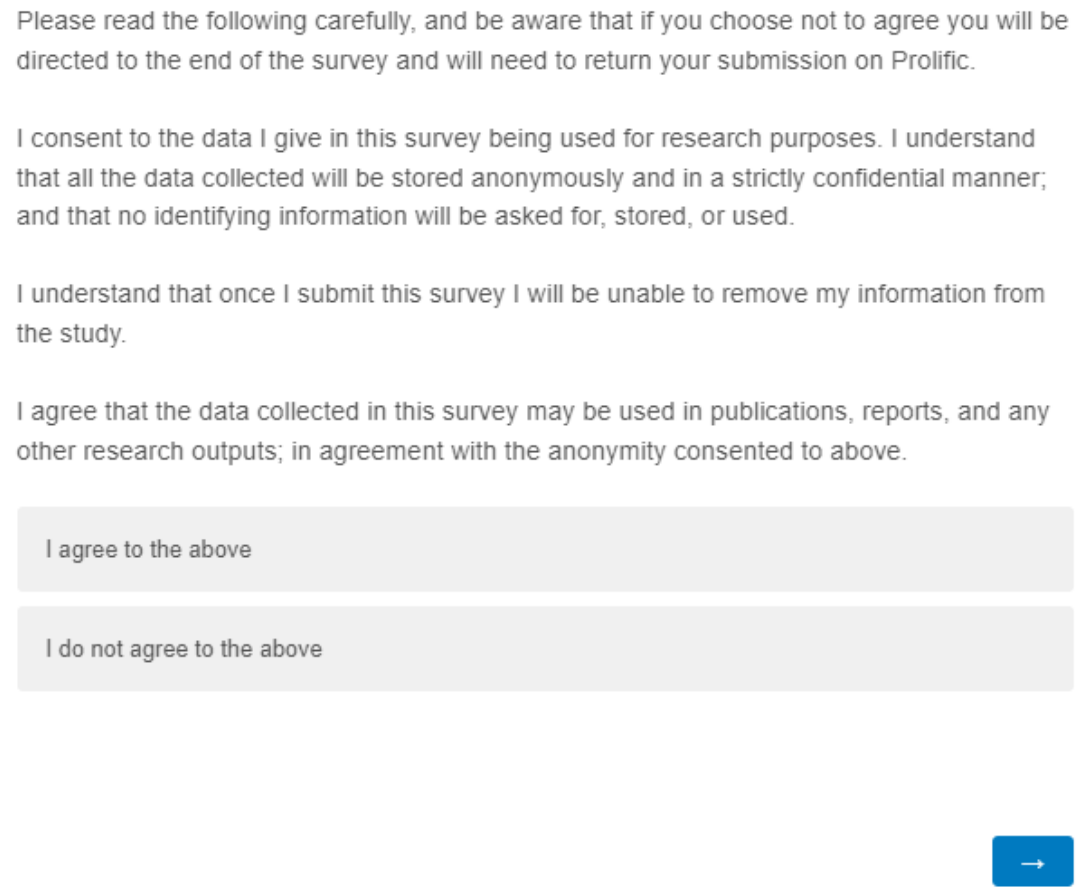


Figure B.3: Medical professional survey consent

At this point, the survey only continues if participants agree. If participants do not agree, the survey ends and no further data is collected.

Please enter your Prolific ID:

In what capacity do you/ have you worked in the rehabilitation field?

How long have you worked in the rehabilitation field?

Have you specialised in stroke or upper limb rehabilitation at any time; and for how long?
(Please select an answer and then include the length of time in the text box beneath)

- Yes; in stroke rehabilitation
- Yes; in upper limb rehabilitation
- Yes; in both stroke and upper limb rehabilitation
- No; never specialised but do carry out upper limb rehabilitation
- No; never specialised and do not carry out stroke or upper limb rehabilitation at all
- Other; please specify

Figure B.4: Questions 1-4 of the medical professional survey

What would you consider to be the best environment for patients to carry out rehabilitation in?

- Only in hospital (100% of the sessions)
- Only at home (100%)
- Mostly in hospital (approx. 70%); some at home (approx. 30%)
- Mostly at home (approx. 70%); some in hospital (approx. 30%)
- Both equally; 50% at home and 50% in hospital

If a patient was using a robotic device that took measurements during a rehabilitation session and provided feedback to you that allowed for tracking of the patient's progress during remote sessions; do you think face-to-face meetings are necessary?

Assuming in this case that the face-to-face sessions would be therapy sessions carried out in hospital; remote sessions would be carried out at home; and the patient carries out a therapy session once a week.

- Yes; every week
- Yes; every other week
- Yes; every month
- Yes; every other month
- Yes; fewer than once a month
- Not at all

Figure B.5: Question 5 & 6 of the medical professional survey

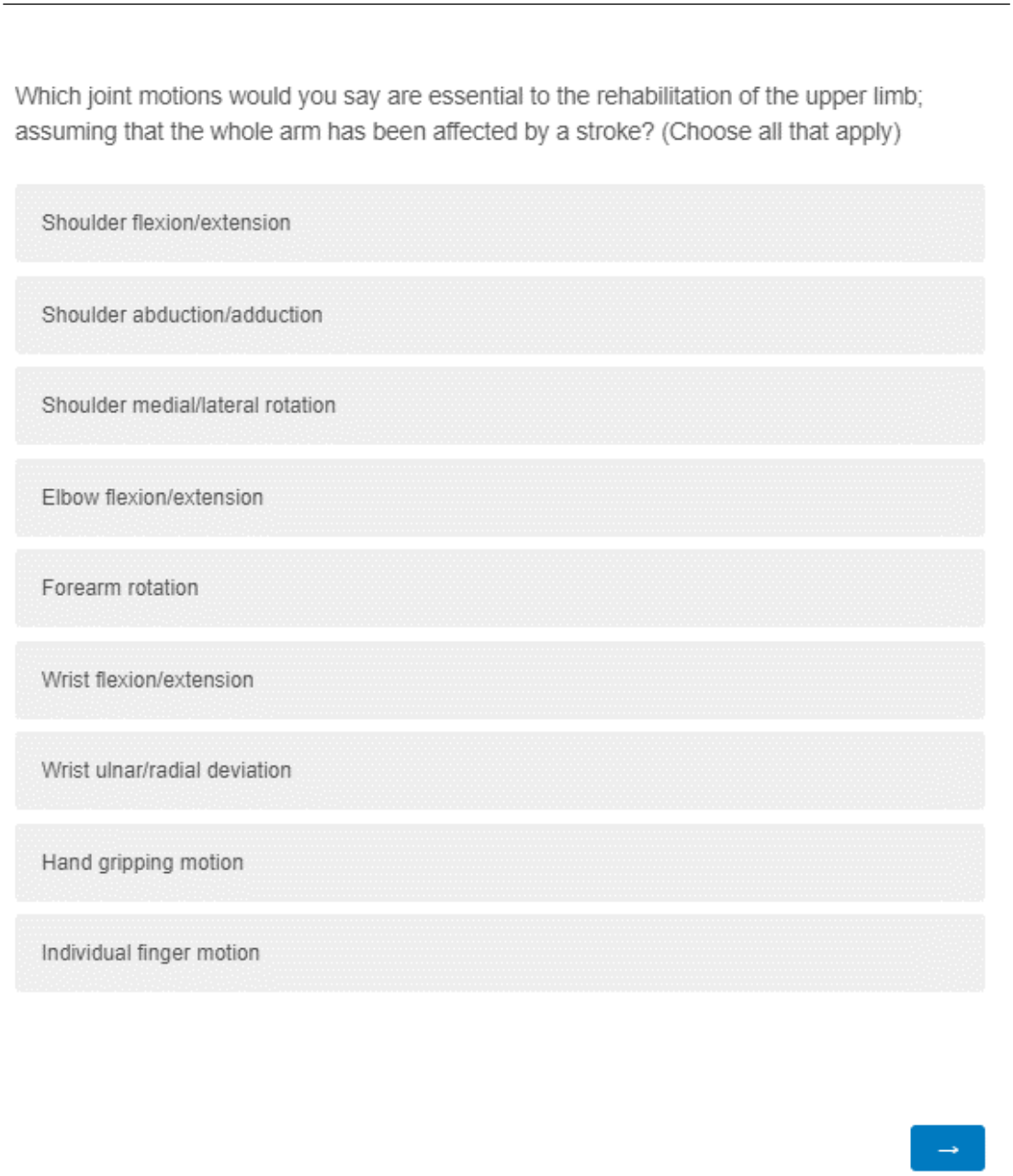


Figure B.6: Question 7 of the medical professional survey

Do you currently use any of these technologies in your rehabilitation sessions; or would like to use them in the future? (Choose all that apply)

	Usage		
	Currently use	Would use in future	Would never use
Assistive Exoskeletons - movement controlled by the patient; exoskeleton providing assistance in movement	☐	☐	☐
Active Exoskeletons - movement controlled by the exoskeleton; patient is passive to the movement	☐	☐	☐
Computer games for patient participation using an exoskeleton	☐	☐	☐
Computer games for patient participation with other technology	☐	☐	☐
Computer games for patient participation and no additional technology	☐	☐	☐
Sensors to collect data for quantitative feedback	☐	☐	☐
Sensors to collect data for qualitative feedback	☐	☐	☐
Other; please specify (Select would never use if you do not have anything else)	☐	☐	☐

How would you ensure that patients actively engage in their rehabilitation?

