Design, implementation and analysis of a cost-effective rehabilitation robot for children with cerebral palsy

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Qiang Fu

School of Mechanical, Aerospace and Civil Engineering

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ABBREVIATION

CP: Cerebral Palsy

ADLs: Activities of Daily Livings

UCD: User Centred Design

MIME: Mirror Image Motion Enable

ARAMIS: Automatic Recovery Arm Motility Integrated System

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ABSTRACT

Background: Cerebral palsy is neurological damage that results in severe physical disability in children. It often affects the motor control of the upper limb, leading to difficulties in performing activities of daily living. The core mechanisms of rehabilitation interventions to promote upper limb function involve targeted and highly intensive practice of functional tasks, which drives neural plasticity to improve motor skills. However, majority of rehabilitation robots are designed for clinical settings where it has challenge of motivation for children to engage with high intensity frequent therapy due to the need to travel to and from the clinic.

Aim: Design, develop and evaluate a low-cost home-based rehabilitation robotic system integrating hand grasping, elbow flexion/extension and forearm pronation/supination movement assistance for children with cerebral palsy.

Methods: Literature review and User Centred Design (UCD) were conducted to identify and understand the requirements of a home-based upper limb rehabilitation robot. Mechanical structure was optimised through topology optimisation. Arduino is used to test the force sensors that will be used in this robot. Basic cost-effectiveness of home-based rehabilitation robot were summarised through literature research.

Conclusions: This research provided a detailed research identifying what a home-based rehabilitation robot should do and providing a reasonable, effective and cost-effectiveness solution for home-based upper limb rehabilitation for children with cerebral palsy. It is helpful for increasing users' motivation and efficiency of post-stroke rehabilitation and reducing the stress on clinical and therapists. After structure optimisation, the final mass of the whole device is estimated about 8300g, reduced the 6.95% mass of original design. In the cost analysis, the ideal rehabilitation robot should have 5 DOF's, weight less than 10kg and cost under £5,000. The cost comparison between clinical intensive treatment, clinical rehabilitation robot-assisted therapy and home-based rehabilitation robot-assisted therapy proves the cost-effectiveness of home-based rehabilitation robot-assisted therapy. A three month trail indicated that robotic-assisted therapy had a lower total cost (£9,265.50) relative to the usual care (£13,956.34) when there is no significant difference of upper limb functional improvement between them.

Contribution: Developed a journal paper involving 4 themes and 63 design requirements from therapists and patients for a home-based rehabilitation robot (has been submitted to the journal topics of stroke rehabilitation and under reviewing). The first analysis of human upper limb joint usage in 21 high frequency ADLs to inform what a home-based upper limb rehabilitation robot should do. Designed and manufactured a prototype of a novel low-cost home-based rehabilitation robot with 5 DOF's. Designed the first force sensing handgrip for a home-based rehabilitation robot which can measure real-time grip strength and promote useful exercise.

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First and foremost I would like to thank Dr. Andy Weightman for his continuous encouragement during my research of this project and giving me the confidence to undertake the essential research. Thank my supervisors Dr. Partha Mandal and Prof. Sarah Tyson for their suggestions about researching robot functionality. Thank Mr. Eddie Whitehouse for his expertise and technique advices on electronics and mechatronics.

Last but not least, I want to appreciate the amazing support from my parents as they gave me both mental and funding support during my MPhil research.

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DECLARATION

I declare that this thesis has been composed solely by myself and that it has not been submitted, in whole or in part, in any previous application for a degree. Except where states otherwise by reference or acknowledgment, the work presented is entirely my own.

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Chapter 1: Introduction

1.1 Background

Cerebral palsy (CP) is one of the most common and disabling health care problems that causing severe disability in children occurring in 2.08/1000 live birth [1]. Children who experience CP have impaired upper limb function and need assistance for activities of daily living (ADL), such as eating, bathing and dressing. Almost two third (65%) of CP survivors leave hospital with a disability [2]. Up to 85% of CP survivors suffer upper extremity weakness and recovery is often limited [3][4][5]. In addition, because of the complexity of upper limb movement, children with CP with upper limb disability usually need to spend much more time to recover upper limb functionality [6]. Therefore, the burden of care for CP survivors is high for the healthcare system and family members or caregivers [7][8]. Improving motor function of children with CP not only improves their functional abilities but also increase their engagement in social context [9].

CP rehabilitation is a complex process that includes substitution, restitution and compensation. Substitution is the reorganizing of alternate neural pathways to relearn lost functions; restitution in relation to damaged nerve tissue; compensation to reduce the deficit in functional ability and environmental requirements [10].

The core rehabilitation interventions to improve upper limb motor function involve intensity of practice, the number of repetitions and goal-oriented training [11]. However, it is a real challenge for therapists to visit every child on their caseload due to resource limitation. Therefore, rehabilitation robots have been explored as a complement to alleviate the burden on physiotherapists and healthcare systems, which provides intensive task-specific training and physical assistance for children with CP through motivating computer games [11][12]. There are two main categories in rehabilitation robot, exoskeleton-based and end-effector-based. Exoskeleton rehabilitation robots are wearable device that attached to patient's upper limb directly [11][13]. End-effector rehabilitation robots only contact patient's upper limb through one single point where is at distal part of the devices [11][[13][14].

There are many upper limb rehabilitation robots currently being used in clinical environments, including the MIT-Manus, InMotion 2 and Automatic Recovery Arm Motility Integrated

System (ARAMIS) [15, 16]. However, the prices of these rehabilitation robots are extremely high, up to £54,19 for MIT-Manus [17] and £64,481 for InMotion 2 [18] that are unaffordable for a normal family. Therefore, this leads the high demand of home-based rehabilitation robots which have advantages of both relatively low cost and can also offer lots of functionalities.

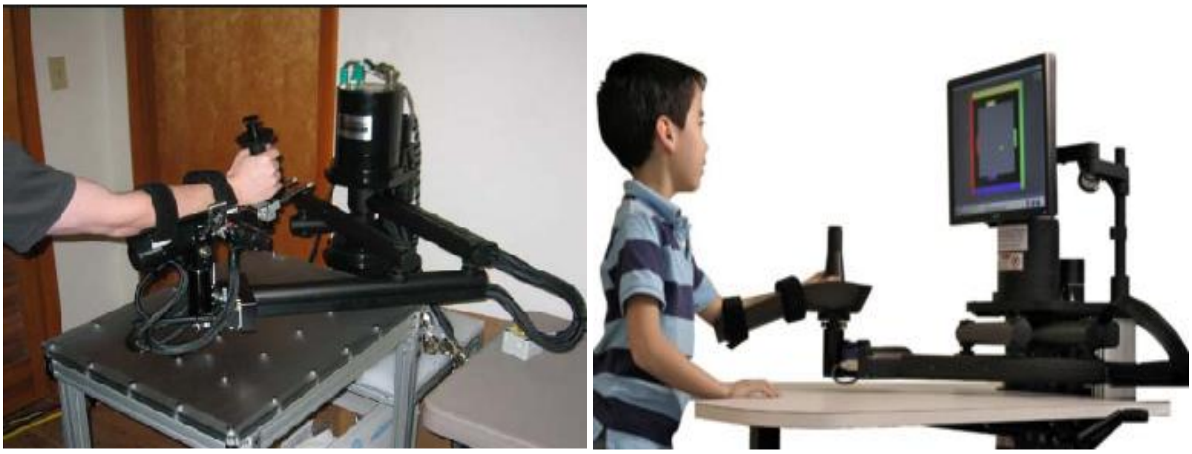

Figure 1. Upper limb rehabilitation robot (left, MIT-Manus; right, InMotion 2)

1.2 Project overview

As can be seen from the background, cerebral Palsy is the most common form of severe disability in children. It often compromises volitional control of the arm such that the children's ability to move their arm and use their hand is limited. The core mechanisms of rehabilitation interventions to promote upper limb function involve intensive practice of functional tasks, which drives neural plasticity to improve motor skills. However, weakness of the upper limb makes it difficult for children to practice at the necessary intensity. Lack of motivation is another common characteristic for conventional therapy.

One way of providing the support required for children to access useful arm exercise is using rehabilitation robotic systems, which can provide physical assistance (customised to the individuals requirements) whilst playing motivating computer games. The potential of these devices has been internationally recognised but cost and fitness-for-purpose are limiting factors. The area of home-based system remains underexplored which is the focus of my research.

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My research will involve the design, implementation and analysis of a cost-effective rehabilitation robot for children with cerebral palsy to provide useful intensive practice of upper limb exercises and activities.

The scope of this project is to create specifications for a hardware design of the mechanical portion of an upper limb rehabilitation robot, and to evaluate the resulting prototype with respect to safety and functionality. This does not include the computer-user interface, software, or games/activities the system would eventually have.

1.3 Thesis outline

This thesis is split into nine chapters which are described below:

Chapter 1 provides a general introduction of the research area, overview of the project and thesis outlines.

Chapter 2 a literature review is presented which covers the definition, classification, causes and effects of cerebral palsy, an overview of motor learning and control in neurological recovery and robot assisted therapy.

Chapter 3 presents the research motivation and gaps and the aim and objectives of this research.

Chapter 4 explains the preliminary design of the upper limb rehabilitation robot. This leads to a systematic review paper related to design requirements from patient's and therapist's points of view. Besides, ADL analysis based on ABILHAND-KIDs provides what functionality is required for the devices. Workspace design determined an area where children perform robot-assisted rehabilitation within this area. A Needs-Metrics Matrix identifies the correlation between user requirements and technical requirements. And product design specification develops a product that meets the needs of the user.

Chapter 5 describes development of the rehabilitation robot end effector to measure real time grip force during therapy.

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Chapter 6 presents an economic analysis of cost-effective rehabilitation robot for children with Cerebral Palsy.

Chapter 7 presents the topology optimisation of the rehabilitation robot prototype to reduce the mass and thus improve usability to the device, a key design requirement.

Chapter 8 evaluation of prototype cost-effective home-based rehabilitation robot with stakeholders.

Chapter 9 summaries the novelty and contribution to knowledge of the prototype rehabilitation robot, conclusions and discusses future work.

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Chapter 2: Literature review

2.1 An introduction to cerebral palsy

Before designing a rehabilitation robot, it is very important to fully understand cerebral palsy rehabilitation mechanisms. In this section, studies related to the definition, classification, causes and effects of cerebral palsy are reviewed.

2.1.1 Definition of cerebral palsy

Cerebral palsy (CP) is a common cause of physical disability in children. In Europe, the prevalence of cerebral palsy is 2.08/1000 live births [1]. The current definition of cerebral palsy was proposed by Bax 'Cerebral palsy (CP) describes a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing foetal or infant brain. The motor disorders of cerebral palsy are often accompanied by disturbances of sensation, perception, cognition, communication, perception, and/or behaviour, and/or a seizure disorder' [19]. Therefore, CP is considered as a group of disorders rather than a single condition. This definition is applied very widely.

2.1.2 Classification and causes of cerebral palsy

The definition states that the core feature of CP is abnormal motor behaviour. Considering CP has wide range of clinical symptoms and degrees of activity limitations, it is necessary to further categorise each individual with CP [19]. Conventional classification of CP has focused on topographical distribution, movement abnormality and functional motor abilities [19].

Classification of CP by topographical includes monoplegia, hemiplegia, paraplegia, diplegia and quadriplegia [20]. As the name suggests, this type of classification is based on the distribution of affected limbs of the body [1]. The most common terms used are hemiplegia (30%) and diplegia (50%) [4]. A child with hemiplegia typically has motor problems on upper and lower extremity restricted to one side [1]. Diplegia describes problem on lower limbs more involved than upper limbs [1]. However, other terms are also used, such as quadriplegia (four limbs are affected) or paraplegia (lower half of the body are effected).

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Physiologically, cerebral palsy can be divided into spastic (80%), dyskinetic, ataxic, hypotonic and mixed [21]. Spastic is the most common type of CP which affects approximately 80 percent of people. It causes stiff muscles and exaggerated reflexes. People who experience dyskinetic have trouble controlling their body leading to involuntary movements [22]. Ataxic is the least common type of CP [23]. It involves involuntary muscle movements that causing problem with coordination and balance [22]. Hypotonic is characterized by causing diminished muscle tone and overly relaxed muscles [23]. Mixed type of CP often involve spastic with dyskinetic disorders [23].

Alternatively, a recent classification called Gross Motor Function Classification System (GMFCS) that classifies children by functional motor abilities relating to their ages [23]. This classification describes five levels, from level 1 with nearly normal gross motor function to level 5 with lack independence in basic motor activity [20].

Cerebral palsy is not usually diagnosed at birth except in severe cases [23]. However, most children are diagnosed between 6 months and 2 years [24]. Abnormal movement due to abnormal muscle tone is the earliest sign of CP. In most cases, the cause of CP is not known [23]. Genetic factors, premature birth, infections of the pregnant mother all play a part to increase the risk of developing cerebral palsy [23]. The most significant risk factor seems to be low birth weight (<1500g), which contributes more than 70 % [1].

2.1.3 Physical and neurological effects of cerebral palsy

The effects of CP can be grouped into two categories: physical and neurological [25]. Typically, children with CP typically have problems with controlling muscle function and coordinating movements. This effect is caused by damage to the central nervous system, which is a place in the brain. In addition, there are delays in acquiring motor abilities at specific age, such as sitting, standing, walking and eating [23].

As for neurological effect, children with CP have intellectual disabilities, language and vision disorders. These kinds of deficits can be more disastrous for children with CP than the motor disabilities as they feel anxiety, depression, panic, shyness or emotional pain. Intellectual disabilities can lead to difficulties in learning [23].

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Besides, chest muscles are affected by abnormal muscle tone causing breath problem thus also interrupt sleeping [26]. Proper nutritional intake and weight gain also can be affected due to difficult in eating. Such these deficiencies can lower bone density of children.

2.2 Overview of motor learning and control in neurological rehabilitation

Could rehabilitation robot effectively enhance motor learning compare with conventional therapy methods? To address this question, we need to fully understand the principles of motor learning and motor control. In order to better understand the motor function of children with CP, a literature was reviewed, which included theory of motor control and motor learning, motor disabilities performance, conventional rehabilitation programs and motor rehabilitation challenges.

2.2.1 Theories of motor learning, motor control and motor rehabilitation

Motor learning and motor control are two areas where physical therapists interest in. Motor learning emphasizes the acquisition of motor skills which involves the performance enhancement or re-acquisition of skills that cannot be performed due to injury or disease [1]. In other words, permanent changes are occurred resulting from practice or experience a certain skill. In recent finding, motor learning can be broken into dynamic and kinematic [27]. It covers three stages, cognitive stage, associative stage and autonomous stage [28]. During the initial cognitive stage, the aim is to develop an overall understanding of the skill. What to do is more focused than how to do. In the next associative stage, the learner begins to concern with skills in performing and refining. Gradually, the motor skill becomes mostly automatic in the final autonomous stage. For example, walking occurs automatically for kids without conscious thought.

Unlike motor learning, motor control concerns on how muscles and limb coordinate to perform individual controls movement [29]. When analysing the motor control from specific movement of patient, the therapist will focus on several motor programs that are operating together, for example, arm swing, heel strike of both legs, postural control of the head and axial muscles and trunk in open and closed chain environment [29]. All of these motor programs are sequentially controlled by the Central Nervous System (CNS) [30]. Some patients with neurological disorder may lose one of the multitudes of programs. Therefore,

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motor control theory provides an explanation of how learning and re-learning movement works [31].

The process of motor rehabilitation is a kind of motor learning which aims to re-establish or improve patient's functional motor skill [32]. Based on therapists' approach, it has been demonstrated that intensity of therapy, repetition, task-specific and goal-oriented movements are key factors to efficiently improve motor rehabilitation [5]. Current studies pay attention to maximize the benefits of motor rehabilitation by effective interventions to promote motor learning [33]. Thus, there is a critical need for developing novel approaches for motor rehabilitation.

2.2.2 Upper extremity motor disabilities in children with cerebral palsy

CP affects the motor area of the children brains' outer layer that controls muscle movement. Therefore, children with CP present a wide variety of symptoms, including hypertonia (restricted movement caused by muscle stiffness), involuntary movement, impaired coordination (such as hand-eye coordination) and sensory difficulty [34]. An important common feature in many children with CP is abnormal movement of upper extremity through muscle weakness, abnormal muscle tone, lack of mobility and lack of sensitivity [35].

2.2.3 Conventional motor rehabilitation programs

Conventional physical therapy suggests that providing sufficient practice for children may improve their motor performance [36]. One potential approach is constraint-induced movement therapy (CIMT) and becoming increasingly popular [37]. CIMT is a physical treatment consisting of a 3-week long program to improve arm motor function by performing a large number of repetitions of task-specific training with weaker arm while restraining the stronger arm in a light-weight cast (Figure 2) [37]. CIMT has produced promising results in small trails. However, CIMT cannot be applied to patients with severe impaired upper limbs because they should be able to perform fundamental ADLs.