What scales or methods do you use to track patients' improvements? e.g. Fugl Meyer, Barthel Index etc.

Figure B.7: Questions 8-10 of the medical professional survey

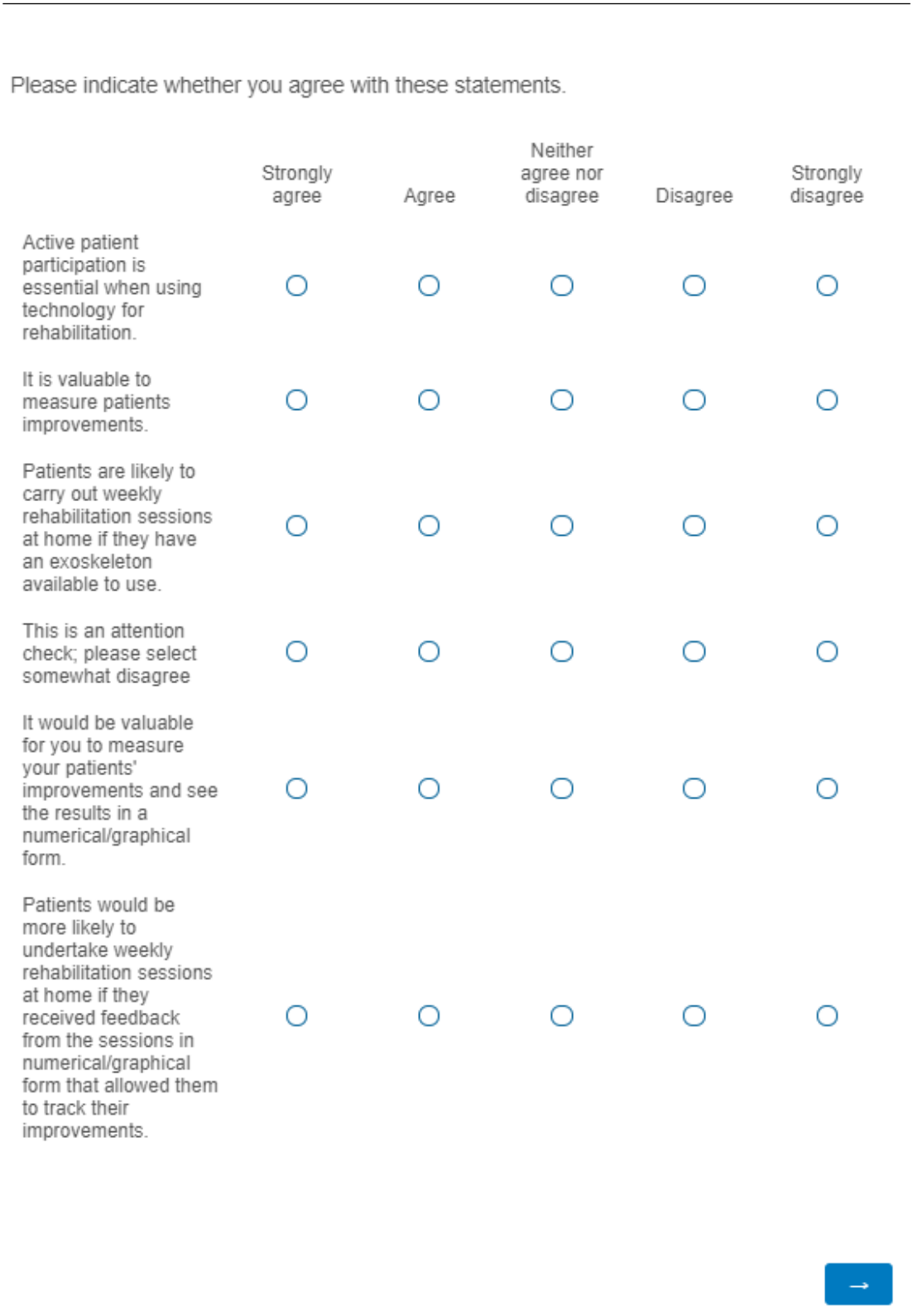


Figure B.8: Question 11 of the medical professional survey

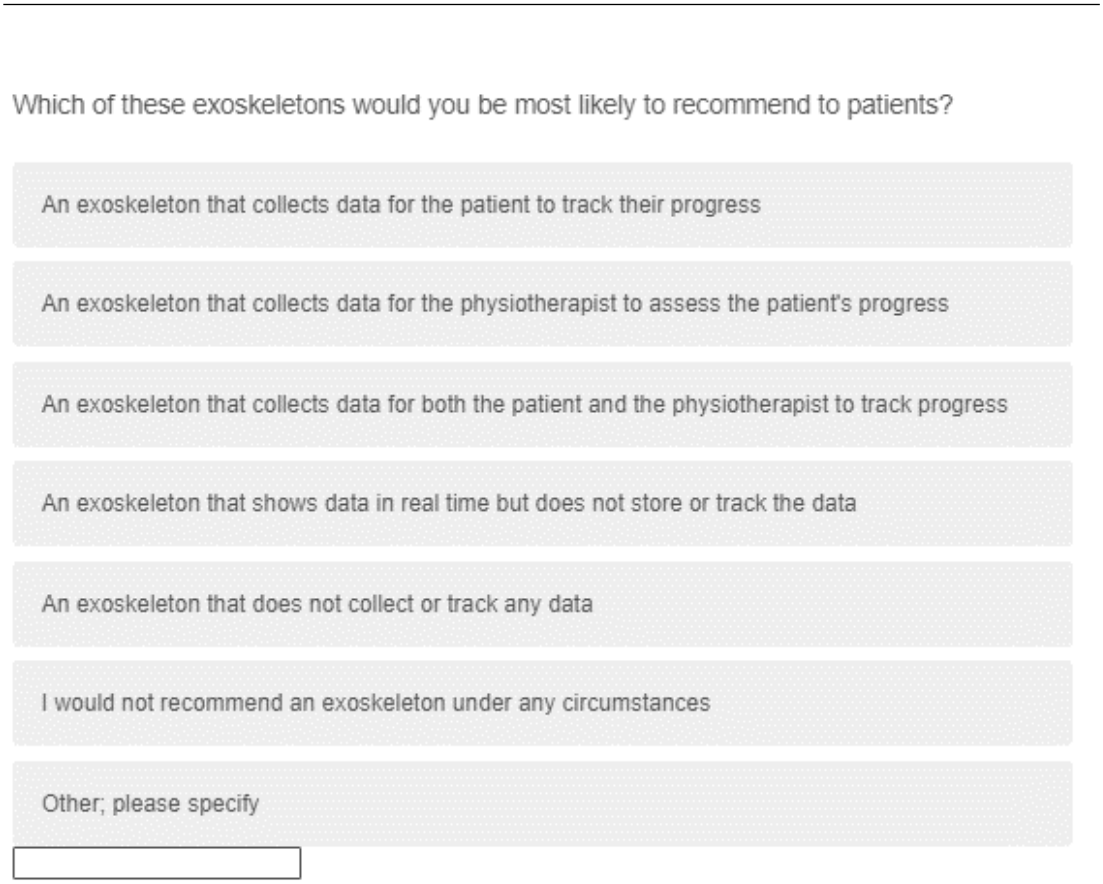


Figure B.9: Question 12 of the medical professional survey

Please rate the following aspects of exoskeleton design. This is how important each of these aspects is to the design in terms of patient use, and not how important they are in comparison to each other. Please rate these aspects on a scale of 1-5; with 1 being not very important for the patient, and 5 being completely essential for the patient.