Figure 2. CIMT, restricted unimpaired hand [37]

Botulinum toxin is a medical treatment to relax the contracted muscles by injecting Botulinum toxin in arm or hand muscles [38]. The main limitation is Botulinum toxin injection has to be repeated every 2 to 3 months in regular to maintain treatment effect. In addition, if injections decrease muscle tone, they have limited to no effect on other impairments such as muscle weakness [39]. Therefore, drug treatment should be a complement to physical therapy.

2.2.4 Motor rehabilitation challenges

Therapists provide one-to-one and high intensity rehabilitation programs tailored to the special needs for individual child is labour-intensive and expensive [40]. Besides, the limitation of physical resource hinders the optimal therapy conditions and reduces the dosages of rehabilitation measures. Stroke survivors receive arm rehabilitation training on average 4 minutes per therapy sessions due to labour and time constraints [41]. Moreover, a great number of people suffering from neurological disorders due to population aging or life expectancy have high demand in rehabilitation services.

Rehabilitation often continues after patients are discharged from clinic, when movement practice at home is encouraged, however, this can be challenging for severely affected

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patients who require physical assistance to move. Further, motivating a child to practice repetitive and boring movements can be difficult [12]. It is therefore a priority to develop methods for providing high quality, high intensity physical therapy to service children with cerebral palsy that providing optimal motor recovery and re-establish their abilities.

2.3 Robot-assisted rehabilitation

2.3.1 Clinical needs of rehabilitation robot

To address the conventional therapy limitation, robot-assisted rehabilitation system has been developed as a new approach to encourage children undertaking intensive practice [12]. The robot can be defined as ''the application of electronic, computerized control systems to mechanical devices designed to perform human functions'' [43]. The benefits of rehabilitation therapy has been statistically demonstrated which include improvement in kinematic parameters (movement path, time and smoothness of reach observed) [44]. Rehabilitation robot can also record the kinematic measurements of children's movements such as torque, force, speed and store in electronic file that can be seen by therapists.

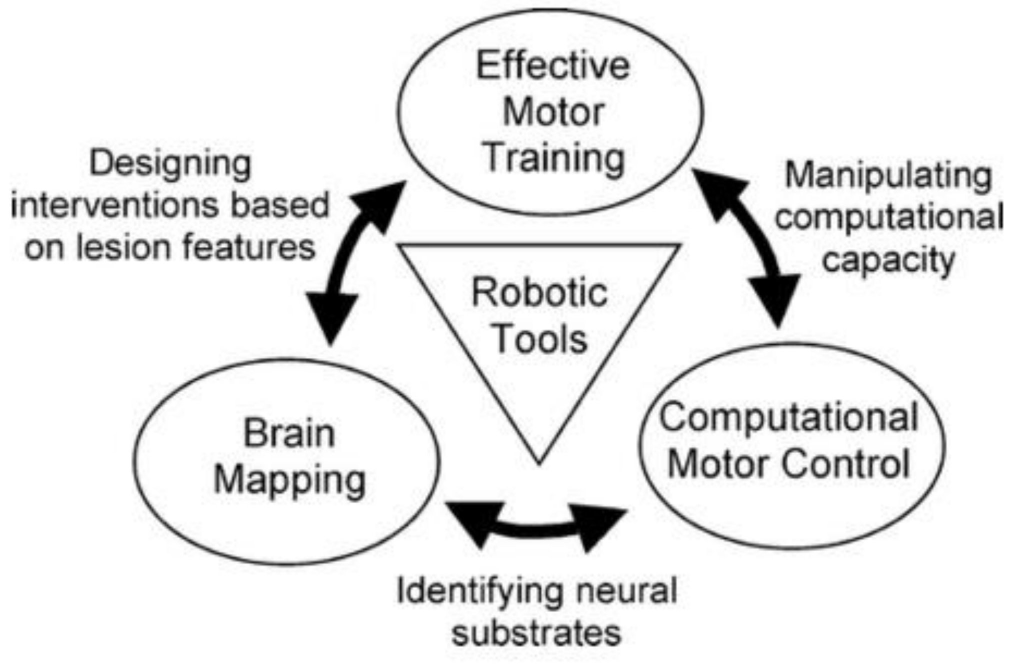

Figure 3. Robots play a synergy part between computational mechanisms and neural substrates of motor learning to improve motor rehabilitation [42].

Lack of motivation is a common characteristic for conventional therapy. Rehabilitation robot can be actuated to provide interaction for children to practise movements to facilitate motor recovery [45]. To encourage children's motivation, rehabilitation robot provides an

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interactive computer play-based therapy [46]. This kind of therapy provides an interactive game for children through a computer interface. The interactive computer play-based therapy is very popular in children because of popularity of video games has grown in the past few decades. Games difficulty can be increased by amplifying error and using adaptive control algorithms to optimally challenge the user [47].

More importantly, current rehabilitation therapy is predominately delivered by therapists, it is impossible for therapists to work with multiple patients simultaneously. However, these devices will solve the resource limitation and lower the cost of labour. Besides, rehabilitation robot enables children to be used in the home environment without travelling to rehabilitation clinics and the help of therapists.

2.3.2 Characteristics and development of rehabilitation robot

Many rehabilitation robots have been designed and put into use for upper limb rehabilitation in the past two decades. These devices often fall into two categories by comparing the mechanical structure: end-effector-based and exoskeleton-based [45]. Exoskeleton-based devices are wearable and attached to patient's upper limb directly. Complex design of exoskeletons makes them have a high number of degree of freedom (DOF). Therefore, each joint can be concurrent control to perform particular movement. However, it is necessary to adjust the length of the segment to fit with different individuals to prevent patient injury. According to complexity and cost issues, these kinds of devices are not very suitable for home environment used.

Instead, end-effector-based system only contact patient's upper limb through one single point where is at distal part of the devices [45]. Normally, the end effector is a handle or an actuated joystick. The significant advantages of this kind of devices are simper structure and control algorithm that contribute to simple in design and more affordable for patients [48]. Because of the single point contacts with the user, the number of Degree of Freedom (DOF) of end-effector devices is less than exoskeletons. Therefore, it is difficult to control complex movements of the patient's upper limbs. Instead, a single movement related to ADL is used. In my project, end-effector-based system is considered as a solution to achieve low cost and home-based for upper limb rehabilitation.

The most representative end-effector systems include MIT-MANUS, MIME, ARM Guide and GENTLE/s. MIT-MANUS is the first rehabilitation system developed by Hogan et al., which receives most clinically studies [43]. This device has 2 DOF and backdrivability, which is essential for safe when robots operated by patients. The planar 2 DOF assists arm and shoulder to perform upper limb reaching movements with an impedance controller [49]. Patient places forearm on a supper tray and moves the joystick to simulate simple ADL, as shown in Figure 4. A computer display provides visual and audio feedback to patient accordingly.

Figure 4. The commercial version of MIT-MANUS, InMotion 2 [43]

Lum et al. have developed Mirror-Image Motion Enable (MIME), a shoulder and elbow rehabilitation device based on the principle of bilateral movement [50]. This device comprises a six DOF PUMA 560 robot (Staubli Unimation Inc., www.staubli.com). The actuators of end effector apply force to paretic arm through a customized splint [43] as shown in Figure 5. A sensor in this robot can measure the forces and torques between the device and the patient’s upper limb. There are four main modes of robot-assisted movement: passive mode, active-assisted mode, active-constrained mode and bilateral mode [43].

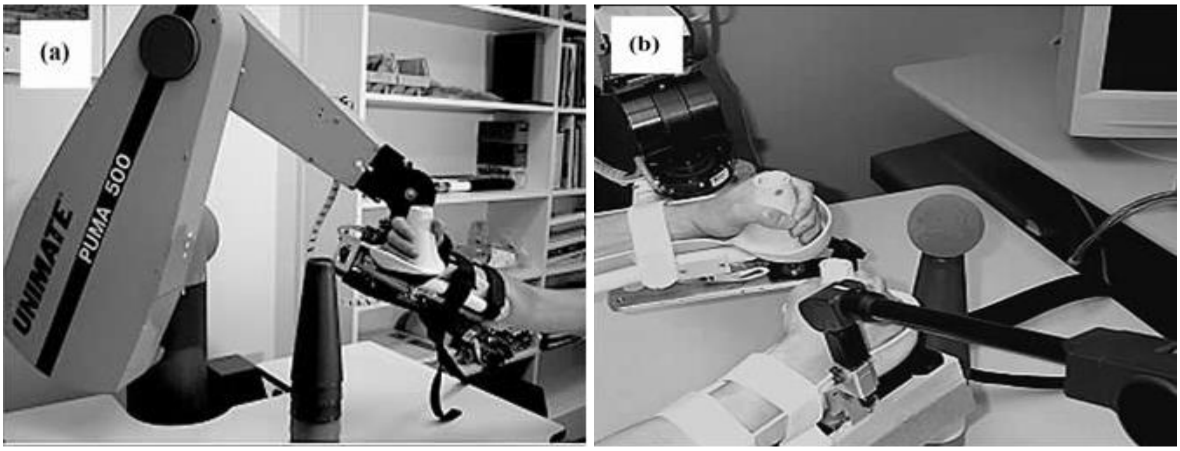

Figure 5. Patient performs movements through MIME in two modes (a) unilateral and (b) bilateral [51].

Like MIT-MANUS and MIME, the Assisted Rehabilitation and Measurement Guide (ARM Guide) was designed by Reinkensmeyer et al. to assist reaching movements and multi-joint coordination [52]. This device consists of four DOF (3 DOF robot + 1 actuated DOF) [43]. The major difference is that ARM Guide uses a linear slide to guide reaching movement across the arm's workspace of patients, as shown in Figure 6.

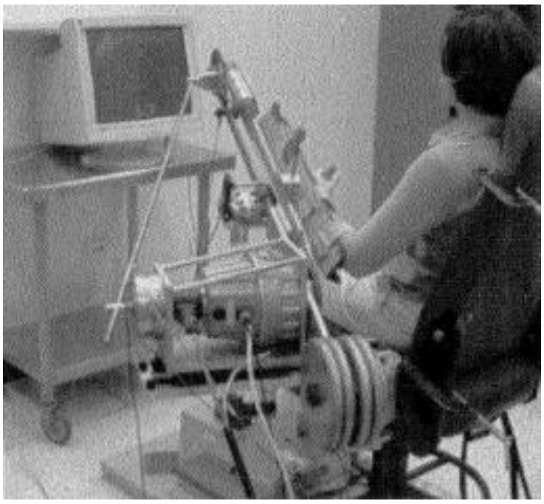

Figure 6. The ARM Guide [52]

Loureiro et al. developed the GENTLE/s system, comprising a commercial HapticMaster robot, a virtual reality (VR) display, a wrist connector, an elbow orthosis, shoulder supports, a chair, a large monitor with speaker, a keypad and an exercise table [53]. The GENTLE/s system provides 3 active DOF that can provide training of 3D reaching movement. The patient's arm is suspended on a support device to overcome its gravity effect that can be seen in Figure 7. There are three modes in this device: the passive mode, where the passive arm is moved by the robot; the patient active assist mode, where the robot assists the user movements in the same direction, and patient active mode, where the user directly moves the device [53].

Figure 7. The GENTLE/s system [53]

2.3.3 Control strategy of rehabilitation robots

Control strategy (algorithm) is one of the important terminologies used in rehabilitation robot. It falls into two categories, 'high-level' and 'low-level' control strategy [45]. 'high-level' strategy induces motor plasticity that includes passive, assistive, resistive and error amplifying [46]. In passive control strategy, patient performs movements through guidance from the robot without any force exerted. The assistive mode makes tasks easier and safer. The robot provides a restoring force when patient deviates from the desired trajectory. The resists control strategy resists the desired movement, thus making the movement more difficult. In this mode, patient has to pay much effort and attention. The error amplifying strategy amplifies its visual representation on the screen by producing disturbing force and tracks the deviations from the desired trajectory.

According to Marchal-Crespo and Reinkensmeyer suggestion, the terminology of 'low-level' control strategies determine how 'high level' control are implemented in a device [54]. Due to the interaction between the human body and rehabilitation robots, these strategies are developed to ensure the safety and reliability for patients. Although many 'low level' control strategies have been proposed with the development of rehabilitation robots, the most widely used strategies are admittance control and impedance control [45]. Admittance control measures the force exerted from the user and leads device to produce corresponding displacement. On the contrary, impedance control measures the movement of upper limb

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through position, velocity or acceleration to determine how much force and torque are applied to the device.

2.3.4 Clinical outcome when using of upper-limb rehabilitation robot

The effective of upper-limb rehabilitation robot still remain insufficient. The possible reasons are the most effective interventions to optimize neural plasticity are not very clear so far and the results of current clinical controlled trails are difficult to compare with each other [45]. However, there are more and more evidences for the therapeutic benefit of upper-limb rehabilitation robot for patients with neurological disorders. Robot-assisted therapy with the MIT-MANUS has shown significant decreases in elbow and shoulder impairment when compared to traditional therapy [55]. In addition, MIME has shown muscle activation and impairment improvement for stroke survivors in two random controlled trails (RCTs), where one study involved 27 chronic stroke patients and the other had 30 subacute patients [50],[51]. 20 chronic stroke survivors had a higher rate of recovery when using the GENTLE/s rehabilitation system according to Coote et al [56].

Although robot-assisted therapy is relatively new, the potential development prospect is large and worth to be investigated. For preliminary design of a rehabilitation device, functionality, DOF, safety, user's design requirement are taken into account and it will be fully introduced in the chapter 4.

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Chapter 3: A cost-effective rehabilitation robot for children with CP

3.1 Research motivation and gaps

Clinical robotic-assisted therapy has demonstrated that it is an effective therapy in children with CP when compared with traditional CP therapy [60][61]. Clinical acceptance of a robotic rehabilitation device may also be related to robotic capabilities that would be difficult to achieve with conventional therapy [62][63]. Considering most commercially available rehabilitation robots, e.g. AremoPower, are based at clinics and hospitals, then there is a challenge with how easy it easy for children to engage with a suitable frequency and intensity of therapy , especially people living in rural places [64]. A home-based rehabilitation robot would satisfy this need, and this is the motivation for my research. Furthermore, limited healthcare resources such as the number of rehabilitation clinics, rehabilitation robots, therapists as well as care givers results in many children with CP unable to get effective rehabilitation treatment.

Cost is another barrier that has limited the adoption of robotic-assisted therapy. The price of a rehabilitation robot on the market can range from £64,481 to £ 213,329 [18][64][65][66]67]. Lu et al [68] conducted an online survey with 5 occupational therapists and tried to determine how much a hospital would pay for such a robot . All the therapists agreed a price of around £5000 would be acceptable. In addition to the cost of the rehabilitation robots the costs of maintenance, training, and therapist set up time should be considered. Normally, the higher the degree of freedom the rehabilitation robot provides, the higher the price. When designing a home-based rehabilitation robot, a key challenge is balancing the cost and functionalities; I will address this challenge in my research.

Identifying a suitable size and footprint of rehabilitation robot is important as it will determines how much it is used [69]. Some users may not have enough space to install rehabilitation robots at home due to size limitation. Some users may want to transport the robot from the living room to the bedroom according to their preferences, or store the robot between each use. However, for most existing home rehabilitation robots, the size is too large to be easily transported; I will address this challenge in my research.

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The novelty of my research is to satisfy the aforementioned challenges. To summarise there is a need for home-based rehabilitation robots which are low cost, a suitable size and can also promote upper limb movements to aid rehabilitation of upper limb function. It is imperative to obtain an understanding of requirements of therapists and children with CP and why the currently available robots are not commonly used, for this reason I will adopt a user-centred design approach.

3.2 Aim and objectives

Aim: design, develop and evaluate a low-cost home-based rehabilitation robotic system integrating hand grasping, elbow flexion/extension and forearm pronation/supination movement assistance for children with cerebral palsy.

Objectives:

1. Identify a design specification of rehabilitation robotic systems through both a literature review and stakeholder (therapists, engineers) engagement.
2. Designs and manufacture a novel low-cost home-based rehabilitation robotic system which meets the design specification considering functionality (hand grasping, elbow flexion/extension and forearm pronation/supination), manufacturability and cost.
3. Evaluate the prototype robotic system with stakeholders and its mechatronic performance.
4. Identify areas the robotic system should be refined and future research areas.