	1	2	3	4	5
Lightweight	○	○	○	○	○
Wearable	○	○	○	○	○
Allows full range of motion	○	○	○	○	○
Comfortable	○	○	○	○	○
Able to be independently used	○	○	○	○	○
For home use	○	○	○	○	○
Clinically relevant	○	○	○	○	○
Attention check; select 4	○	○	○	○	○
Reuseable	○	○	○	○	○
Adjustable to fit each patient	○	○	○	○	○
Durable	○	○	○	○	○
Safe to use	○	○	○	○	○
Easy to maintain and clean	○	○	○	○	○
Low cost (to hospital)	○	○	○	○	○
Low or no cost (to patient)	○	○	○	○	○
Attention check; select 1	○	○	○	○	○
Active participation	○	○	○	○	○
Quantitative feedback	○	○	○	○	○
Exercises that mimic Activities of Daily Living	○	○	○	○	○
Rechargeable; long battery life	○	○	○	○	○

→

Figure B.10: Question 13 of the medical professional survey

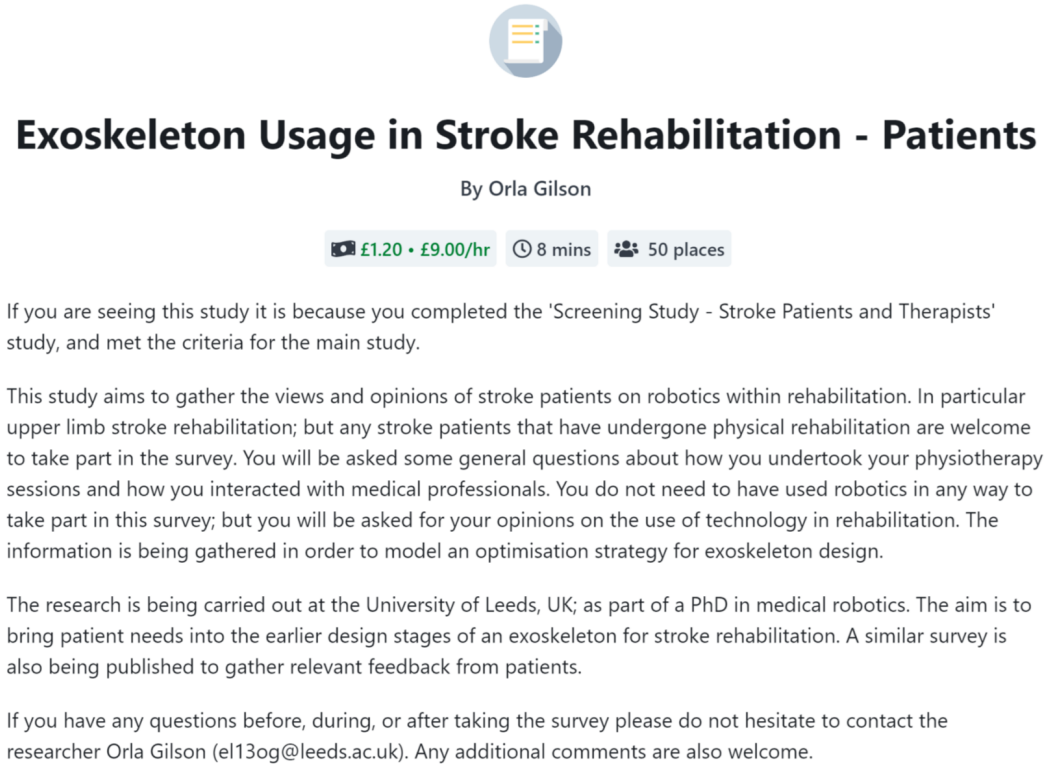
Thank you for completing the survey.
Please copy this completion code and enter it on Prolific:
69A7736A
If you have any further comments or queries feel free to contact the researcher:
Orla Gilson (el13og@leeds.ac.uk)

Figure B.11: Completion message for the medical professional survey

Appendix C

Patient Survey

Patient Survey - given to participants identified in pre-screening.



Exoskeleton Usage in Stroke Rehabilitation - Patients

By Orla Gilson

£1.20 • £9.00/hr | 8 mins | 50 places

If you are seeing this study it is because you completed the 'Screening Study - Stroke Patients and Therapists' study, and met the criteria for the main study.

This study aims to gather the views and opinions of stroke patients on robotics within rehabilitation. In particular upper limb stroke rehabilitation; but any stroke patients that have undergone physical rehabilitation are welcome to take part in the survey. You will be asked some general questions about how you undertook your physiotherapy sessions and how you interacted with medical professionals. You do not need to have used robotics in any way to take part in this survey; but you will be asked for your opinions on the use of technology in rehabilitation. The information is being gathered in order to model an optimisation strategy for exoskeleton design.

The research is being carried out at the University of Leeds, UK; as part of a PhD in medical robotics. The aim is to bring patient needs into the earlier design stages of an exoskeleton for stroke rehabilitation. A similar survey is also being published to gather relevant feedback from patients.

If you have any questions before, during, or after taking the survey please do not hesitate to contact the researcher Orla Gilson (el13og@leeds.ac.uk). Any additional comments are also welcome.

Figure C.1: Prolific introduction screen for the patient survey

This survey aims to gather information from people that have suffered from a stroke and consequently undergone rehabilitation of the upper limb. I would like to gather information on your opinions and experiences of undergoing rehabilitation after stroke, as well as how you view the use of robotics within rehabilitation. You do not need to have used robotics in rehabilitation before.

The image below shows an exoskeleton that has been designed for use in stroke rehabilitation. This is the type of device the majority of the questions in this survey are about. An exoskeleton is a device worn on the body that can move the users body either with or without assistance from the user. The aim of using an exoskeleton within stroke rehabilitation would be to begin by moving the arm without assistance from the patient to build up the range of motion of each of the joints in the arm. As the patient recovers and begins to gain more movement, the exoskeleton would give less assistance, and eventually would begin to apply resistance to movement to encourage the patient to build muscle strength. This way the exoskeleton could be used at all stages of rehabilitation no matter the severity of the disability in the arm.

Patients would start at whichever stage was most suitable and would then progress at the rate recommended by the physiotherapist overseeing the rehabilitation.

The research is being undertaken at The University of Leeds in the UK. If you have any questions about the information in this survey or have further information you would like to share, you can contact the researcher (Orla Gilson) by email: el13og@leeds.ac.uk

Figure C.2: Patient survey introduction

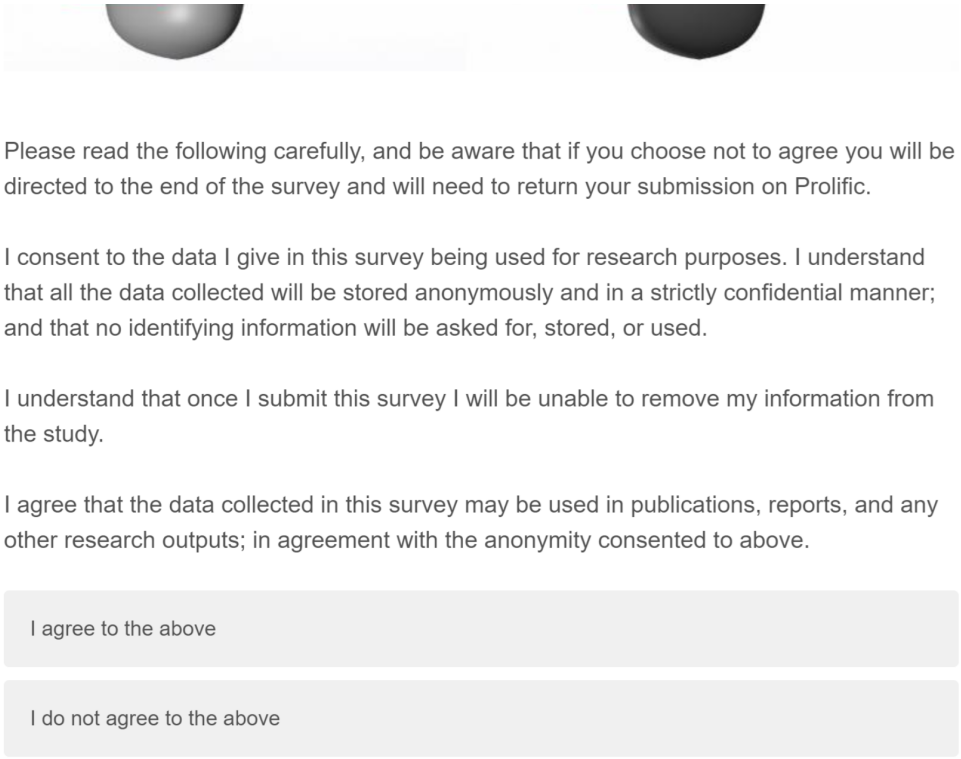


Figure C.3: Patient survey consent

At this point, the survey only continues if participants agree. If participants do not agree, the survey ends and no further data is collected.