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Chapter 4: Preliminary design of the upper limb end-effector rehabilitation robot

This chapter introduces the preliminary design of the upper limb rehabilitation robot. In order to identify the design requirements for a home-based upper limb rehabilitation robot, we did a literature review and synthesis. This leads to a scope review paper related to design requirements from patient's and therapist's points of view that was published in the Journal of topics of stroke rehabilitation. . Besides, analysis of upper limb movements based on ABILHAND-KIDs questionnaire giving design requirements for the device. Workspace design determined an area where end effector of rehabilitation robot moving within this area. A Needs-Metrics Matrix identifies the correlation between user requirements and technical requirements. And product design specification develops a product that meets the needs of the user. As this preliminary design is intended as a start point, there will be some changes in the finial prototype.

4.1 Scoping review of design requirements for upper-limb end-effector robot-assisted devices

4.1.1 Introduction

Neurological disorders, such as stroke and cerebral palsy are a significant burden on society and the individual [70]. Stroke is the commonest form of severe adult disability affecting 150, 000 people every year [71], whilst cerebral palsy is the commonest form of severe physical disability in children affecting 2.08/1000 of live births [1]. People affected by neurological disorders often have upper limb difficulties which limit activity [45]. The goal of rehabilitation is to improve the patients' independence in activities of daily life and therefore quality of life.

Traditional therapy for the upper limb involves a therapist physically guiding a patient to practice movements/tasks to promote motor learning [72]. Robot-assisted therapy has been proposed as an adjunct to traditional therapy to promote greater practice of beneficial upper limb movements [43] which then translates to an increase in the ability to use the upper limb in every-day activities [73]. The paradigm of robot-assisted therapy for the upper limb involves a patient playing motivating games on a computer [74] through a robotic manipulandum that enables a greater intensity of useful therapeutic practice. The games' designs are based on the activities of daily life.

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Robot-assisted therapy devices can be divided into two categories [11]; end-effector-based and exoskeleton-based. End-effector-based systems only contact a patient's upper limb through one single point, thus they give the user relatively light support and guide the patient's movements. In contrast exoskeleton-based devices are wearable and attached to patient's upper limb at several points [45]. They give the users' upper limb greater support and precisely control the movement at each joint. However, exoskeletons are complex in their mechanical design and the control algorithms that are utilised with them [45]. Consequently, they tend to be large, very expensive and complicated to use [75]. There is some evidence that end-effector devices may be of greater benefit to patients as they constraint the degree of freedom of the limb less than exoskeletons and thus promote greater motor learning [11].

Hughes et al [76] cited barriers to clinical translation of Assistive Technology (including rehabilitation robotics) as lack of knowledge, education, awareness and access. Furthermore, Hughes et al emphasize the need for better design to realize improved cost-effective upper limb stroke rehabilitation. It has been acknowledged that accommodating users' needs can determine the success or failure of technology development and product quality [77][78][79]. Given the significance of user-centred design on healthcare technology, the aim of this paper was to review the design requirements for upper limb robot-assisted therapy devices to inform the design of future end-effector rehabilitation robotic devices.

4.1.2 Methods

A computerised literature search was undertaken of the following electronic databases: Pubmed (include MEDLINE), CINAHL PLUS, IEEE Xplore, Web of Science and Scopus between January 1995 and May 2016. The time span started from 1995 as the first successful upper limb rehabilitation robot, MIT-MANUS was introduced in 1990s [80].

To identify relevant studies, the following search categories were used: "users", "upper limb", "rehabilitation", "design", "neurology". The search terms used were '(design or spec* or require*) AND (robot* or exercise system or rehab* system or rehab* technology) AND (upper limb or upper extremit* or arm or wrist or hand or manipul* or finger or thumb or reach or elbow or grasp or grip) AND (train* or Therap* or exercise*) AND (patient or service user or user or therap* or clinic*) AND (cerebral palsy or stroke or head injury or neurolog*

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or central nervous system or CNS)'. The language was limited to English and Chinese. We did not utilize MESH terms as our aim was to identify the largest range of literature for the review. Utilizing MESH terms would have resulted in a narrower range of literature. We include Cerebral Palsy and Stroke as they are the commonest forms of childhood and adult disability respectively and rehabilitation robotics has predominately focused on these conditions. Head injury, neurology and CNS were included as broad areas to identify other literature.

To prevent important publications being missed during the database search, the reference list of related review papers and from the selected papers were also screened. Where necessary, we also contacted study authors to ascertain whether they had an unpublished data regarding therapists' or patients' design requirements involved in their robots' development.

4.1.3 Selection and exclusion criteria

Studies were required to meet the selection and exclusion criteria as follow:

1. Concerning upper limb movement for adults or children with a neurological condition using a robotic-assisted device.
2. Robot devices which were not wheelchair-based.
3. End-effector rehabilitation robotic systems, not exoskeleton types.
4. Included therapist' or patients' requirements or opinions on end-effector robotics or rehabilitation systems.

Since the aim of this review was to summarize the patients' and therapists' design requirements, studies in any setting were included. We discarded studies where wheelchair-based devices were described, as this type of device assists the movement of the disabled arm rather than rehabilitating it.

4.1.4 Study selection process

The first author (QF) conducted the initial searches and screened all titles and abstracts. Then the full-text of the selected studies were independently screened against the selection criteria by two authors (QF and ZH). Any disagreements were resolved through a third reviewer (AW).

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4.1.5 Methodological quality assessment

Methodological quality of the selected papers was assessed using the Critical Appraisal Skills (CASP) checklists [16], as it is user friendly. “CASP Qualitative Checklist” propagates a systematic process through which the strengths and weaknesses of a research can be identified. It contains 10 items, scored as YES, NO and CAN’T TELL. A “YES” was given a score of 1 point; and a “No” or “Can’t tell” scored 0 points. QF and ZH independently scored each selected study against the checklist. Any discrepancies were discussed between the reviewers and disagreements on the scores of studies were resolved by consensus.

4.1.6 Data extraction and presentation

The following information was extracted and tabulated:

1. Author information
2. Participants: number, age, sex, medical condition and duration (if a patient), profession and years of experience (if a therapist)
3. The method of data collection
4. The design requirements identified
5. Experience of users with a robot
6. Main findings

4.1.7 Design requirements identified and classified

Through critical analysis of the identified literature, we identified four main categories of design requirements, namely: “Individualized therapy”, “recording of performance”, “movements and tasks promoted”, and “safety and usability”. ‘Individualized therapy’ includes the features that are needed to make the robot suitable for a wide range of users’. ‘Recording performance’ included everything about recording or measuring the users’ performance, while ‘movements and tasks’ include what was to be practiced, and ‘safety and usability’ included relevant requirements to ensure safety of the device.

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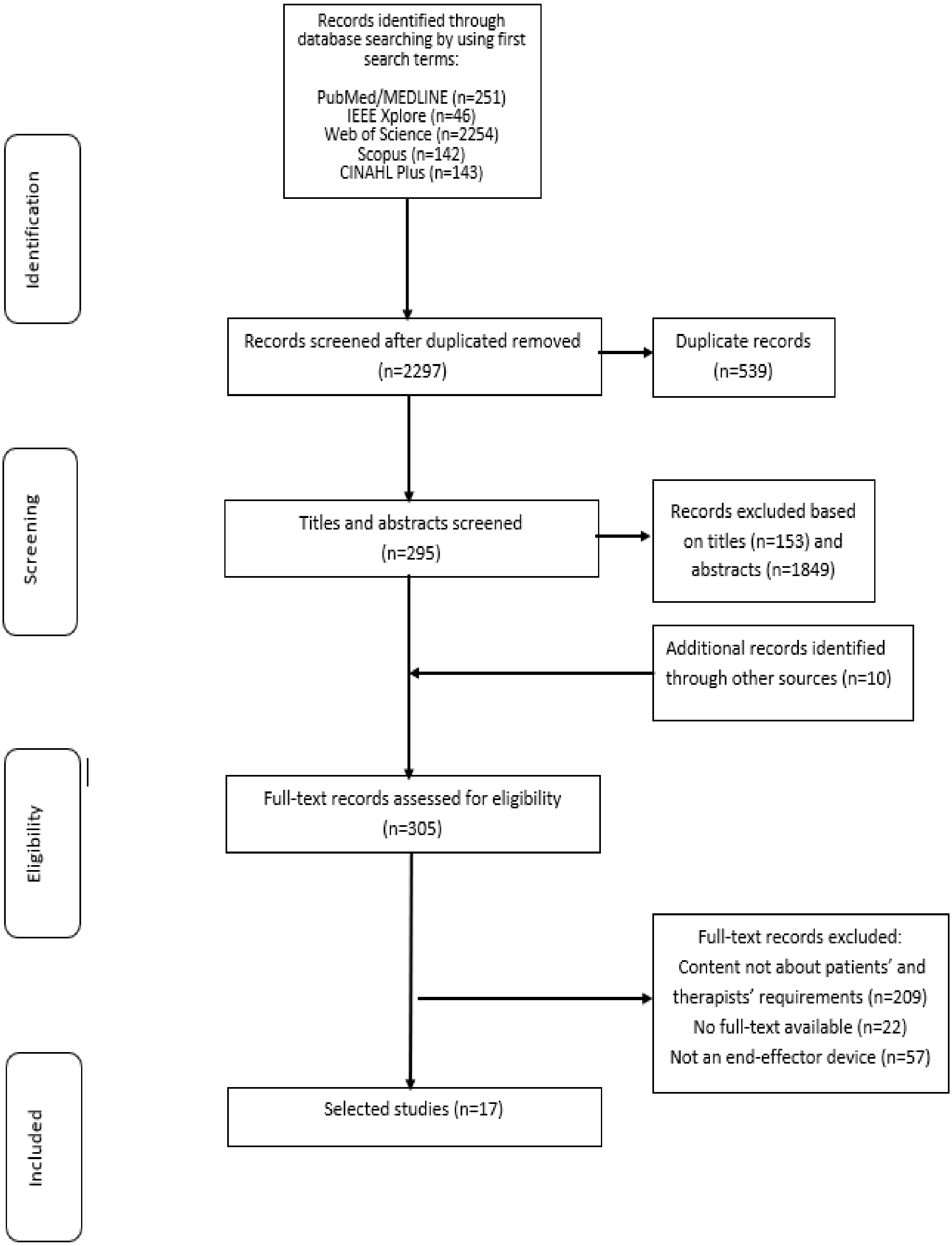

Figure 8. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) study selection flow chart.

A total of 2836 studies were identified after duplicates had been removed (Figure 8). This reduced to 305 once the title and abstracts were screened. Of these 305 papers, 289 were excluded because: (i) the content was not about patients' or therapists' design requirements (n=209); (ii) the full-text was unavailable (n=22); or (iii) the device was not an end-effector type (n=57). The remaining 17 studies were selected.

The 17 selected papers involved the opinions of 55 therapists and 40 patients. Through analysis of the author affiliations, we identified that 76% most of the authors (76%) were engineers (mechanical, electrical and computer). Only 18% of authors had a clinical background including medical doctors, occupational therapists and physiotherapists. The professions of the remaining authors (6%) could not be identified.

Table 1 summarizes the details of participants, method of data collection, proposed design requirements and the CASP checklist scores. All studies except Hughes et al. (2011) included therapists' opinions, of whom there were 20 physiotherapists, 30 occupational therapists, 4 medical doctors and 1 nurse [12][84][89][91][95]. Of these selected studies [12][82][86][88] [93] included 1 stroke, 5 stroke, 6 stroke, 1 stroke and 5 cerebral palsy patients respectively.

Four qualitative methods were utilized; self-administered questionnaires [86][88] semi-structured interviews [82][87][93][96], focus groups [84][89][90][91][94][95] and observation [81][83].

Table 1. Details of the selected papers.

Study	Participants	Methodology	Design requirements Identified
Atlihan et. al 2014 [81]	1 physiotherapist	Observation	Therapists' requirements: • An easy to use interface **(Safety and Usability)**
Azzam et. al 2013 [82]	1 woman (56 years old) with neurofibromatosis and 1 physiotherapist	Semi-structured interview	Therapists' requirements: • An inclined plane is the most useful for performing exercise similar to activities of daily living like eating or shaving **(Movements and Tasks Promoted)** • Increasing the game difficulty by increasing the speed or objects occur in random positions **(Individualized therapy)** • Apply different levels for the games **(Individualized therapy)** Patients requirements: • Prefer using robot lying on the bed than on the chair **(Individualized therapy)** • The device should look friendly and not like a scary device **(Safety and Usability)**
Babaiasl et. al 2015 [83]	Therapists (number and profession unspecified)	Observation	Therapists' requirements: • The robot should be adaptable to the human limb in terms of segment length, Range of Motion and Degree of Freedoms **(Individualized therapy)** • The robot should be easy to use **(Safety and Usability)**
Furuhashi et. al 2009 [84]	Hospital based therapists (number and profession unspecified)	Focus group	Therapists' requirements: • The robot should promote training programs using the following motions: circular window cleaning, turning a handle, arm wrestling, and pushing and pulling with different resistances (similarly to conventional therapy) **(Movements and Tasks Promoted)**

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Table 1 (Continued)

Hilton et.al 2011 [85]	Stroke survivors from a community-based stroke club; 22 occupational therapists	Focus group and self-administered questionnaire	Therapists' requirements: • Task performance should be measurable **(Recording of performance)** • Designing a score system to develop and evaluate a stroke assessment index **(Recording of performance)** • The task simulated in the system must resemble a real daily activity living task **(Movements and Tasks Promoted)** • The system will intervene as necessary so the patient is unable to perform a dangerous action **(Safety and Usability)** • The equipment should be portable as it may have to be moved and locked away after every trail **(Safety and Usability)** • The patient/user is permitted to attempt the task without the sequence being prescribed **(Movements and Tasks Promoted)** Patients' requirements: • Hospital is a better place to practice tasks than patients' community centre **(Individualized therapy)** • The system should be easy to use **(Safety and Usability)** • Making a hot drink task is a component of assessment of independence and should be included **(Movements and Tasks Promoted)**
Hughes et. al 2011 [86]	5 stroke patients (3 men and 2 women), mean age 52 years; time since stroke = 8 months to 8.4 years. 3 right hemiplegia and 2 = left,	Self-administered questionnaire	Patients' requirements: • Prefer to use robot at home **(Individualized therapy)** • Picking up a cup would be an important task. **(Movements and Tasks Promoted)** • When doing the arm movement, prefer doing something with fingers at the same time. **(Movements and Tasks Promoted)**

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Table 1 (Continued)

Ivanova et. al 2015 [87]	5 therapists from two rehabilitation clinics	Semi-structured interview	Therapists' requirements: • The robot software should be easy to navigate i.e. clear and simple form **(Safety and Usability)** • A touchscreen monitor would be ideal **(Safety and Usability)** • The robot should store an electronic patients' file with the demographical data and the results of clinical assessment **(Recording of performance)** • The robot should store an Individual therapy plan and the goal setting for each patient **(Recording of performance)** • The robot should record range of motion, accuracy, tempo and number of executed movements, percentage ratio of correct body posture during training **(Recording of performance)**
Jackson et al. 2007 [88]	6 stroke survivors; 2 physiotherapists and 2 occupational therapists	Self-administered questionnaire	Therapists' requirements: • The robot should promote potentially therapeutic movements within a desired range of movement **(Movements and Tasks Promoted)** Patients' requirements: • The robot must be comfortable when moving or stationary **(Safety and Usability)** • It should be easy to attach/unattach the robot to the upper arm and lower arm **(Safety and Usability)** • The robot should be safe to use **(Safety and Usability)**
Krebs et al. 2004 [89]	Therapists (number and profession unspecified)	Focus group	Therapists' requirements: • The robot should incorporate protraction when patients undertake initial movement against gravity **(Movements and Tasks Promoted)** • The device should monitor scapular protraction when the patient makes functional reaching movements as this is beneficial **(Movements and Tasks Promoted)** • No support of device is needed at the elbow **(Safety and Usability)** • Keep the robot's visual display simple to avoid confusion **(Safety and Usability)**

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Table 1 (Continued)

Lam et al. 2008 [90]	4 physical therapists and 4 occupational therapists (all female), average of 4.0 years of experience with upper-limb stroke rehabilitation	Focus group	Therapists' requirements: • Patients can operate the robot in various positions **(Movements and Tasks Promoted)** • The robot should promote a wide range of shoulder movements **(Movements and Tasks Promoted)** • The robot should promote movements that focus on the lateral rotation range **(Movements and Tasks Promoted)** • A switchable end-effector that applies different hand grasps **(Individualized therapy)** • The robot should be easy to use **(Safety and Usability)** • The robot should ensure safety of the patients' hand as many stroke patients find it difficult to maintain their hand on the end-effector **(Safety and Usability)**
Lenzo et. al 2015 [91]	Physical therapists (numbers unspecified)	Focus group	Therapists' requirements: • Be able to rapidly change the intensity of compensation force when switching from a patient to another **(Safety and Usability)** • Be able to record the movements of the arm **(Recording of performance)**
Loos et. al 2015 [92]	2 physical therapists	Focus group and interview	Therapists' requirements: • The robot should enable two modes: Mirror Mode (visual symmetry) and Wheel Mode (point mirror symmetry) **(Movements and Tasks Promoted)** • The motion modes should be customizable depending on the users' motor abilities **(Individualized therapy)**

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Table 1 (Continued)

Park et. al 2013 [93]	1 stroke patient; 2 rehabilitation therapists	Semi-structured interview	Therapists' requirements: • The robot can help patients at the beginning, and let them use the device independently once they become accustomed to it **(Individualized therapy)** • The handle movement velocity must be adjustable according to patient's condition **(Individualized therapy)** • The handle should be comfortable **(Individualized therapy)** • Reasonable cost of the robot **(Safety and Usability)** Patients' requirements: • Prefer therapist guidance more than self-training **(Individualized therapy)** • Include grasping training and extension training function in the robot **(Movements and Tasks Promoted)**
Rodriguez-De-Pablo et. al 2012 [94]	9 clinicians; 4 doctors, 2 occupational therapists, 2 physiotherapists and 1 nurse	Focus groups	Therapists' requirements: • Vertical force is not appropriate for early post-acute patient **(Safety and Usability)** • Apply different levels for the games **(Individualized therapy)** • Promoting primarily extension task to train abnormal synergies **(Movements and Tasks Promoted)** • 2D movement is a better way to start and incorporating 3D components for patients' practice **(Movements and Tasks Promoted)**
Schoone et al. 2007 [95]	Therapists (number and profession unspecified)	Focus group	Therapists' requirements: Note: this robot had a support for the arm. • The arm support and strapping of the robot should be adequate for different on sizes, weights (of arms)and functionality **(Individualized therapy)** • Therapists can step back and observe patients during their exercises as this easy to correct abnormal movements **(Recording of performance)**

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Table 1 (Continued)

Weightman et. al 2010 [12]	37 able-bodied children and 5 children with cerebral palsy; medical doctors, paediatric physiotherapists (numbers unspecified)	Focus group and self-administered questionnaire	Therapists' requirements: • Highlighted the importance of the safety operation of the rehabilitation system **(Safety and Usability)** • The rehabilitation system should match the desired movement that a physiotherapist will encourage a child to do **(Movements and Tasks Promoted)** Patients' requirements: • Graphic user interface should be more enjoyable in comparison to other computer games **(Safety and Usability)** • A smaller joystick (i.e. robot) is desirable (the author didn't mention the detail of the size) **(Individualized therapy) (Safety and Usability)** • 3. Games should become more complicated to overcome repetition and hence boredom **(Individualized therapy)**
Weiss el. al 2014 [96]	1 physiotherapist	Semi-structured interview	Therapists' requirements: • There should be a visualization of the torque measurements of a healthy subject's exercise data in comparison with patients **(Movements and Tasks Promoted) (Recording of performance)** • The patient should not be able to see the visual feedback when undertaking the task **(Movements and Tasks Promoted) (Recording of performance)**

Three studies used combinations of these methods [12][85][92]. Among the 17 articles, the methodological rigor of the included studies (Table 2) scores ranged from 5 to 10. The average score was 7.4 indicating a good standard of methodological rigor. The aims; choice of method and design were appropriately addressed and the findings were clear. Methodological details that were less consistently addressed were how the method addressed the research question; the relationship between researcher and participants and the analysis (with lack of attention to trustworthiness and rigour). The recruitment strategy was often poorly detailed with a lack of detail about how participants were identified and recruited. The numbers recruited were often very small (1-37, typically less than 10) such that it is unlikely that data saturation was reached and the representativeness of the participants is uncertain.

Table 2. The methodological quality of the selected papers

Study first author last name	Were the aims clearly stated?	Is the method appropriate?	Was design appropriate for the aims?	Was the recruitment strategy appropriate to the aims?	Did data collection address the research question?	Was the relationship between researcher and participants considered?	Have ethical issues been addressed?	Was analysis rigorous?	Were the findings clear?	How valuable is the research?	Scored
Atlihan et. al 2014 [81]	YES	YES	YES	CAN'T TELL	YES	CAN'T TELL	CAN'T TELL	CAN'T TELL	YES	YES	6
Azzam et. al 2013 [82]	YES	YES	YES	CAN'T TELL	YES	CAN'T TELL	YES	YES	YES	YES	8
Babaiasl et. al 2015 [83]	YES	YES	YES	CAN'T TELL	CAN'T TELL	CAN'T TELL	CAN'T TELL	CAN'T TELL	YES	YES	5
Furuhashi et. al 2009 [84]	YES	YES	YES	CAN'T TELL	CAN'T TELL	YES	YES	YES	YES	YES	8
Hilton et.al 2011 [85]	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	10
Hughes et. al 2011 [86]	YES	YES	YES	YES	YES	CAN'T TELL	YES	YES	YES	YES	9

Table 2 (Continued)

Ivanova et. al 2015 [86]	YES	YES	YES	YES	YES	CAN'T TELL	CAN'T TELL	CAN'T TELL	YES	YES	7
Jackson et al. 2007 [87]	YES	YES	YES	CAN'T TELL	YES	CAN'T TELL	CAN'T TELL	YES	YES	YES	7
Krebs et al. 2004 [88]	YES	YES	YES	CAN'T TELL	CAN'T TELL	CAN'T TELL	CAN'T TELL	YES	YES	YES	6
Lam et al. 2008 [89]	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	10
Lenzo et. al 2015 [90]	YES	YES	YES	CAN'T TELL	YES	CAN'T TELL	CAN'T TELL	CAN'T TELL	YES	YES	6
Loos et. al 2015 [91]	YES	YES	YES	CAN'T TELL	YES	CAN'T TELL	CAN'T TELL	YES	YES	YES	7
Park et. al 2013 [92]	YES	YES	YES	CAN'T TELL	YES	CAN'T TELL	CAN'T TELL	YES	YES	YES	7
Rodriguez-De-Pablo et. al 2012 [93]	YES	YES	YES	YES	YES	YES	CAN'T TELL	YES	YES	YES	9
Schoone et al. 2007 [94]	YES	YES	YES	YES	CAN'T TELL	CAN'T TELL	CAN'T TELL	YES	YES	YES	7
Weightman et. al 2010 [12]	YES	YES	YES	YES	YES	CAN'T TELL	YES	YES	YES	YES	9

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Table 2 (Continued)

Weiss el. al 2014 [95]	YES	YES	YES	CAN’T TELL	CAN’T TELL	CAN’T TELL	CAN’T TELL	CAN’T TELL	YES	YES	5
											Average score	7.4

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4.1.8 Summary of the design requirements of end-effector rehabilitation robot from therapists' and patients' perspectives

A total number of 62 design requirements were identified from the selected papers; which were summarized in table 3.

Table 3. Summary of the design requirements of end-effector rehabilitation robot from therapists' and patients' perspectives

Categories we have identified	Design requirements	Therapists' agreements	Patients' agreements
Individualized therapy	Settings including hospital; community centres and home [85][94]	×	√
	Ensuring the robot is suitable for individual size of patient and levels of severity of disability [83][95]	√	×
	The importance of a range of different grip and grasp movements [12][90][93]	√	√
	Body related: segment length(limb) and weights of patients' body [92]	√	×
	Robot related: range of workspace, velocity of motion and degrees of freedom of the robot [83]	√	×
	User related: amount of arm support given to the limb [93]	√	×
	Complexity and difficulty (speed, number of objects, randomness) of the tasks to be practiced and games [12][82][85][88][92][93]	√	√
Recording performance	Patients' arm performance including the range of motion, accuracy, type of forces produced and number of executed movements during training [85][87][91]	√	×
	The need for the robot to record the patients movement performance e.g., patients perform a task with or without assistance, whether the movement taken by patients was correct or incorrect according to the therapists, and the time spent in each action [85]	√	×
	Clinical notes regarding the patients goals; treatment plan, treatment delivered and progress made on clinical assessments [85][87]	√	×
	Therapists should be able to observe patients' movements during the exercise [95]	√	×

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Table 3 (Continued)

Movements and tasks to be promoted	Movements and games that simulated real activities of daily living, such as coffee making, picking up a cup, eating and shaving [12][82][85][86] and grasping extension tasks [86][93][94]	√	√
	2D movements promoting a wide range of movements, e.g. reaching movements, shoulder lateral rotation, extension, grasping and finger movement [86][88][89][90][93][94]	√	×
Safety and usability	Ease and comfort to use the robot [83][88][90][93]	√	√
	A simple interface to navigate the robot user interface [81][87][89]	√	×
	The importance of handles and end effectors e.g. size and shape [12]	×	√
	Friendly appearance of the robot and enjoyable user interface for the patients to use [12][82]	×	√
	Portability of the robot for secure storage [85]	√	×
	Reasonable cost of the robot [93]	√	×
	Safety when using the robot particularly when attaching the hand [12][88][90]	√	√
	Swapping rapidly between users [91] to prevent dangerous actions [85][94]	√	×

"Individualized therapy" included features to make the robot, tasks and games suitable for a wide range of users which could be adapted as the user progressed. The features needed to be adaptable so treatment could be individualized to different sizes of patients and levels of disability to accommodate progress and prevent boredom.; "Recording performance" refers to the need for the device to record users' performance; "Movements and tasks" include what was to be practiced, and "safety and usability" included users emphasized the importance of safety and usability when using the device.

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4.2 Activities of daily living analysis of upper limb rehabilitation robot movements

4.2.1 Aim

A home-based upper limb rehabilitation robot needs to enable practice movements and tasks related to ADL. To identify the important functional movements that robot should promote, an ADL analysis of upper limb movements was undertaken using the ABILHAND-Kids.

4.2.2 Participant demographics

Two physical therapists (both from UK) have experience with cerebral palsy survivors more than 10 years were participated in. One worked in community-based care and another worked in school.

4.2.3 Method

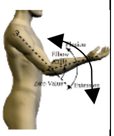
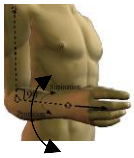
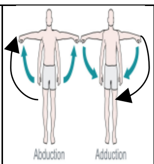
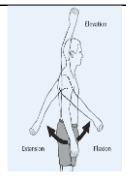
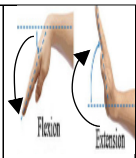
ABILHAND-Kids [97] is an outcome measure (questionnaire) to measure the manual ability of children with upper limb impairments. It consists of 21 high frequency ADLS that require the use of the upper limbs for children. Each ADL was considered with respect to specific limb movements (e.g. elbow flexion/extension). The result of ADL analysis was checked by two participants. They analysed the 21 ADLs assessed in the ABILHAND questionnaire to identify the limb movements which were used most often and thus should be prioritised for robot aided therapy.

4.2.4 Data

The questionnaire results were summarized on the table 4 below.

Table 4. ADL analysis of upper limb rehabilitation robot movements

	Limb movements									
ADL	**Elbow Movement**	**Forearm Movement**	**Shoulder Movement**			**Wrist Movement**	**Type of grip/grasp**			
	Flexion& Extension	Pronation & Supination	Abduction & Adduction	Internal& External Rotation	Flexion& Extension	Flexion& Extension	Grab Grip	Pinch& Key Grip	Pencil Grip	Hook Grip

Illustration of upper limb movements										
1. Opening a jar of jam	√					√	√			
2. Squeezing toothpaste onto a toothbrush								√		
3. Putting on a hat	√				√			√		
4. Buttoning up trousers/ pants	√		√			√		√		
5. Zipping-up trousers	√					√		√		
6. Washing the upper-body	√	√	√		√					
7. Buttoning up a shirt/sweater	√					√		√		
8. Putting on a backpack/schoolbag	√		√	√	√		√			√
9. Opening a bag of chips/ crisps	√					√		√		
10. Sharpening a pencil		√						√	√	
11. Fastening the snap of a jacket	√	√						√		
12. Zipping-up a jacket	√					√		√		
	Elbow Movement	**Forearm Movement**	**Shoulder Movement**			**Wrist Movement**	**Type of grip/grasp**			
	Flexion& Extension	Pronation & Supination	Abduction & Adduction	Internal& External Rotation	Flexion& Extension	Flexion& Extension	Grab Grip	Pinch& Key Grip	Pencil Grip	Hook Grip
13. Unscrewing a bottle cap	√	√						√		

14. Opening a bread box	√						√			
15. Unwrapping a chocolate bar	√	√						√	√	
16. Opening the cap of a toothpaste tube		√					√	√		
17. Taking a coin out of a pocket	√							√		
18. Switching on a bedside lamp			√		√				√	
19. Filling a glass with water		√			√		√			
20. Taking off a T-shirt	√	√	√	√	√		√			
21. Rolling-up a sleeve of a sweater	√	√	√	√	√	√	√	√		
Frequencies	16	9	6	3	7	7	7	14	3	1
Percentage	76.2%	42.9%	28.6%	14.3%	33.3%	33.3%	33.3 %	66.7%	14.3%	4.8%

4.2.5 Results and discussion

Table 4 indicates the usage of upper limb joints during common ADLs. The most commonly used movement was elbow extension and flexion (16/21 activities 76.2 %,). The second most common was forearm supination and pronation (42.9%) followed by vertical shoulder flexion and extension (33.3%) and shoulder abduction and adduction (28.6%). Horizontal shoulder flexion and extension was the least used (14.3%, 3/21 activities). In terms of grasp type: pinch grip was the most commonly used (66.7%, 14/21 activities), followed by grab grip (33.3%, 7/21 activities). Only one activity used a hook grip. Therefore, elbow flexion/extension pinch/key grip, forearm pronation/supination are important upper limb movements that engineer should consider when design rehabilitation robots. To identify the importance of hand movements, a further literature was undertaken (see appendix 2).

Table 5. Summary of hand functions of current developed upper limb rehabilitation robots

	Grasp grip	Pinch/key grip	Pencil grip	Hook grip

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Total number of robots	60	11	1	2
Percentage	47.6%	8.7%	0.8%	1.6%

Over 120 rehabilitation robots were involved in this literature. As the result, current available upper limb rehabilitation robots pay more attention to grasp grip (47.6%) then pinch/key grip (8.7). As the pinch/key grip is the 3rd high frequent ADL, it is very important to involve pinch/key grip when designing a new rehabilitation robot, especially when the robot focuses on hand function.

4.3 Workspace design

4.3.1 Workspace definition

In order to guarantee users' safety during use of the robot, the speed of each joint is limited within 75% of that of healthy adults. The upper limb movement of healthy adult is shown in Table 6, consisted of slow speed, medium speed and fast speed. 75% of the medium movement speed of healthy adult is used as the maximum movement speed of rehabilitation robot.

Table 6. Human upper limb movement speed

Motion type	**Average angular speed (%)**					
	Elbow joint		**Shoulder joint**		**Wrist joint**	
	100%	75%	100%	75%	100%	75%
Slow speed	21.48	16.11	31.00	23.25	10.67	8.00
Medium speed	35.68	26.76	46.67	35.00	14.58	10.94
Fast speed	120.63	90.47	102.33	76.75	62.35	46.76

To protect users from secondary injuries caused by extreme range of motion, the functionality workspace was assumed as 75% of that of a healthy child and loading capability was assumed as 175% of the weight of the forearm of a healthy children.

`

The desired rehabilitation robot should include a large reachable workspace to allow for training on a wide array of functionally relevant reaching tasks. The workspace here is defined as an area where children perform robot-assisted rehabilitation within this area. The size of the area is determined by the maximum forward and side reaching movement. From the literature review, there is no direct data about reaching distance. However, it can be calculated from the anthropometric date children's upper arm and forearm length. I assumed that the children would sit with their torso against the edge of the table (i.e., would be unable to compensate using their trunk), so only the arm length of the subject was factored into our calculation. Then theoretical analysis was performed using MATLAB simulations.

4.3.2 Joystick workspace schematic and area calculation

The reaching training movement will not be beneficial to train the muscle of the patient, if the compensation angle of the patient is not prevented, see Figure 9 below.