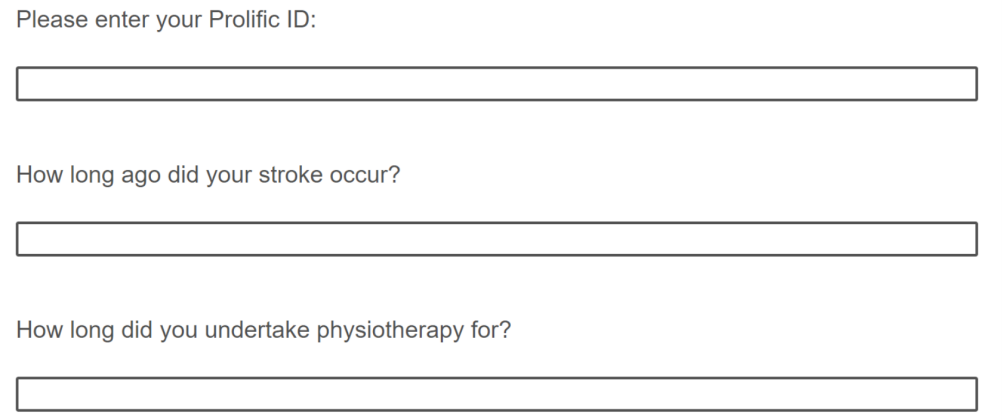


Figure C.4: Questions 1-3 of the patient survey

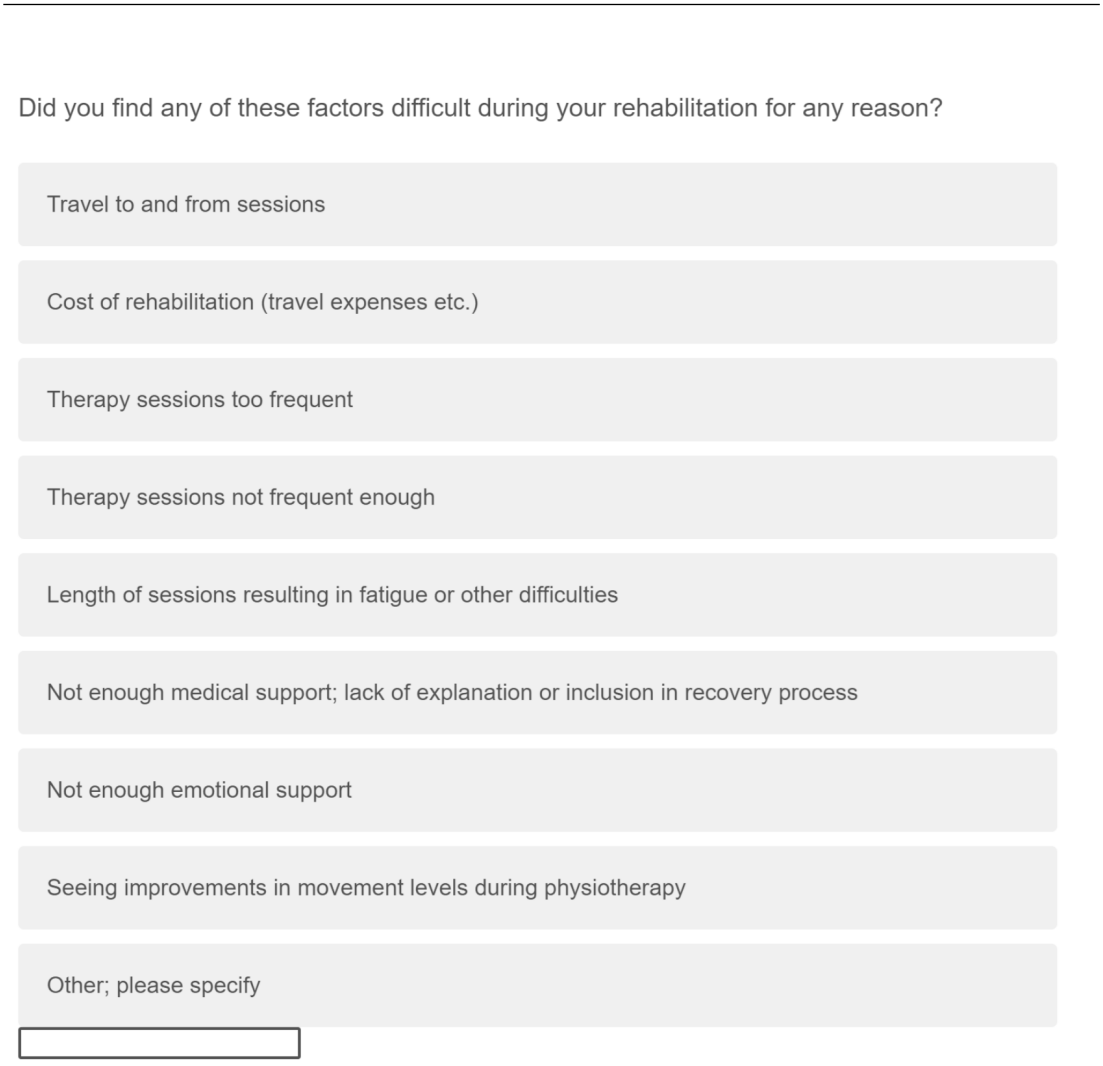


Figure C.5: Question 4 of the patient survey

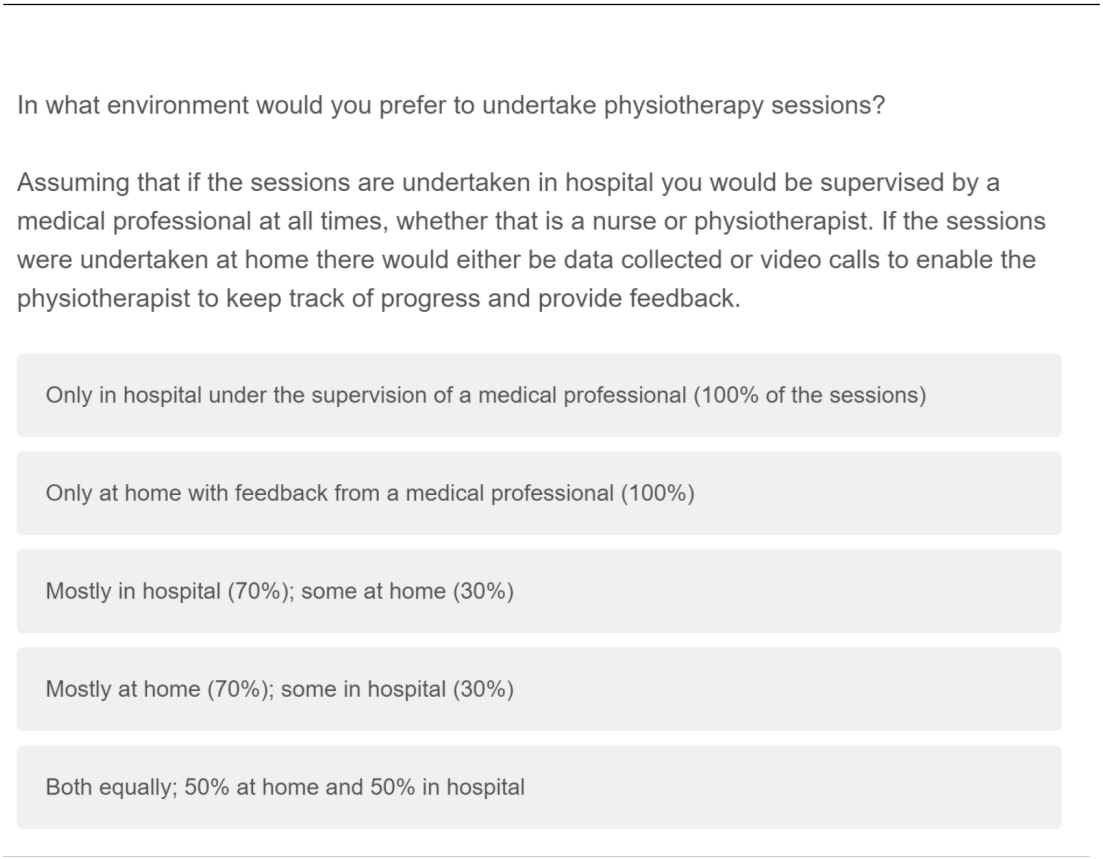


Figure C.6: Question 5 of the patient survey

If you were using a robotic device that took measurements during a remote rehabilitation session and provided direct feedback from those measurements; do you think face-to-face meetings are also necessary?