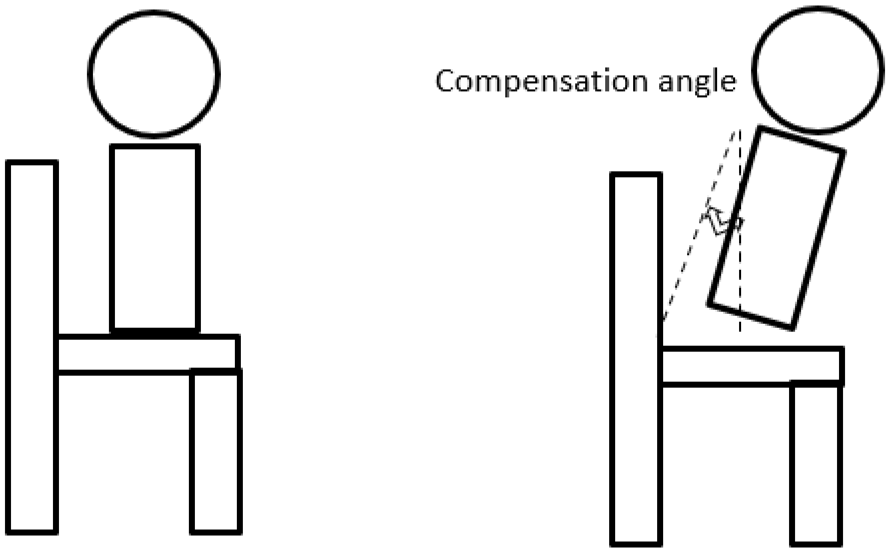

Figure 9. Left, without compensation angle movement; Right, with compensation angle movement

The children is assumed sitting a forearm's length from the table without compensation angle, and the angle between upper arm and forearm is assumed to be 90° in the initial position that can be seen above.

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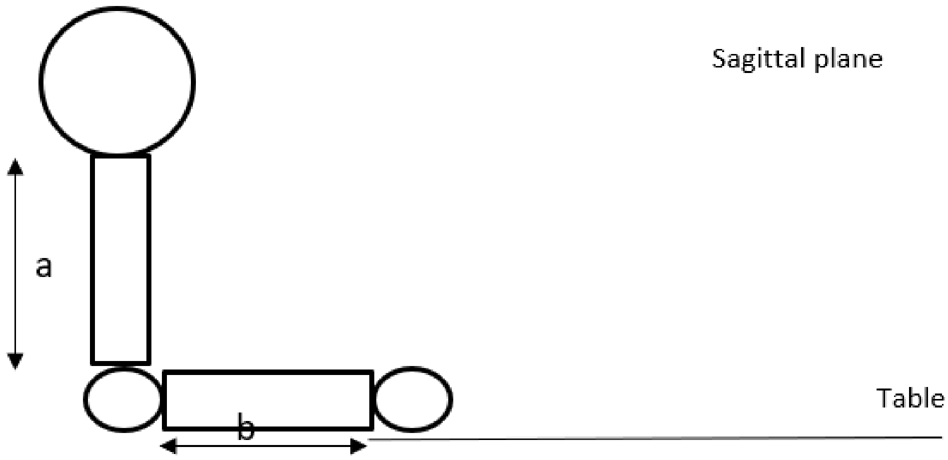

Figure 10. Initial position of children using robots

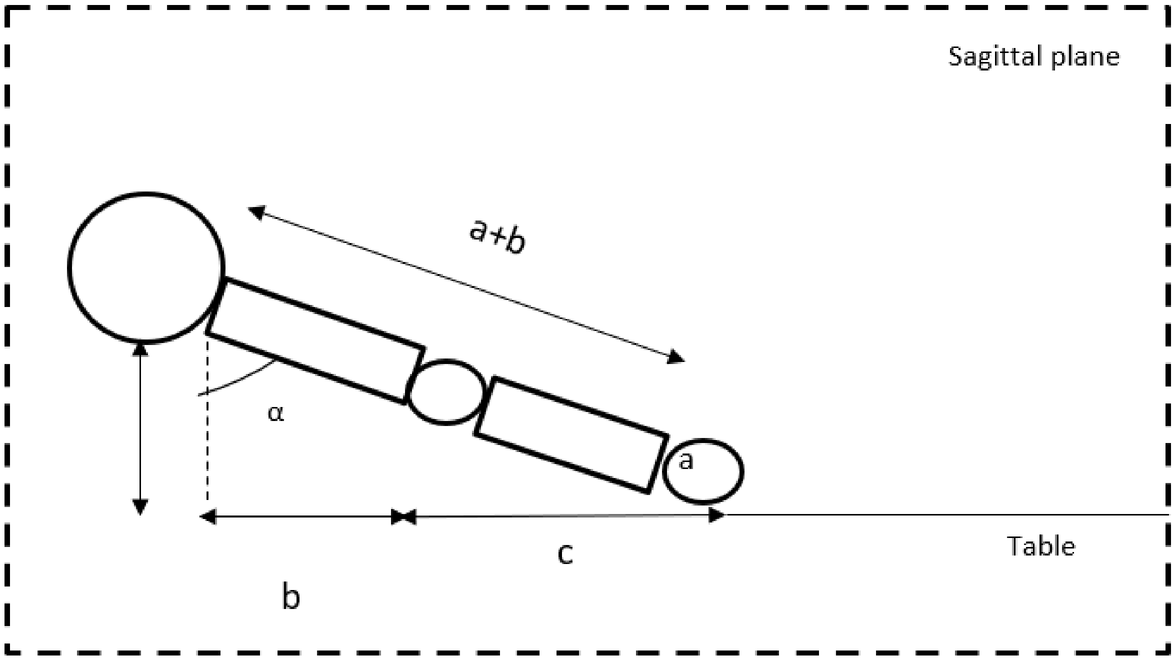

Figure 11. Forward reaching movement

In the calculation, forward reaching distance can be determine by the equation below

$a^2 + (b + c)^2 = (a + b)^2$ (4-1)

$\mathrm{c} = \pm\sqrt{b^2 + 2ab} - \mathrm{b}$ (4-2)

$\alpha = \cos^{-1}(\frac{a}{a+b})$ (4-3)

where

a= upper arm length (mm)

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b= forearm length (mm)

c= forward reaching distance (mm)

α= angle between body and whole arm (fully straight) when doing maximal forward reaching (degree)

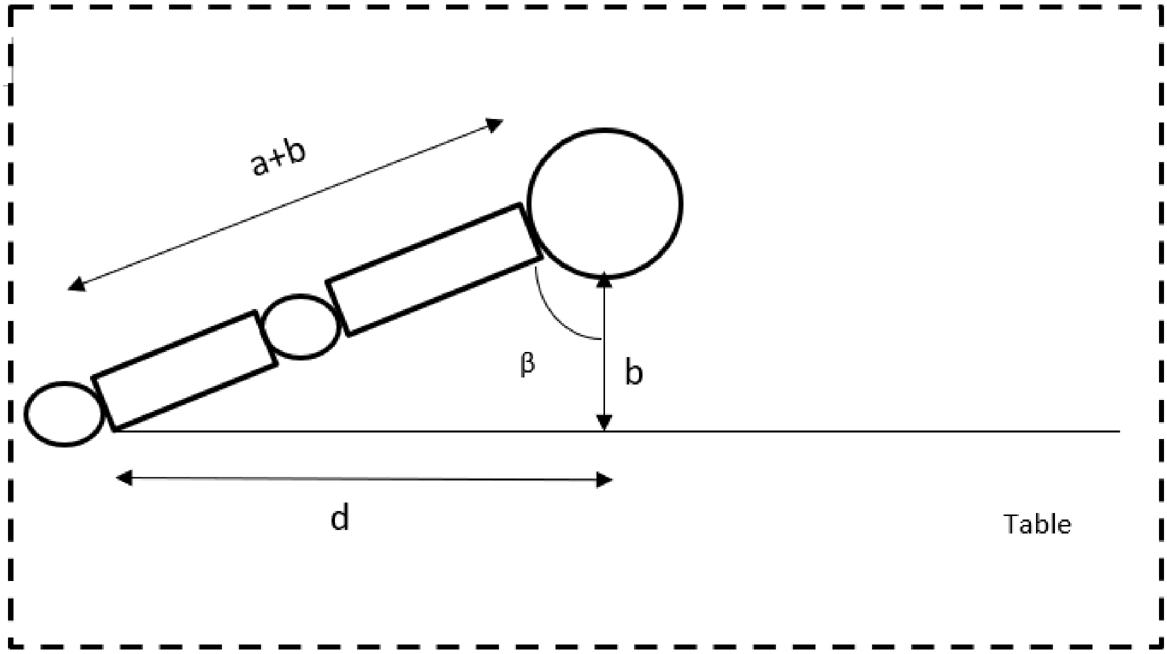

Figure 12. Side reaching movement

According to Figure 11, the side reaching distance can be determine by the equation below

$$d = \sqrt{(a+b)^2 - b^2} \quad (4\text{-}4)$$

$$\beta = \cos^{-1}(\frac{b}{a+b}) \quad (4\text{-}5)$$

Where

d= side reaching distance (mm)

β=angle between the thorax and the whole arm (fully straight) in the transversal plane when doing side reaching (degree)

From the anthropometric data (see appendix 3), 95th percentile is used to accommodate the middle 95 percent of the user population. The calculation results are shown on table 7 below.

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Table 7. The results of forward and side reaching distance according to different age groups.

Age group (yrs)	Forward reaching distance c(mm)	Side reaching distance d(mm)	α(°)	β(°)
2.0-3.5	143.02	329.35	54.96	64.80
3.5-4.5	152.51	351.17	54.92	64.83
4.5-5.5	163.27	375.83	54.84	64.91
5.5-6.5	174.25	401.13	54.86	64.89
6.5-7.5	185.06	426.75	55.34	64.45
7.5-8.5	194.42	447.78	54.99	64.77
8.5-9.5	202.96	467.22	54.86	64.89
9.5-10.5	214.35	492.63	54.34	65.36
10.5-11.5	220.01	506.10	54.63	65.09
11.5-12.5	232.02	534.74	55.18	64.59
12.5-13.5	243.09	559.88	55.00	64.75
13.5-14.5	252.19	581.38	55.26	64.52
14.5-15.5	255.30	586.87	54.41	65.29
15.5-16.5	262.22	603.18	54.62	65.10
16.5-17.5	265.48	610.61	54.59	65.13
17.5-19	271.27	624.86	55.03	64.73

According to the schematic, the children workspace looks like a rectangle shape that is shown below.

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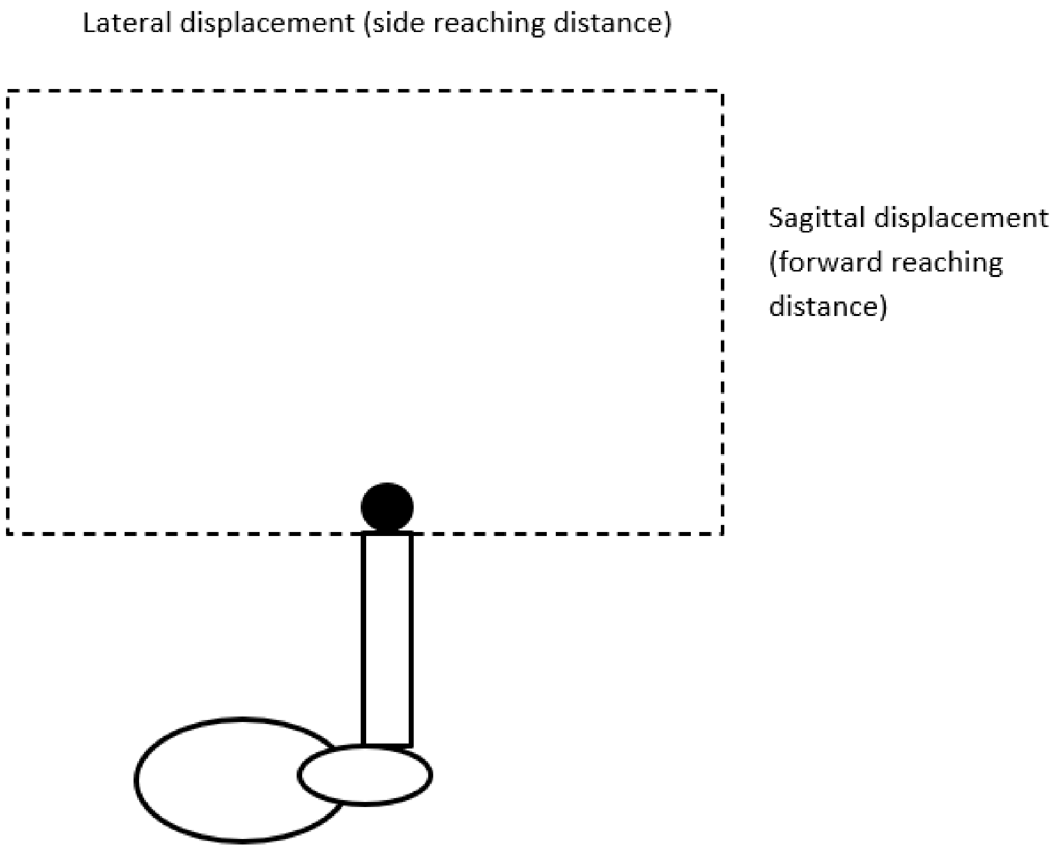

Figure 13. Schematic of workspace

The final workspace is drawn by Matlab and shown below, the unit is mm.

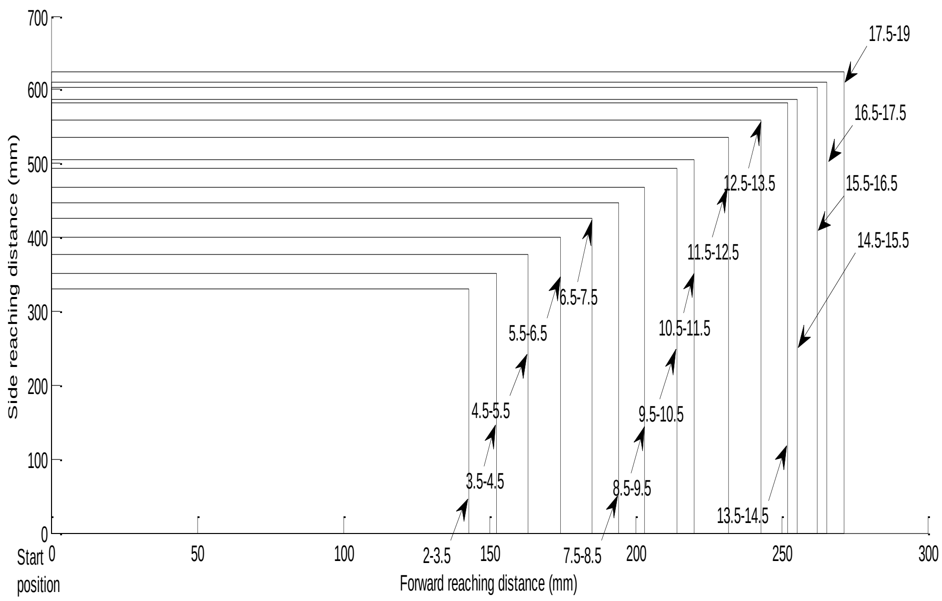

Figure 14. The results of workspace according to different age groups

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4.3.3 Relation between workspace and robot

According to the results above, the maximum and minimum workspace are 624.86 mm × 271.27 mm for the age group 17.5-19 and 329.35 mm × 143.02 mm for the age 2-3.5. As the aim of this project is developing a low –cost rehabilitation robot for the children with cerebral palsy, therefore we focus the age of children from 6-17. These workspaces affect the end position and joint angles of the robot. Two links lengths of 250 mm and 300 mm respectively will allow for a reasonable sized workspace with a maximum workspace of 610.61 mm × 265.48 (age 17.5) and a minimum workspace of 426.75 mm × 185.06 mm (age 6.5), where the end effector is able to move anywhere in a central area.

4.4 Needs-Metrics Matrix

According to the patient's and therapist's design requirements and the ADL analysis, a Needs-Metric Matrix is made to transfer target group requirements into design (see table 8). Needs-Metric Matric is a visual tool for systematically mapping the customers' requirements (wants, expectations and needs) and the functional requirements (engineering metrics). The needs from end users are listed on the right side of the chart, and the metrics are listed on the top. Through critical analysis of the identified literature, five main categories of customer requirements were identified, namely: "robot functionality", "usability", "accessibility", "safety" and "motivation". The columns present the technical requirements. "Robot functionality" referred to requirements needed to support user's motor relearning and was further broken down into movement patterns, degrees of freedom, speed, ability to assist or resist, and feedback. "Usability" included everything about programming such as recording or measuring the users' performance and the game design and was broken down into patient interface, therapist interface, and general control interfaces. "accessibility" ensured the robot would be feasible and acceptable to use in the home. "Safety" included relevant requirements to ensure safety of robot and to fulfil all relevant medical device regulations. "Motivating factors" (Motivate) referred to desired visually motivating games and activities which would help their patients be more compliant with exercise programs and were further broken down into ADL activities and fun activities. The customer requirements are evaluated against technical requirements to see their interrelation, where the high interactions are marked with an 'H', the medium correlation are marked with a 'M', the low correlation are marked with a

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'L'. As some of customer requirements did not fit into any of the technical requirements, these spaces are left blanks. The results are taken into consideration when the device will be designed.

Table 8. Interrelation matrix of customer requirements and technical requirements

Upper limb end-effector-based rehabilitation robot			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
			Yaw	Pitch	Roll	Resistive	Assistive	Acceleration	Length	Width	Height	Weight	Links	Joints	End effector	Power requires	Sensors	Actuator	Compatibility	Meets standards	Stability
	Customer requirements																				
1	Robot functionality	Improve coordination	H	H	H								M	H	H		M	M			
2	Robot functionality	Few high -quality movements better than many poor quality															H				
3	Robot functionality	Bilateral movements																	H		
4	Robot functionality	Wide range of shoulder movement	H	H	H									M							
5	Robot functionality	Grasping movement													H		H				
6	Robot functionality	Slow movements						H								M		H			
7	Robot functionality	Movement graded						H										H			
8	Robot functionality	Resistance based on user performance				H	H	M								L		H			
9	Robot functionality	Keep track of progress														L	M				
10	Robot functionality	Biofeedback to patient														L	H				
11	Robot functionality	Biofeedback to therapist														L	H				
12	Robot functionality	Maintain joint alignment															H				
13	Usability	Separate interface for users																			
14	Usability	Touch screen														L					
15	Usability	Seated position																		L	

16		Adjustable and comfortable handhold													H						
17	Accessibility	High intensity focused therapy				M															
18		Home-used										H				L	L		H	M	
19		Low cost													L	H	M	M		M	
20		Portable							H	H	H	H									
21		Simple training method																			
22		Modular											L	L	H		H		H		
23	Safety	Emergency stop																			
24		Arm stability																			H
25		Prevent damage children's arm																M			
26	Motivation	The task simulated as a real daily activity living task																			
27		Fun games																			

4.5 Product design specification (PDS) for a cost-effective home-based rehabilitation robot

After I identified the implementation barriers, requirements and priorities for a home-based upper limb rehabilitation robot through literature review and UCD with therapists, a product design specification of table mounted rehabilitation robot with five degrees of freedom to enable practice of the most commonly used upper limb movements and grips at home was developed. PDS is a document created during the problem definition activity in the early design process. It acts as the control for the total design activity because it sets the boundaries for the subsequent design. The purpose of the PDS is to ensure that your design actually addresses your customer needs. A third version of PDS is shown below.

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Introduction

In recent years, the field of pediatric neurorehabilitation has rapid developed with the introduction of rehabilitation robot. It can provide physical assistance for children with cerebral palsy when they playing functional and motivated games. The system should be user friendly and easy to use for both therapist and patient. However, the cost and customized becomes key limiting factors. Therefore, a low-cost, individualized rehabilitation robot is designed to provide intensive upper limb practice for children with cerebral palsy.

Scope

This specification covers general operational characteristics of the product and provides an overview of the requirements for the rehabilitation robot. It will not include manufacturing details of the robot.

Performance

- The rehabilitation robot should perform hand grasp, forearm pronation/supination, elbow flexion/extension and shoulder protraction/retraction movement.
- The robot movement must be in a 2D plane.
- The torque of motor provides for elbow movement <2.33N.m
- The torque of motor provides for forearm movement<0.35N.m
- The RoM of forearm pronation/supination between 70°pron-70°supin
- The RoM of elbow extension between 5°-120°
- The handle is adjustable and comfortable combined with a force sensor to measure the force <66.50N
- 22-inch screen for displaying virtual task simulation for patient
- The robot set up time is less than 15 mins
- The interface is easy to use
- The system must have an emergency stop button
- The system is able to rapidly change the system setting when switching to other patients
- The motion modes are customized according to different patient
- A database to record information and treatment of patient and therapist
- The platform is portable

Size and weight restrictions

- The whole system weight should not exceed 50 kg
- Height not to exceed 100mm
- Length not to exceed 150mm
- Width not to exceed 100mm

Standards

- Compliance to any relevant health and safety standards on medical electrical equipment

Environment

- The rehabilitation is used in the home environment and the noise level of device <50 dB
- Temperature ranges: -30 degree

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- The product may experience humid conditions

Life in service

- The product should withstand an operating period of 1 hour uninterrupted use per day for 5 years.

Target cost

- The cost of the prototype should be less than £5000
- The cost of the manufacture should be less than £1000

4.6 Prototype conceptual design

The prototype was designed in consultation with therapists. Therapists surveyed wanted a robot to facilitate many types of movements, requiring more DoF. However, they indicated they wanted a low-cost robot. It was determined that 4 DoF would be a good start point. The prototype was designed using SolidWorks 2014 (www.solidworks.com), see Figure 14. And the isometric view of this robot is shown on figure 15

Two aluminium square hollow links length of 300mm and 400mm respectively would allow for a seasonable sized workspace, with a maximum workspace of 624 mm (sagittal axis) × 271 mm (lateral axis). The end effector part will be introduced in the next chapter.

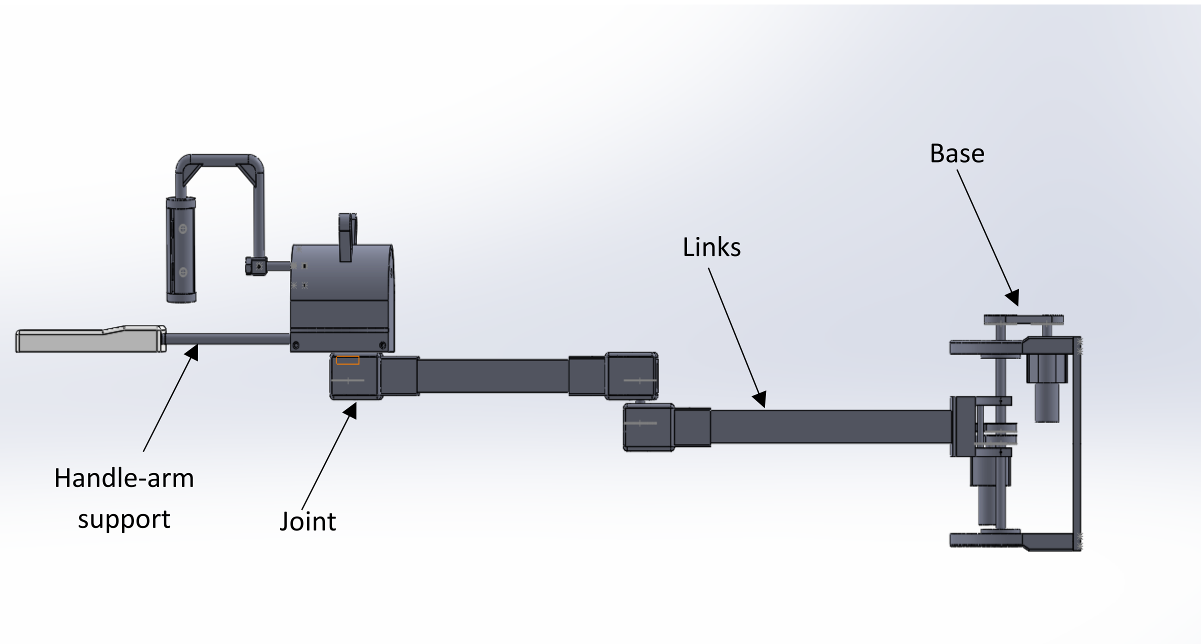

Figure 15. SolidWorks conceptual design of an upper limb rehabilitation robot

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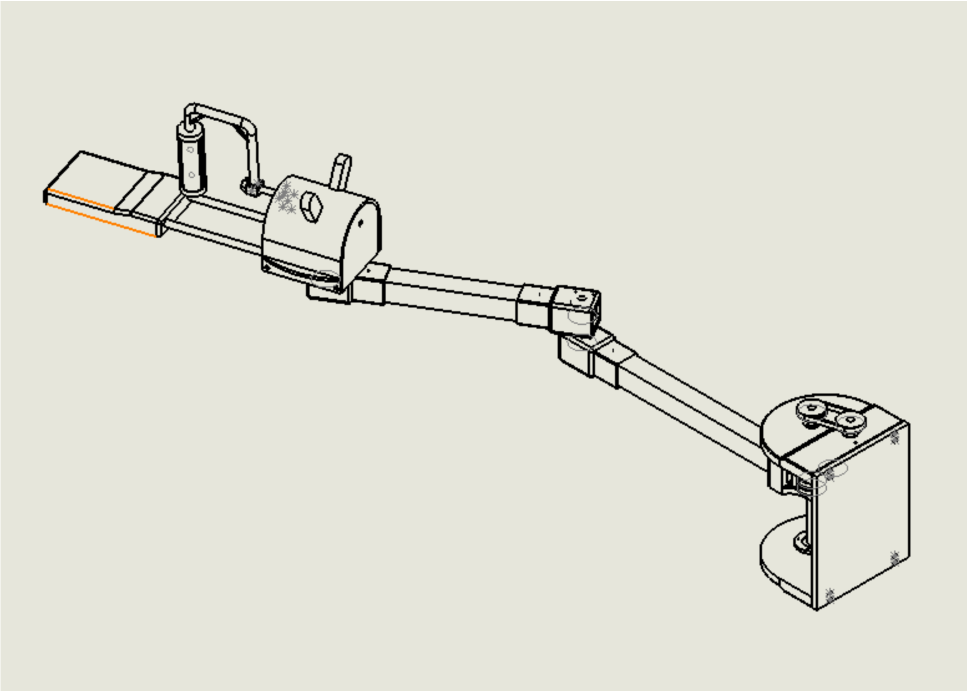

Figure 16. Isometric view of an upper limb rehabilitation robot

4.7 Actuation and sensing

4.7.1 Actuator selection

The selection of actuators is based on the values of torque and power required of each joint. Other factors such as reliability, cost, size and positioning accuracy also affect the selection of actuators. Normally, there are three types of actuators, electric, hydraulic and pneumatic [98].

Table below summarizes the advantages and disadvantages of actuators applied in home-based rehabilitation robot.

Table 9. Summary of different types of actuator applied in home-based rehabilitation robot

Actuators	Application in home-based rehabilitation robot	
	Advantages	Disadvantages
Pneumatic actuators	➢ Low weight ➢ Low inherent impedance ➢ Cleanliness ➢ Safe	➢ Slow and non-linear dynamic response ➢ Noise issue from compressor

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		➢ Difficult to control due to air compressibility
Hydraulic actuators	➢ Only special designed hydraulic actuators are used in rehabilitation robotics.	➢ High cost ➢ Heavy and large footprint ➢ Problem of oil leakage ➢ Noise issues
Electric actuators	AC motors	➢ Low cost, less maintenance, small motor size	➢ Difficult to control speed and position
	DC brushed motors	➢ Low cost, small size, Torque and speed easy to control	➢ Not highly efficient than brushless DC motors
	Brushless DC motors	➢ Run smooth at low speed, better heat dissipation, high performance motion control, reduced noise	➢ Very costly, require more complex electronic speed control
	Stepper motors	➢ relatively low cost, doesn't need feedback	➢ Its movement is not continuous, causing positioning errors

Each actuator has its own good points, pneumatic actuators have good performance in point-to-point motion, hydraulic actuators offer large force capability and electric motors are clean and capable of high precision [98]. However, for home-based environment, hydraulic and pneumatic actuators are bulky and cannot be easily controlled. Within the electric motor category, DC brushed motors have advantage in easy to control, longer lifetime, reduced noise and low cost. Therefore, brushed DC motors are selected for rehabilitation robotics.

To achieve forearm pronation and supination, elbow flexion and extension and shoulder flexion and extension, there are 3 brushed motors needed. Normally, a DC brushed motor provides a limited torque at high speed [99]. To solve this problem, a gearbox is coupled with a motor to magnify its torque by reducing its speed. The equation below shows the output torque of geared motors:

$$Output\ Torque = Motor\ Output\ Torque \times Gearbox\ Ratio \times Gearbox\ Efficiency \quad (4\text{-}1)$$

Where motor output torque, gearbox ratio and gearbox efficiency can be found directly from the product specification.

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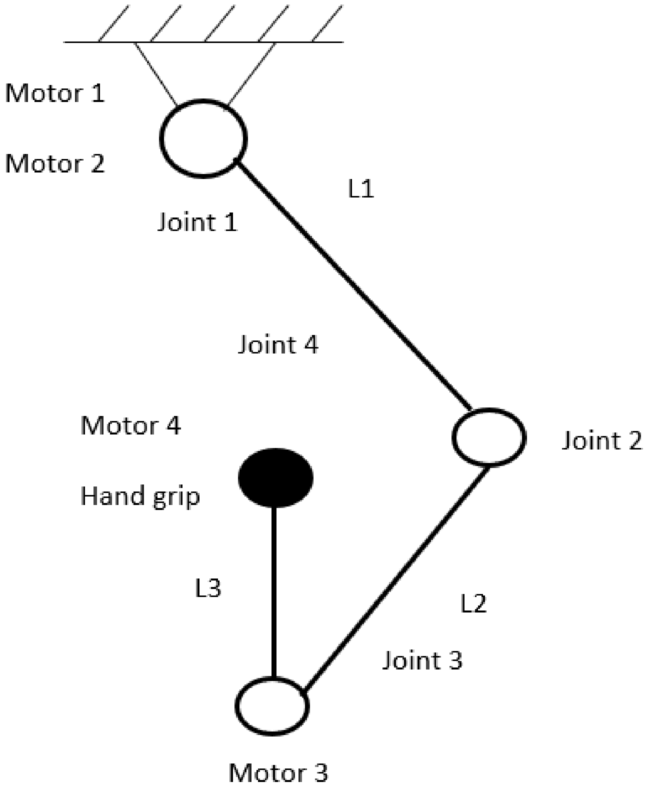

Figure 17. Schematic of motor position in the rehabilitation robot

Table 10. Motor selected in the rehabilitation robot

Motor number	Motor type	Torque required (NM)	Support movement	Supply voltage (V)
Motor 1	Crouzet DC geared motor-82869009	2.33	Not applicable	12
Motor 2	Crouzet DC geared motor-82869010	1.76	Elbow flexion/extension	12
Motor 3	Crouzet DC geadxcz\red motor-82862003	1.2	Wrist flexion/extension	12
Motor 4	Crouzet DC geared motor-82862003	0.35	Forearm pronation/supination	12

4.7.2 Sensor selection

In the preliminary design, the rehabilitation robot will be equipped with two types of sensors: kinematic and kinetic. Kinematic sensors refer to the sensors for angular position,

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acceleration and velocity measurement. Kinetic sensors are used for measuring the force of user applied for the device.

Three absolute rotary encoders and incremental rotary encoders are equipped with each motor at each joint (forearm, elbow and shoulder) respectively. Absolute encoders are fixed to the output of the actuator transmission so that they can provide absolute positioning. Incremental encoders are connected in series with the motor and transmission to maximize their accuracy.

Gurley model A37 absolute encoder is chosen for absolute encoder, which has 12 bits of resolution and 37 mm in diameter. Crouzet incremental rotary encoder is selected that is capable of detecting 1000 counts per revolution. This encoder is considered because it can be tightly packaged within the actuator as a component set.

In order to measure the force exerted by the user, force sensors are applied in the rehabilitation system. The force sensor is a mechanical component to convert mechanical force into an electrical signal. Two JR-3 Force Moment Sensors are installed at elbow joint and handle respectively to measure the supination/pronation torque and grasping force.

4.8 Summary

Designing a device which would meet user requirements, and yet be cost effective was a challenge. From the therapist's points of view, performing functional activities was important, as well as allowing the device to be compact and portable enough to be used at home.

The scoping review paper identified the clinical and technical requirements of home-based upper limb rehabilitation robots, reflecting the actual needs and development trends for CP survivors and their therapists. 17 papers were selected involving 55 therapists and 40 patients. 62 specific design requirements were proposed by patients (n=16) or therapists (n=46). Four main requirement themes were identified; functionality, usability, software and safety. These were that devices should incorporate movements and tasks which are similar to activities of daily living; be suitable for a wide range of users and settings; individualized to users' needs; record performance and be safe, easy and appealing to use.

`

This is the first paper to summarize users' design requirements for upper-limb end-effector rehabilitation robots: the need for a safe, comfortable, easy to use device which could be individualized and produced specific movements and tasks emerged. Although user involvement in the technology development is known to determine its success or failure, we found the literature to be limited and sometimes tokenistic. Further robust research is warranted and we encourage the community to publish the design requirements that informed their own system development.

Four barriers to implementation have been detailed, namely operational details; adherence, space and cost. A home-based upper limb rehabilitation robot needs to enable practice movements and tasks related to ADL; be suitable for wide range of users and settings but provide personalised therapy, be safe, easy and appealing to use, and small and easy to store, and inexpensive. These findings form the basis for the next stage of the authors' research; designing and developing a novel low-cost home-based upper limb rehabilitation robot which meets these requirements. The significance of the research we present provides clear guidance for designers and researchers about real-world needs for home-based upper limb rehabilitation robots enabling them to develop new systems which are fit for purpose.