Assuming in this case that the face-to-face sessions would be therapy sessions carried out in hospital; remote sessions would be carried out at home; and therapy sessions are carried out once a week.

- Yes; every week
- Yes; every other week
- Yes; once a month
- Yes; fewer than once a month
- Not at all

Figure C.7: Question 6 of the patient survey

Which of these joint movements were included in your rehabilitation sessions? Simultaneous movements for multiple joints. (Choose all that apply)

- Hand/Finger
- Wrist
- Elbow
- Shoulder
- Wrist & Elbow
- Elbow & Shoulder
- Wrist, Elbow & Shoulder
- Table-top exercises (any joints)
- Freestanding full range of motion exercises (any joints)

→

Figure C.8: Question 7 of the patient survey

Do you currently use; or did you use; any of these technologies during your rehabilitation sessions; or would you want to be able to use them in the future? (Choose all that apply)

	Usage		
	Currently use	Would use in future	Would never use
Assistive Exoskeletons - movement controlled by the patient; exoskeleton provides assistance for the movement	☐	☐	☐
Active Exoskeletons - movement controlled by the exoskeleton; patient has no input	☐	☐	☐
Computer games played with an exoskeleton	☐	☐	☐
Computer games played with other technology	☐	☐	☐
Computer games without technology	☐	☐	☐
Sensors worn on the body to collect data for feedback purposes	☐	☐	☐
Sensors in the room (external, not worn on the body) to collect data for feedback purposes	☐	☐	☐
Other; please specify (Select would never use if you do not have an answer for this)	☐	☐	☐

Figure C.9: Question 8 of the patient survey

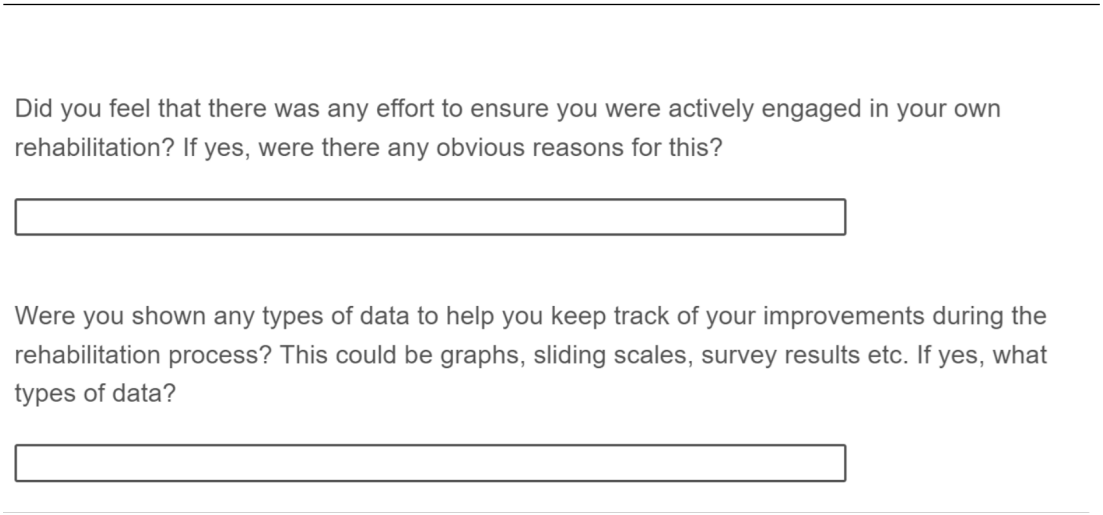


Figure C.10: Questions 9 & 10 of the patient survey

Figure C.11: Question 11 of the patient survey

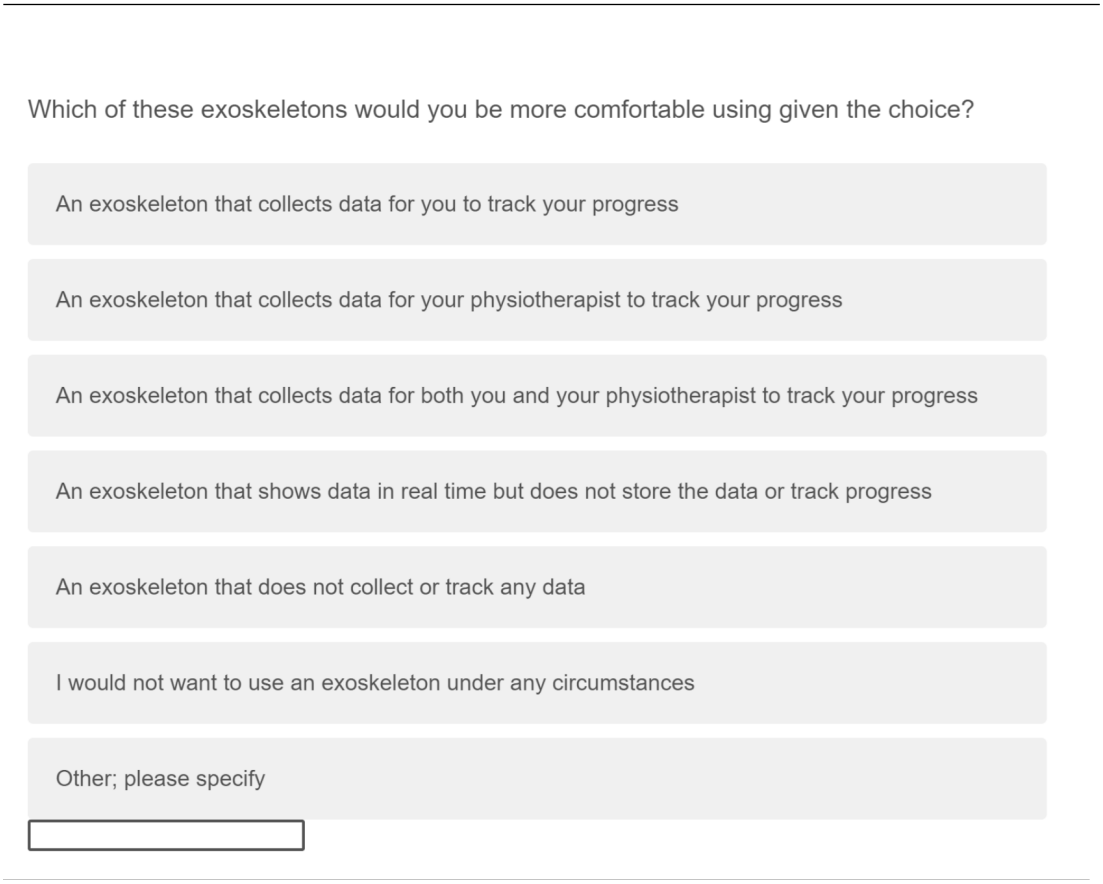


Figure C.12: Question 12 of the patient survey

Please rate the following aspects of using an exoskeleton. This is how important each of these aspects is to the design in terms of use, and not how important they are in comparison to each other. Please rate these aspects on a scale of 1-5; with 1 being not very important to you, and 5 being completely essential for you.

	1	2	3	4	5
Lightweight	○	○	○	○	○
Wearable; not tethered	○	○	○	○	○
Comfortable	○	○	○	○	○
Easy to take on and off	○	○	○	○	○
For home use	○	○	○	○	○
State of the art technology	○	○	○	○	○
Aesthetically appealing	○	○	○	○	○
Attention check; select 4	○	○	○	○	○
Fully adjustable to fit anyone	○	○	○	○	○
Made to fit you specifically	○	○	○	○	○
Durable	○	○	○	○	○
High levels of safety	○	○	○	○	○
Easy to maintain	○	○	○	○	○
Low cost to rent	○	○	○	○	○
Low cost to own	○	○	○	○	○
Attention check; select 1	○	○	○	○	○
Requires active participation in rehabilitation sessions	○	○	○	○	○
Visual feedback; graphs/images etc.	○	○	○	○	○
Easy to store when not in use; e.g. able to fold up	○	○	○	○	○
Rechargeable; long battery life	○	○	○	○	○

→

Figure C.13: Question 13 of the patient survey

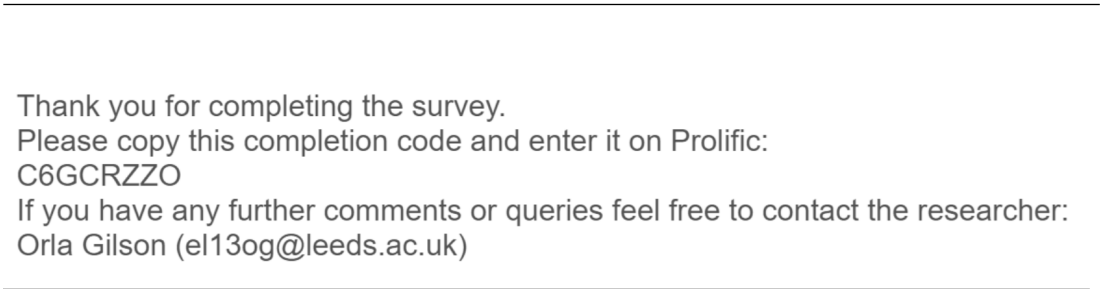


Figure C.14: Completion message for the patient survey

Appendix D

Ethical Approval Form

University Research Ethics Committee - application for ethical review

Please email your completed application form along with any relevant supporting documents to ResearchEthics@leeds.ac.uk (or to FMHUniEthics@leeds.ac.uk if you are based in the Faculty of Medicine and Health) at least 6 weeks before the research/ fieldwork is due to start. Dentistry and Psychology applicants should follow their School's procedures for submitting an application.

Ethics reference (leave blank if unknown)	Student number (if a student application)	Grant reference (if externally funded)	Module code (if applicable)
	200767581		

Faculty or School Research Ethics Committee to review the application (put a 'X' next to your choice)		
		Arts, Humanities and Cultures (PVAR)
		Biological Science (BIOSCI)
		ESSL, Environment and LUBS (AREA)
	X	MaPS and Engineering (MEEC)
		School of Dentistry (DREC)
		School of Healthcare (SHREC)
		School of Medicine (SoMREC)
		School of Psychology (SoPREC)

Indicate what type of ethical review you are applying for:		
	X	Student project (PhD, Masters or Undergraduate)
		Staff project (externally or internally funded)

Section 1: Basic project details				
1.1 Research title		A Wearable Bilateral Exoskeleton for Maximising the Effectiveness of Stroke Treatment in a Home Environment		
1.2 Research start date (dd/mm/yy)		Proposed fieldwork start date (dd/mm/yy)	Proposed fieldwork end date (dd/mm/yy)	Research end date (dd/mm/yy)
01/12/17		01/08/22	30/09/22	31/10/22
Yes	No			
X		1.3 I confirm that I have read and understood the current version of the University of Leeds Research Ethics Policy. *The Policy is available at http://ris.leeds.ac.uk/ResearchEthicsPolicies.*		
X		1.4 I confirm that I have read and understood the current version of the University of Leeds Research Data Management Policy. *The policy is available at https://library.leeds.ac.uk/info/14062/research_data_management/68/research_data_management_policy*		
X		1.5 I confirm that I have read and understood the current version of the University of Leeds Information Protection Policy. *The policy is available at http://it.leeds.ac.uk/info/116/policies/249/information_protection_policy*		
X		1.6 I confirm that NHS ethical review is not required for this project. *Refer to http://ris.leeds.ac.uk/NHSethicalreview for guidance in identifying circumstances which require NHS review*		

Figure D.1: Page 1 of the ethical approval form

	X	1.7 Will the research involve NHS staff recruited as potential research participants (by virtue of their professional role) or NHS premises/ facilities? *Please note: If yes, NHS R&D management permission or local management permission may also be needed. Refer to http://ris.leeds.ac.uk/NHSethicalreview.*

Section 2: Contact details	
2.1 Name of applicant	Orla Gilson
2.2 Position (eg PI, Co-I, RA, student)	PhD Student
2.3 Department/ School	School of Electronic and Electrical Engineering
2.4 Faculty	Faculty of Engineering and Physical Sciences
2.5 Work address (usually at the University of Leeds)	School of Electronic and Electrical Engineering Woodhouse, Leeds LS2 9JT
2.6 Telephone number	+44 (0) 7795175814
2.7 University of Leeds email address	el13og@leeds.ac.uk

Section 3: Summary of the research
3.1 In plain English provide a brief summary of the aims and objectives of the research. (max 300 words). The summary should briefly describe • the background to the research and why it is important, • the questions it will answer and potential benefits, • the study design and what is involved for participants. *Your answers should be easily understood by someone who is not experienced in the field you are researching, (eg a member of the public) - otherwise it may be returned to you. Where technical terms are used they should be explained. Any acronyms not generally known should be described in full.*
This research aims to gather information from patients and medical professionals about the use of exoskeletons in therapy after stroke. Existing designs include feedback at the testing and validation stage, rather than during the design and optimisation stage. It is important to consider the needs of patients at this earlier stage to ensure that the final design of the exoskeleton is not only well engineered, but also so that it is medically relevant. The research will be carried out through the use of two online surveys. One will be for patients that have completed or are currently undergoing therapy after a stroke; and the other will be for medical professionals in the therapy field. Each survey will be specifically designed for each of these groups so that the questions asked will be relevant and correctly worded, i.e. specific medical language will be used in the survey for medical professionals but not in the one for patients. Participants will first fill in a general survey to confirm which survey they qualify for, and then they will fill in the relevant survey. The surveys will be undertaken on Prolific.co, and participants will receive financial compensation for their time. This study into patient needs will gather information on how patients and medical professionals would use an exoskeleton for stroke rehabilitation; what they would want this exoskeleton to be able to do and how it would be able to improve their rehabilitation experience.

Figure D.2: Page 2 of the ethical approval form

3.2 Where will the research be undertaken?	Online; Prolific.co
3.3 Who is funding the research?	Shane Xie; Supervisor
NB: If this research will be financially supported by the US Department of Health and Human Services or any of its divisions, agencies or programmes please ensure the additional funder requirements are complied with. Further guidance is available at http://ris.leeds.ac.uk/FWAcompliance and you may also contact your FRIO for advice.	

Section 4: Research data and impact You may find the following guidance helpful: • Research data management guidance • Advice on planning your research project • Dealing with issues relating to confidentiality and anonymisation • Funder requirements and University of Leeds Research Data Management Policy	
4.1 What is the data source? (Indicate with an 'X' all that apply)	
X	New data collected for this research
	Data previously collected for other research
	Data previously collected for non-research purposes
	Data already in the public domain
	Other, please state: _____.
4.2 How will the data be collected? (Indicate with an 'X)	
	Through one-to-one research interviews
	Through focus groups
X	Self-completion (eg questionnaires, diaries)
	Through observation
	Through autoethnographic research
	Through experiments/ user-testing involving participants
	From external research collaborators
	Other, please state: _____.
4.3 How will you make your research data available to others in line with: the University's, funding bodies' and publishers' policies on making the results of publically funded research publically available (in compliance with UK data protection legislation)? (max 200 words)	
The consent forms will specify that the data will be kept in compliance with data protection legislation and will also specify how long the data will be kept for. The results of the surveys will be published through papers and presented fully in the final thesis.	
4.4 How do you intend to share the research data, both within and outside the research team? (Indicate with an 'X)	
	Depositing in a specialist data centre or archive
X	Submitting to a journal to support a publication
	Depositing in a self-archiving system or an institutional repository
	Dissemination via a project or institutional website

Figure D.3: Page 3 of the ethical approval form

	Informal peer-to-peer exchange
	No plans to report or disseminate the data
	Other, please state: _____.
4.5 How do you intend to report and disseminate the results of the study? (Indicate with an 'X)	
X	Peer reviewed journals
	Internal report
X	Conference presentation
	Publication on website
	Other publication
	Submission to regulatory authorities
	No plans to report or disseminate the results
	Other, please state: _____.
4.6 Give details of the expected impact of the research. Further guidance is available at http://www.rcuk.ac.uk/innovation/impacts. (max 200 words)	
This research aims to impact the use of robotic devices used in stroke rehabilitation by contributing to the user-centred design of a new wearable bilateral upper-limb exoskeleton. This should impact the future design of these types of exoskeletons in that the user is taken into account at the initial stages of design and not just at the iteration process stage.	