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Chapter 5: Design, testing and evaluation of the rehabilitation robot end effector

5.1 Introduction

Because of having the ability to monitor grip strength of children during therapy is of great interest in our research of rehabilitation robot. However, current market available upper limb rehabilitation robots do not usually measure grip strength, rather they focus on rehabilitating upper limb movements [18]. Therefore, improving grip strength can be an important aspect of upper limb rehabilitation.

Typically, Grip strength is measured through a hand dynamometer [98]. Although it is effective by using a dynamometer, it only measure grip strength in one direction and is a single function mechanical device [99]. Several studies have approved that grip strength is varied depending on the hands' orientation, making grip measurement in only one direction is not appropriate [100]. Besides, the dynamometer cannot be easily installed and incorporated into a rehabilitation robot. Therefore, we develop an approach to measure grip force at the end effector of the rehabilitation robot to provide real-time measurement of grip force during therapy.

5.2 Sensor selection

Generally in haptic and robotic application, force is measured by load cell. However, load cells are typically not well suited for a rehabilitation robot due to the form factor and cost. An alternative choice is using strain gauges, but incorporates a strain gauge with handle requires a compliant material which can increase complexity and weight of the handle. Finally, we considered using Force Sensing Resistors (FSRs) as it has the ability to combine lightweight and simple circuit into a rehabilitation device. Teskcans FlexiForce A301 sensor is selected as its small size to fit in the handle (shown in Figure 17), 0-111N force range, 3% linearity (error), 2.5% repeatability, 4.5% hysteresis, 5% drift and 5 µsec response time. The sensor is 25.4 mm (1 in) long, 14 mm (0.55 in) width and 9.53 mm (0.375 in) diameter sensing area.

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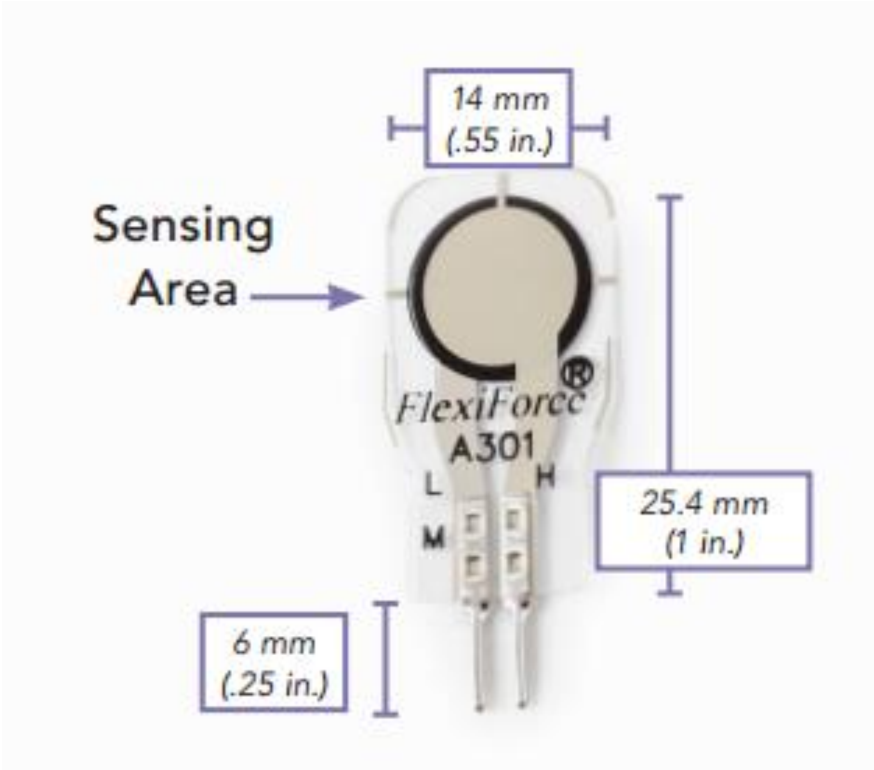

Figure 18 Actual size of the FlexiForce A301 sensor

5.3 Design requirements for the rehabilitation robot end effector

When designing an end effector of the rehabilitation robot, it is necessary to consider compact and lightweight design. The end effector must be compactable, so as not to have conflict with other upper limb movements promoted by rehabilitation robot. As for lightweight, it contributes on reducing the cost on material directly and ease the burden of motors that mounted on the base of the rehabilitation robot. An additional consideration of the end effector is having a suitable diameter that is comfortable to users. As this project is focusing on children with age 7-18, the target diameter for the cylindrical handle is chosen as 40mm, so as to be in the optimal diameter range.

To meet the design requirements, an end effector prototype was developed, shown in the figure 18 below, which can measure grip force and interaction force in three principal directions by using six thin film force sensing resistors (Tekscan's FlexiForce Sensor A301). To enable real-time monitoring of grip strength for the purpose of assessment of rehabilitation efficacy, we use Arduino to programme the sensors.

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Figure 19. The Grip Force Sensing Joystick

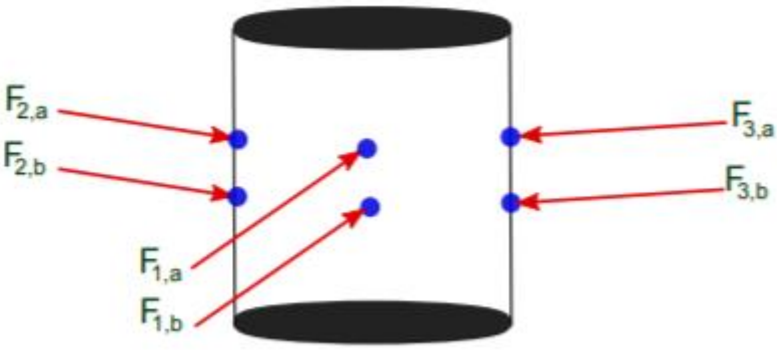

Figure 20. Positions of the six Flexiforce sensors and the representations of the six forces on them

The FlexiForce Sensors measure grip forces between the user and the handle during therapy. The six sensors are divided into three sets, each set has two sensors which are placed on the inner surface of the handle as shown in Figure 19. The other two sets are placed evenly placed on the inner circumference of the handle. Two flats on the shell housing facing the sensing area of the sensors that are used to transfer all the grip force from uses to the FlexiForce sensors. To control the load area on the FlexiForce sensors, 2.5 mm thick and 13.5 mm diameter plastic cylinders are placed between the sensing area of the FlexiForce sensors and

`

the flats on the shells, increasing the repeatability of the FlexiForce sensors response to the force applied from the users. The reason for two sensors per shell slice is allowing for a stable grip and accurate measurement when compare to only one sensor. The shell housing and the main body of the handle were manufactured by a rapid prototyping method (3D printing) with The Dimension Elite 3D Printer. The resolution is up to 0.178 mm and model material used was Acrylonitrile Butadiene Styrene (ABS) plastic. When consider the hand anthropometric data of children aging 7-18, the whole handle weights 107 g, 120 mm in height and 40 mm in diameter.

Using the measurements from each of the Flexiforce sensor, the grip force on the sensor can be determined. Due to the flats on the shells and plastic disks placed on the Flexiforce sensors, all load is transferred directly from the shells to the sensors (forces shown in Fig. 19). When grip force is being measured, the forces can be summed from

$$F_s = F_{i,a} + F_{i,b} \tag{5.1}$$

where i = 1, 2, 3, are in vertical planes.

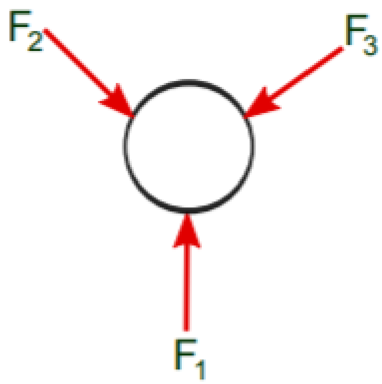

Figure 21. Forces applied to the end effector are simplified to horizontal plane problem.

The resulting forces can be averaged to obtain a measure of grip force. If instead interaction forces are being measured, the difference in applied vertical and horizontal forces could be used to obtain the equivalent 3D force/torque vector applied at the end effector.

5.4 Sensor testing, signal conditioning and calibration

Testing the sensor before using it in a specific application is necessary. According to the datasheet of FlexiForce A301 sensor, we incorporated it into a force-to-voltage circuit (Figure 21).

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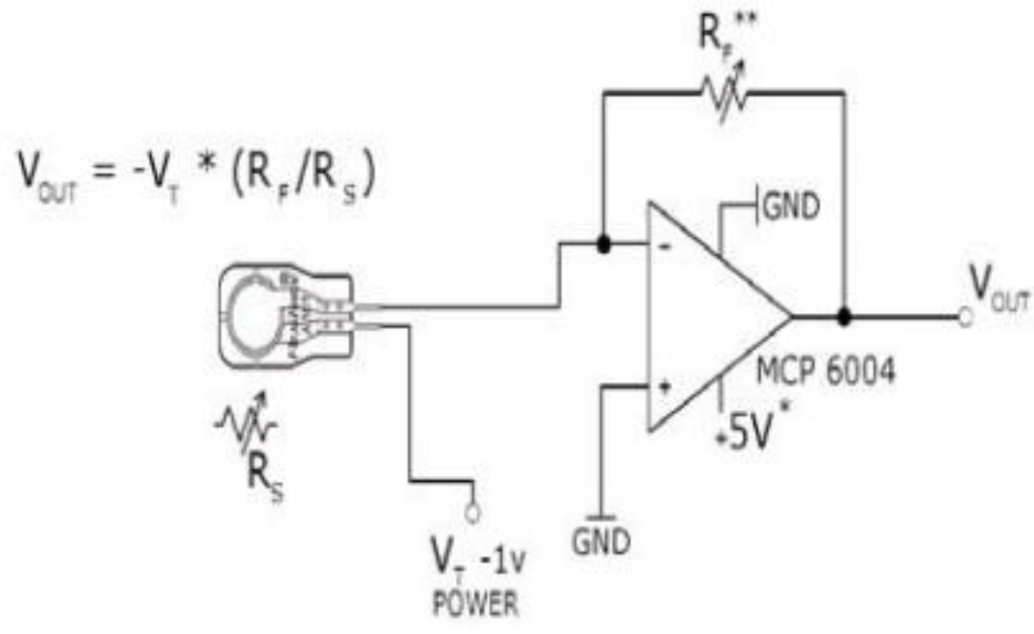

Figure 22. Recommended Circuit for A301 sensor

The output voltage of the sensor is given by

$$V_{out} = -V_{in}\frac{R_f}{R_s} \tag{5-2}$$

Where V_{out} is the output voltage from the sensor, V_{in} is the input voltage to the sensor, R_f is the reference resistance (1kΩ to 100kΩ) and R_s is sensor resistance. For this study, V_{in} was chosen to be -5V and R_f was chosen to be 100kΩ as a low reference resistance will make the sensor less sensitive.

The FlexiForce sensor ranges its resistance between near infinite when not being touched, to under 25kΩ when approaches its weight limit. We can measure the change of the resistance by using Arduino's analogue input (shown in Figure 22). The driven voltage is provided by Arduino Mega 2560. The Arduino code used for testing the sensor is below (Appendix 4).

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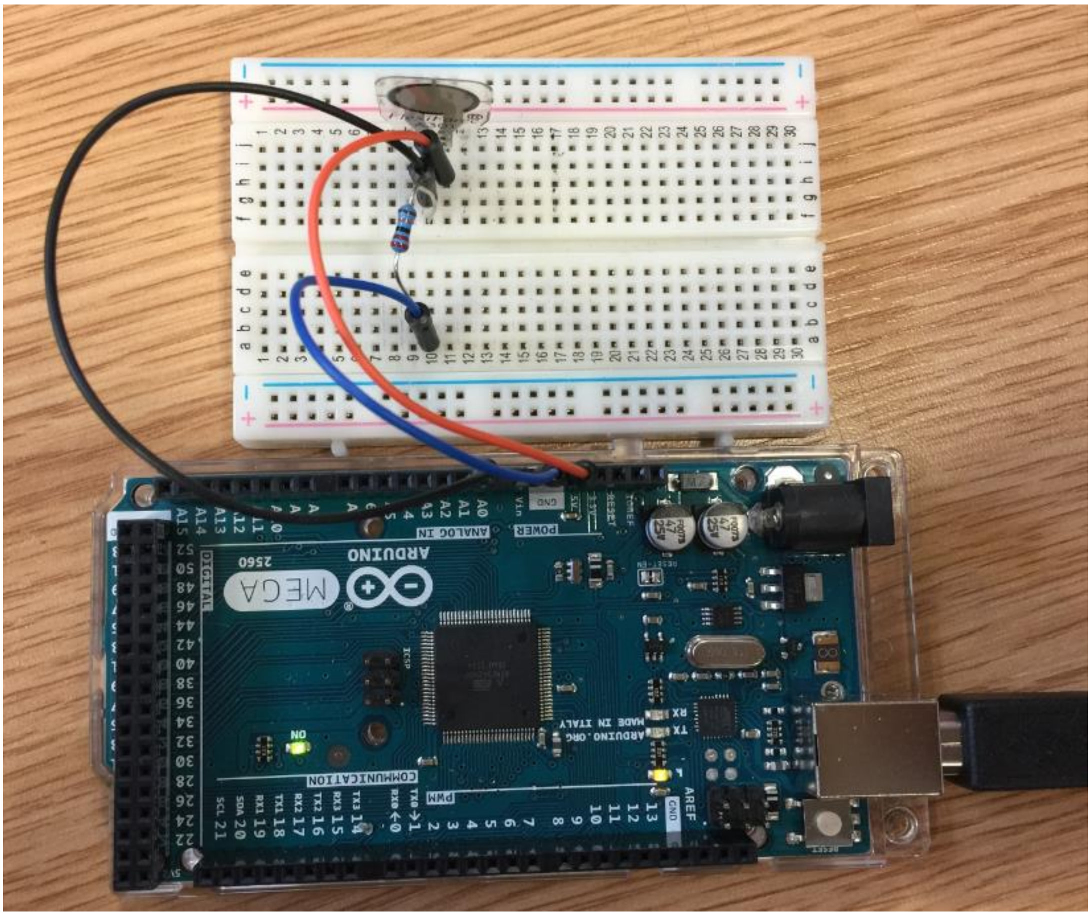

Figure 23. Test circuit of the sensor

After uploading the code, open serial monitor, and set the baud rate to 9600 bps. When apply pressure to the FlexiForce sensors, resistance and estimated pressure calculations begin to appear.

Conditioning the sensor before calibration is essential in achieving accurate results. We placed the 99 N (110% of the test weight) on the sensor, allow the sensor to stabilize, and then remove the weight. We repeated this process in four times.

The reading from the FlexiForce sensor was calibrated with the INSTRON 4507 Compression machine (Figure 23) by applying increasing levels of force in the compression direction. A metal is cutting to fit in the sensing area of the sensor before using the compression machine to get more accurate result. The conductance of the sensor is linear to applied force so utilizing an inverting op-amp allows for a linear relation between output voltage and applied force (Figure 24).