Section 5: Protocols		
Which protocols will be complied with? (Indicate with an 'X'). There may be circumstances where it makes sense not to comply with a protocol, this is fine but should be clarified in your application.	X	Data protection, anonymisation and storage and sharing of research data
	X	Informed consent
		Verbal consent
	X	Reimbursement of research participants
		Low risk observation

Section 6: Additional ethical issues	
6.1 Indicate with an 'X' in the left-hand column whether the research involves any of the following:	
X	Discussion of sensitive topics, or topics that could be considered sensitive
	Prolonged or frequent participant involvement
	Potential for adverse environmental impact
	The possibility of harm to participants or others (including the researcher(s))
	Participants taking part in the research without their knowledge and consent (eg covert observation of people in non-public places)
	The use of drugs, placebos or invasive, intrusive or potentially harmful procedures of any kind
	Food substances or drinks being given to participants (other than refreshments)
	Vitamins or any related substances being given to participants
	Acellular blood, urine or tissue samples obtained from participants (ie no NHS requirement)

Figure D.4: Page 4 of the ethical approval form

X	Members of the public in a research capacity (participant research)
	Participants who are particularly vulnerable (eg children, people with learning disabilities, offenders)
	People who are unable to give their own informed consent
	Researcher(s) in a position of authority over participants, eg as employers, lecturers, teachers or family members
	Financial inducements (other than reasonable expenses and compensation for time) being offered to participants
	Cooperation of an intermediary to gain access to research participants or material (eg head teachers, prison governors, chief executives)
	Potential conflicts of interest
X	Internet participants or other visual/ vocal methods where participants may be identified
	Scope for incidental findings, ie unplanned additional findings or concerns for the safety or wellbeing of participants.
	The sharing of data or confidential information beyond the initial consent given
	Translators or interpreters
X	Research conducted outside the UK
	An international collaborator
	The transfer of data outside the European Economic Area
X	Third parties collecting data
	Other ethical clearances or permissions

6.2 For the ethical issues indicated in 6.1 provide details of any additional ethical issues the research may involve and explain how these issues will be addressed. (max 200 words)

Some patients may find that participating in the research may bring up negative reminders of their own experience with stroke. Participants are at no point required to take part in the research, it is all voluntary. Participants can leave the online survey at any time before completing it but due to the anonymous nature of Prolific.co, it may be hard to remove data from the study once the survey has been submitted.

As the survey site being used has users from all over the world it is possible that some participants may complete the surveys from outside the UK. This has not been deemed to be an issue as the research is not necessarily specific to the UK, although the surveys could be limited to the UK using the survey site if necessary.

All data collected by Prolific is made anonymous before it reaches the researcher, and no identifying questions are being asked during the survey.

Section 7: Recruitment and consent process
For guidance refer to http://ris.leeds.ac.uk/InvolvingResearchParticipants and the research ethics protocols.

7.1 State approximately how much data and/ or how many participants are going to be involved.

Figure D.5: Page 5 of the ethical approval form

The aim is to have approximately 50 patients and 50 medical professionals take part in the research. Each survey has approximately 15 questions, with mainly multiple choice or rating questions with at most 1 or 2 text questions.
7.2 How was that number of participants decided upon? (max 200 words) *Please note: The number of participants should be sufficient to achieve worthwhile results but should not be so high as to involve unnecessary recruitment and burdens for participants. This is especially pertinent in research which involves an element of risk. Describe here how many participants will be recruited, and whether this will be enough to answer the research question. If you have received formal statistical advice then please indicate so here, and describe that advice.*
The number of participants was decided primarily from previous literature, and partly through the consideration of the available funds. Participants will receive payment for their time when taking the survey, and 100 participants overall is a good basis for considering patient needs in general while allowing for some outliers. It is also not too much data to analyse.
7.3 How are the participants and/ or data going to be selected? List the inclusion and exclusion criterial. (max 200 words)
Each of the 2 surveys will have separate criteria. The patient survey inclusion criteria is that they must have suffered from a stroke at some point in their lives and undergone physiotherapy as a result of it. The physiotherapy survey inclusion criteria is that the participant must work or have previously worked in the physiotherapy field in a medical position. There is no limit on the length of time they must have done this for, but the survey does ask for this information.
7.4 For each type of methodology, describe the process by which you will obtain and document freely given informed consent for the collection, use and reuse of the research data. Explain the storage arrangements for the signed consent forms. *Guidance is available at http://ris.leeds.ac.uk/InvolvingResearchParticipants. The relevant documents (information sheet and consent form) need to be attached to the end of this application. If you are not using an information sheet and/ or seeking written consent, please provide an explanation.*
Participants will be asked at the beginning of the survey whether they consent to their data being collected, stored, and used for research purposes. They are informed that all the data will be anonymous, no identifiable data will be asked for, and they are free to withdraw from the survey at any time before they submit it. If a participant does not consent they are redirected to an end of survey page, and if they do consent they are directed to the beginning of the survey. This information is available on the Prolific.co website and only participants that have consented will be able to contribute. Due to the online nature of these surveys, no paper forms or external consent forms will be used.
7.5 Describe the arrangements for withdrawal from participation and withdrawal of data/ tissue. *Please note: It should be made clear to participants in advance if there is a point after which they will not be able to withdraw their data. See also http://ris.leeds.ac.uk/ResearchDataManagement.* (max 200 words)
Participants are able to withdraw at any point during the survey but not after they have submitted the data. This is covered in the consent part of the survey at the beginning, and is due to the timeframe and nature of the research. As the PhD is due to finish this year there may not be time to remove any data before it is included in the final thesis. The data is also all anonymized and once it is included in the analysis it will be difficult to remove.
7.6 Provide details of any incentives you are going to use and explain their purpose. (max 200 words) *Please note: Payment of participants should be ethically justified. The FREC will wish to be reassured that research participants are not being paid for taking risks or that payments are set at a*

Figure D.6: Page 6 of the ethical approval form

level which would unduly influence participants. A clear statement should be included in the participant information sheet setting out the position on reimbursement of any expense incurred.
Participants are being reimbursed for their time taking the survey, this is the only incentive offered. Prolific.co has a cost system set up on their website that ensures as much of the research as possible is fairly costed. The prescreening survey pays participants £0.10, as it takes less than a minute to complete. Each of the main surveys take approximately 8 minutes to complete and therefore participants will be paid £1.00. This is in line with a system of approximately £7.50 an hour. This payment is made clear when the participants select the survey on Prolific.co, and each survey must then be accepted by the researcher before the participant receives payment. This is to ensure that the participant has legitimately answered the survey questions.

Section 8: Data protection, confidentiality and anonymisation *Guidance is available at http://ris.leeds.ac.uk/ConfidentialityAnonymisation*	
8.1 How identifiable will the participants be? (Indicate with an 'X').	
	Fully identifiable
	Identity of subject protected by code numbers/ pseudonyms
X	Fully anonymised
	Anonymised but potentially identifiable
X	Data only in aggregated form
	Other
8.2 Describe the measures you will take to deal with issues of anonymity. (max 200 words)	
The surveys do not ask for any identifiable information. The Prolific.co website functions in a way that means the researcher cannot access any identifiable information about the participants. The data will mainly be presented in an aggregated form in any publications and the final thesis.	
8.3 Describe the measures you will take to deal with issues of confidentiality, including any limits to confidentiality. (Please note that research data which appears in reports or other publications is not confidential, even if it is fully anonymised. For a fuller explanation see http://ris.leeds.ac.uk/ConfidentialityAnonymisation). (max 300 words)	
Participants will not be told that their data will be confidential as the aim is to have the data published in journals and the final thesis. Participants will be told that their data will be anonymized throughout the process, and even the researcher on the project will be unable to identify them.	
8.4 Who will have access to the research data apart from the research team (eg translators, authorities)? (max 100 words)	
Only the lead researcher will have access to the data once it has been collected on Prolific.co. Participants will be aware that Prolific.co also has the data but they have previously consented to this when joining the site. No one else will have access to the data until it is published.	
8.5 Describe the process you will use to ensure the compliance of third parties with ethical standards. (max 100 words)	
The only third party associated with this research is Prolific.co, and they have their own policies on data protection and privacy etc. These policies have been considered and the site has been researched itself to ensure it has positive reviews from other researchers and participants that use it.	

Figure D.7: Page 7 of the ethical approval form

8.6 Where and in what format(s) will research data, consent forms and administrative records be retained? (max 200 words) *Please note: Mention hard copies as well as electronic data. Electronic data should be stored securely and appropriately and in accordance with the University of Leeds Data Protection Policy available at http://www.leeds.ac.uk/secretariat/data_protection_code_of_practice.html.*
All of the data will be stored on the Prolific.co site initially. Once it has all been collected it will then also be stored on the password protected University computer system, with the lead researcher being the only person that knows the password. No hard copies of data will be made, only the electronic data. All data stored on the University system will already be anonymised.
8.7 If online surveys are to be used, where will the responses be stored? (max 200 words) *Refer to:* *http://it.leeds.ac.uk/info/173/database_and_subscription_services/206/bristol_online_survey_accounts and http://ris.leeds.ac.uk/SecuringResearchData for guidance.*
The responses to the online surveys will be stored on the Prolific.co website.
8.8 Give details and outline the measures you will take to assess and to mitigate any foreseeable risks (other than those already mentioned) to the participants, the researchers, the University of Leeds or anyone else involved in the research? (max 300 words)
N/A

Section 9: Other ethical issues		
Yes	**No**	(Indicate with an 'X')
	X	9.1 Is a health and safety risk assessment required for the project? *Please note: Risk assessments are a University requirement for all fieldwork taking place off campus. The risk assessment forms and further guidance on planning for fieldwork in a variety of settings can be found on the University's Health & Safety website along with further information about risk assessment: http://www.leeds.ac.uk/safety/fieldwork/index.htm. Contact your Faculty Health and Safety Manager for further advice. See also http://ris.leeds.ac.uk/HealthAndSafetyAdvice.*
	X	9.2 Is a Disclosure and Barring Service check required for the researcher? *Please note: It is the researcher's responsibility to check whether a DBS check is required and to obtain one if it is needed.*
9.3 Any other relevant information		
N/A		
9.4 Provide details of any ethical issues on which you would like to ask the Committee's advice.		

Figure D.8: Page 8 of the ethical approval form

Section 10: Further details for student projects (complete if applicable) Your supervisor is required to provide email confirmation that they have read, edited and agree with the form above. It is a good idea to involve your supervisor as much as possible with your application. If you are unsure how to answer any of the questions do ask your supervisors for advice.			
10.1 Qualification working towards (indicate with an 'X')			
	Bachelor's degree	Module code:	
	Master's degree (including PgCert, PgDip)		
X	Research degree (ie PhD)		
10.2 Primary supervisor's contact details			
Name (title, first name, last name)		Professor Shane Xie	
Department/ School/ Institute		Faculty of Engineering, School of Electronic and Electrical Engineering, Institute of Robotics, Autonomous Systems and Sensing	
Telephone number		+44(0)113 343 4896	
University of Leeds email address		S.Q.Xie@leeds.ac.uk	
10.3 Second supervisor's contact details			
Name (title, first name, last name)		Professor Rory O'Connor	
Department/ School/ Institute		Faculty of Medicine and Health, School of Medicine, Department of Rehabilitation Medicine, Institute of Rheumatic and Musculoskeletal Medicine	
Telephone number		+44(0)113 392 2615	
University of Leeds email address		R.J.O'Connor@leeds.ac.uk	
Yes	**No**	10.4 To be completed by the student's supervisor	
		The topic merits further research	
		I believe that the student has the skills to carry out the research	

Section 11: Other members of the research team (complete if applicable)	
Name (title, first name, last name)	
Role (eg PI, Co-I)	
Department/ School/ Institute	
Telephone number	
University of Leeds email address	
Name (title, first name, last name)	
Role (eg PI, Co-I)	
Department/ School/ Institute	
Telephone number	
University of Leeds email address	

Figure D.9: Page 9 of the ethical approval form

Name (title, first name, last name)	
Role (eg PI, Co-I)	
Department/ School/ Institute	
Telephone number	
University of Leeds email address	

Section 12: Supporting documents		
Indicate with an 'X' which supporting documents have been included with your application. Wherever possible the research title on consent forms, information sheets, other supporting documentation and this application should be consistent. The title should make clear (where appropriate) what the research is about. There may be instances where a different title is desirable on information to participants (for example – in projects which necessarily involve an element of deception or if giving the title might skew the results of the research). It is not imperative that the titles are consistent, or detailed, but where possible then they should be. Supporting documents should be saved with a meaningful file name and version control, eg *'Participant_Info_Sheet_v1'* or *'Parent_Consent_From_v2'*. Refer to the examples at http://ris.leeds.ac.uk/InvolvingResearchParticipants.		Information sheet(s) *Please note: Include different versions for different groups of participants eg for children and adults if applicable. Refer to http://ris.leeds.ac.uk/InvolvingResearchParticipants for guidance in producing participant information sheets.*
		Consent form(s) *Please note: Include different versions for different groups of participants eg for children and adults if applicable. Refer to http://ris.leeds.ac.uk/InvolvingResearchParticipants for guidance in producing participant consent forms.*
		Recruitment materials *Please note: Eg poster, email etc used to invite people to participate in your research project.*
		Letter/ email seeking permission from host/ gatekeeper
	X	Questionnaire/ interview questions
		Health and safety risk assessment *Please note: Risk assessments are a University requirement for all fieldwork taking place off campus. The risk assessment forms and further guidance on planning for fieldwork in a variety of settings can be found on the University's Health & Safety website along with further information about risk assessment: http://www.leeds.ac.uk/safety/fieldwork/index.htm. Contact your Faculty Health and Safety Manager for further advice. Also refer to http://ris.leeds.ac.uk/HealthAndSafetyAdvice.*
		Data management plan *Refer to https://library.leeds.ac.uk/info/14062/research_data_management/62/data_management_planning*

Section 13: Sharing information for training purposes		
Yes	**No**	(Indicate with an 'X')
	X	I would be content for information in the application to be used for research ethics and research data management training purposes within the University of Leeds. All personal identifiers and references to researchers, funders and research units would be removed.

Figure D.10: Page 10 of the ethical approval form

Section 14: Declaration

1. The information in this form is accurate to the best of my knowledge and belief and I take full responsibility for it.
2. I undertake to abide by the University's ethical and health & safety policies and guidelines, and the ethical principles underlying good practice guidelines appropriate to my discipline.
3. If the research is approved I undertake to adhere to the study protocol, the terms of this application and any conditions set out by the Research Ethics Committee.
4. I undertake to ensure that all members of the research team are aware of the ethical issues and the contents of this application form.
5. I undertake to seek an ethical opinion from the REC before implementing any amendments to the protocol.
6. I undertake to submit progress/ end of project reports if required.
7. I am aware of my responsibility to be up to date and comply with the requirements of the law and relevant guidelines relating to security and confidentiality of personal data.
8. I understand that research records/ data may be subject to inspection for audit purposes if required in future.
9. I understand that personal data about me as a researcher in this application will be held by the relevant FRECs and that this will be managed according to the principles established in the Data Protection Act.

	Applicant	Student's supervisor (if applicable)
Signature		
Name	Orla Gilson	Shane Xie
Date	18/07/22	18/07/22

Figure D.11: Page 11 of the ethical approval form

MEEC 21-036 – A Wearable Bilateral Exoskeleton for Maximising the Effectiveness of Stroke Treatment in a Home Environment

NB: All approvals/comments are subject to compliance with current University of Leeds and UK Government advice regarding the Covid-19 pandemic.

I am pleased to inform you that the above research ethics application has been reviewed by the School of Engineering and Physical Sciences Faculty Research Ethics Committee and on behalf of the Chair, I can confirm a conditional favourable ethical opinion based on the documentation received at date of this email and *subject to the following condition/s which must be fulfilled prior to the study commencing:*

1. ***Patient Survey Document - We would suggest to make the information clear: Initial info mention ~10 minutes to complete the full survey, but then it says ~7-8 minutes right in the next page. It confused me, so it could confuse the participants as well.***
2. ***Patient Survey Document - In the introduction page of the Patient Survey - given to participants identified in pre-screening, I would define "exoskeleton" to clarify the meaning.***
3. ***Patient Survey Document - Do you need any other data to classify the participants, such as current gender, age, age at the time of the stroke? This may not be needed if the class of participants is already homogeneous or if you do not want to correlate answers with specific characteristics of the participants. (For consideration).***

The study documentation must be amended where required to meet the above conditions and submitted for file and possible future audit.

Once you have addressed the conditions and submitted for file/future audit, you may commence the study and further confirmation of approval is not provided.

Figure D.12: Ethical Approval Confirmation

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