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Figure 24. Instron compression machine for sensor calibration

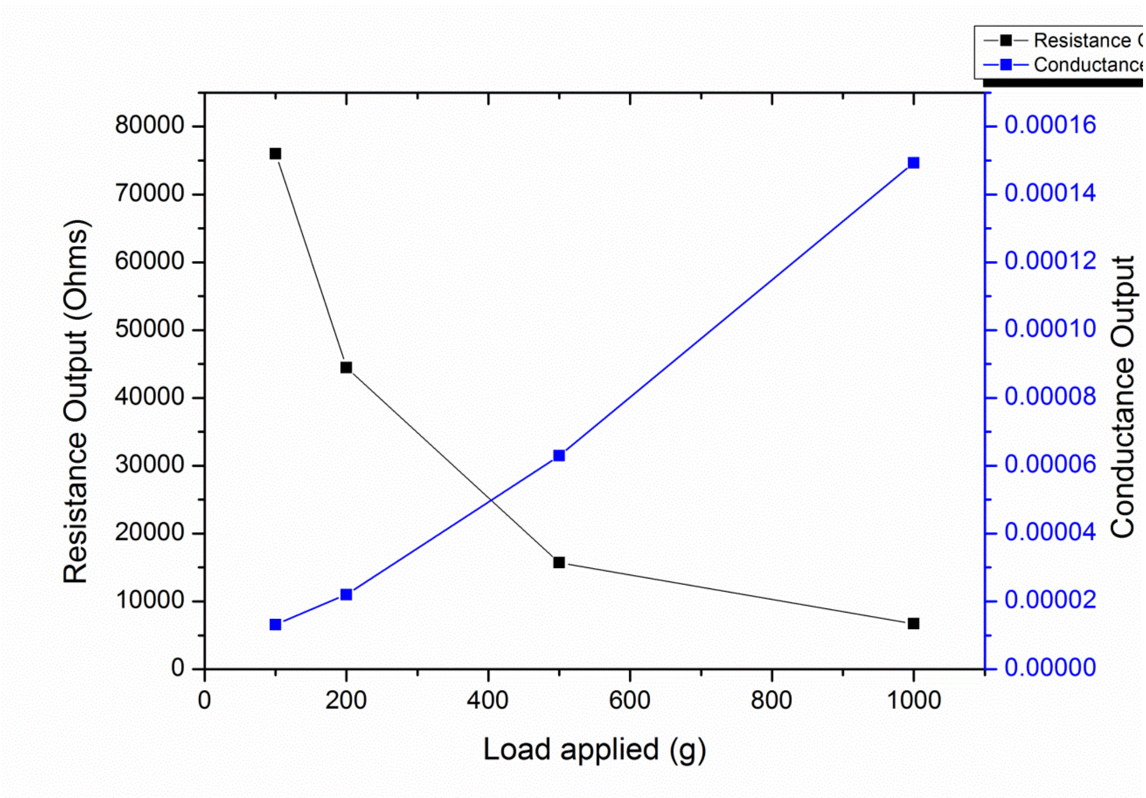

Figure 25. Experimentally measured resistance vs. force curve for the Flexiforece Sensor.

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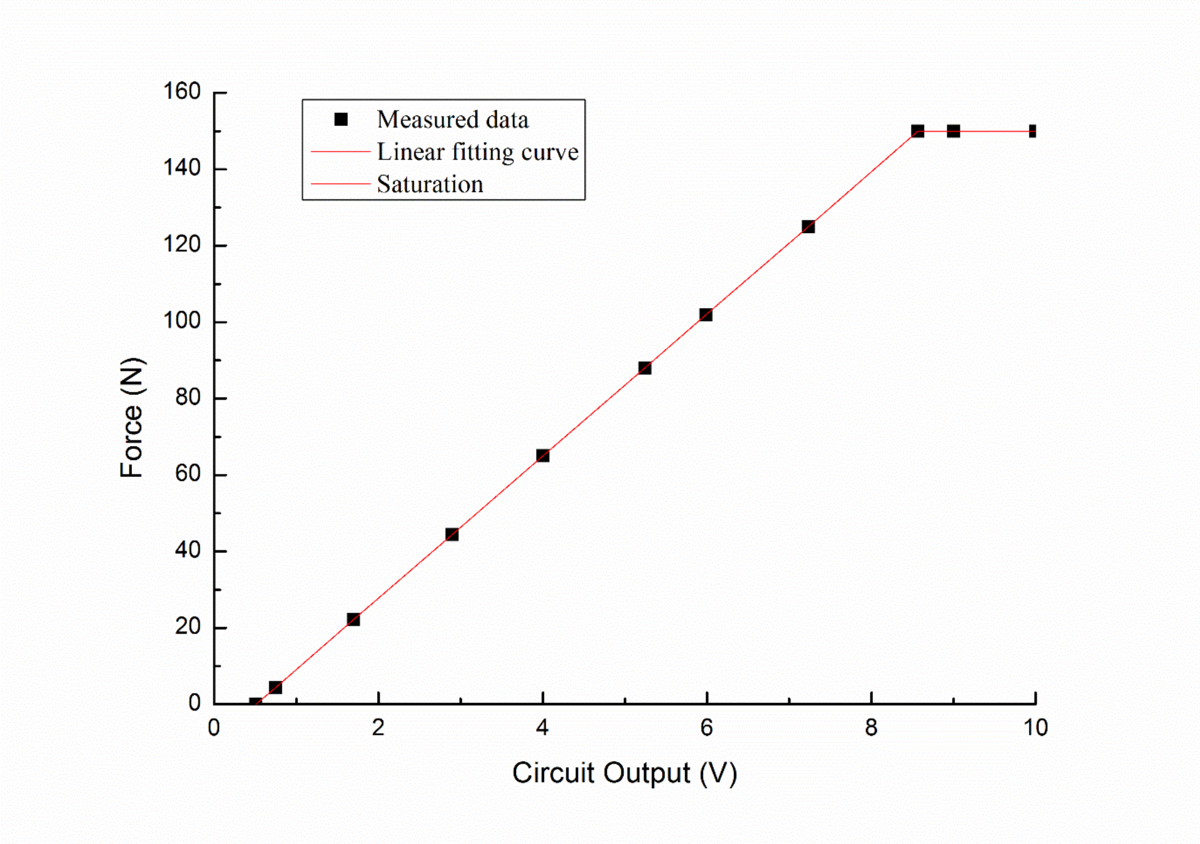

Figure 26. Calibration of the Flexiforece sensor voltage with force applied

For this calibration, we record the circuit output with the sensor unloaded, then we recording force applied when giving different circuit output (see 11). The Saturation force is the point at which the device output no longer varies with applied force. In this case, the saturation force is 150N.

Table 11. Recording force (N) with circuit output (V) increasing

Circuit Output (V)	Force (N)
0.51	0
0.75	4.4
1.70	22.2
2.90	44.4
4.00	65
5.24	88
5.99	102
7.23	125
8.57	150
9.00	150
10.00	150

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From this calibration, the Flexiforce sensor can now measure forces between 0-111 N accurately. This accuracy of the Flexiforce sensor could be acceptable and its accuracy will be evaluated in this study.

5.5 Evaluation of the rehabilitation robot end effector

5.5.1 Aim

The purpose of this consultation was to refine the design and identify areas for further improvement.

5.5.2 Participants

A group of 5 participants was consulted with regards to their satisfaction with rehabilitation robot end effector. Participants were recruited through the authors' personal and professional networks. The focus group ideally take place in the university's buildings where participants feel comfortable and secure with. Before the focus group begins, participants should provide informed consent and where appropriate be informed of compensation procedures.

5.5.3 Method

. Data collected from the literature will be analysed to develop strategic questions for the focus group sessions. These questions, as well as the prototype will be presented to the participants for further advice. A questionnaire was designed to understand the general requirements and suggestions of focus group about the rehabilitation robot end effector. Participants are asked for squeezing the end effector as hard as possible to record the force output as a function of time. Social distancing was considered and we provide PPE gloves for each participant and clean down the end effector between users. The discussion was facilitated by the author using themes and issues that had emerged from the earlier review as a topic guide and recorded using field notes.

Questionnaire:

1. The handle was comfortable to hold?

   Strongly disagree ☐

   Disagree ☐

`

Neutral ☐

Agree ☐

Strongly agree ☐

2. The handgrip feels comfortable when I squeeze it?

Strongly disagree ☐

Disagree ☐

Neutral ☐

Agree ☐

Strongly agree ☐

3. It requires a lot of effort to squeeze the handgrip to the maximum?

Strongly disagree ☐

Disagree ☐

Neutral ☐

Agree ☐

Strongly agree ☐

4. If you have any thoughts or suggestions for a rehabilitation robot end effector, please write down

____

____

____

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5.5.4 Result

Due to the covid-19's restrictions on university lockdown, travel and in-person gathering, the focus group was cancelled. The results of questionnaire are missing in this study and will be put on the future work.

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Chapter 6: Cost analysis of upper limb rehabilitation robot

6.1 Introduction

The cost of cerebral palsy rehabilitation is a huge expense for both society and patients. From 2013 to 2014 in United States, the grand total cost for rehabilitation of cerebral palsy was \$40.1 billion, including \$23.6 billion direct cost and \$16.5 billion indirect cost [101]. Moreover, in the UK, the average medical cost in the first year after diagnosis of cerebral palsy was estimated at £43 billion in 2005. And the cost for rehabilitation of cerebral palsy is estimated \$71.6 billion to \$184.1 billion [101]. Conventional rehabilitation of cerebral palsy suggests that providing sufficient practice for children may improve their motor performance [102]. One potential approach is constraint-induced movement therapy (CIMT) that is a physical treatment aiming to improve arm motor function by performing a large number of repetitions of task-specific training with weaker arm while restraining the stronger arm in a light-weight cast [103].

The economic perspective of the feasibility of home-based rehabilitation robotics has not been extensively analysed. This is an important area to determine if it has the potential to be a cost effective and efficient treatment modality. In this chapter I will focus on this area starting with a review of the literature about the commercial rehabilitation robots available on the market. Clinical robotic-assisted therapy has been demonstrated to be an effective and relatively low-cost therapy compared with traditional clinical intensive therapy [104]. However, a considerable number of children with cerebral palsy may not receive the target rehabilitation due to the inconvenience of travelling to and from hospital and home as well as the limited resources of clinical rehabilitation robots, therapists and rehabilitation centres [105]. Therefore, the demand of low-cost home-based rehabilitation increases rapidly. This chapter aims to identify the cost-effectiveness of home-based rehabilitation robot-assisted therapy from the perspective of society and patients through literature research.

6.2 Current commercial rehabilitation robots on the market

The potential benefits of robot-assisted therapy for the upper limb of people with neurological impairments has led to the development of over 120 rehabilitation robots [16], although only five rehabilitation robots are commercially available, see table 13. In this section I present an analysis of commercially available rehabilitation robots considering functionality and price in order to assess the economic feasibility of the conceptual design I have developed.

Table 12. Price of the rehabilitation robots that is commercially available

Rehabilitation robot name	Figure of the robot	Type	Active degrees of freedom (DOF)	Price (£)
InMotion 2 [18]		End-effector	2 (planar shoulder, elbow arm movements)	64,481
NeReBot [65]		End-effector	3 (planar shoulder, elbow arm movements)	44,242
Mit- Manus [17]		End-effector	2 (planar shoulder, elbow arm movements)	176,050

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ArmeoPower [64]		Exoskeleton	6 (Shoulder – FE, AA, RT; elbow – FE; forearm – PS; wrist – FE)	213,329
ReoGo [67]		End-effector	3 (planar shoulder, elbow arm movements)	68,757

Table 6.1 Price of the rehabilitation robots that is commercially available

Generally, exoskeleton type device is more expensive than end-effector type device, for example ArmeoPower, a exoskeleton device, is about £213K. Besides, the higher the degree of freedom (functionality) of the rehabilitation robot provides, the higher the price will be in commercial market. In addition, clinical-based rehabilitation robot is more expensive than home-based. Table 13 presents the commercial price converted to GBP (at the mean exchange rate in 2017). There are four end-effector types and one exoskeleton type devices on the market, ranging from £64,481 to £213,329.

6.3 Cost analysis of proposed home-based rehabilitation robot design

In this sub-section, a methodology of cost analysis of home-based rehabilitation robot was developed. The total cost for manufacturing is composited of the cost of all resources consumed in the production process, including direct cost and indirect cost (see figure 26). Direct cost is the raw material cost [106]. Indirect cost includes labour cost that people directly participant in production such as the workers in the assemble line and operation applied on the raw materials like welding, machining and cutting. Production overhead consists of indirect materials, indirect labour cost and other indirect manufacturing cost[106].

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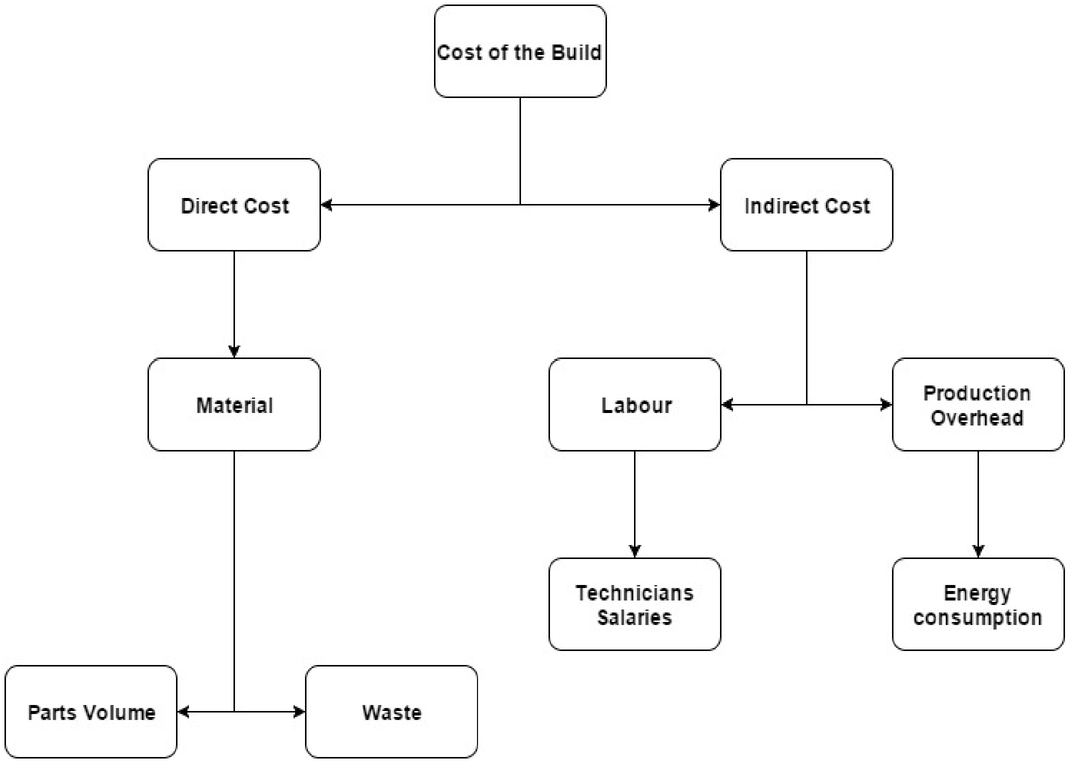

Figure 27. Composition of manufacturing cost of home-based rehabilitation robot

6.3.1 Direct cost of the proposed home-based rehabilitation robot

The table 13 below shows the breakdown of raw materials cost of designed home-based rehabilitation robot. The direct material cost consists of 10 categories, including micro-controller, actuation, power supply, cables, sensors, ball bearings, timing belts, pulleys, plug & socket connectors & components and materials. The total direct cost of proposed home-based rehabilitation robot is £1246.03. The pie chart in Figure 27 indicates that sensors and materials of aluminium and ABS are two most significant components in this proposed home-based rehabilitation robot, accounts for 24.61% and 24.08% respectively, following by actuation (17.34%), pulleys (9.40%), ball bearings (7.03%), micro-controller (6.03%). The percentage of rest categories are power supply (4.36%), cables (2.88%), plug & socket connectors & components (2.32%), timing belts (1.96%).

Table 13. Direct material cost breakdown of this upper limb rehabilitation robot

Category		Unit price £ (GBP)	Amount needed	Total cost £ (GBP)	% of total cost
	10A 5-25V Dual Channel DC Motor Driver	22.55	2	45.10	6.03%

`

Micro-controller	Arduino MEGA 2560 R3 Development Board	29.99	1	29.99	
Actuation	Crouzet DC Geared Motor, Brushed, 12 V dc, 0.5 Nm, 45 rpm, 3 W	85.00	1	85.00	17.34%
	Crouzet DC Geared Motor, Brushed, 12 V dc, 0.5 Nm, 14 rpm, 3 W	93.40	1	93.40	
	CROUZET DC Geared Motor, Ovoid, 3 W, 2.9 rpm, 2 N-m	54.54	1	54.54	
	Crouzet DC Geared Motor, Brushed, 12 V dc, 2 Nm, 7.2 rpm, 3 W	68.18	1	68.18	
Power supply	ENMA 72-10480 Bench Top Power Supply, 0-30V 3A with Single Output	54.29	1	54.29	4.36%
Cables	RS Pro Black, 100m, 2491X PVC Equipment Wire, 0.75 mm² CSA, 750 V 18 AWG	14.31	1	14.31	2.88%
	RS Pro Red, 100m, 2491X PVC Equipment Wire, 0.75 mm² CSA, 750 V 18 AWG	14.31	1	14.31	
	SPP-150, 150mm Insulated Tinned Copper Breadboard Jumper Wire in Black, Blue, Red, White, Yellow	4.37	1	4.37	
	chainflex® CF240 data cable PVC- 5 meter	2.86	1	2.86	
Sensors	Absolute encoder	38.96	4	155.84	24.61%
	Teskcan Flexiforce sensor A301 (pack of 8)	111	1	111	
	Force sensor	9.94	4	39.76	
Ball bearings	SKF (ID: 4mm, OD: 13mm)	3.18	12	38.16	7.03%
	Single Row Radial (ID: 12mm, OD: 28mm)	6.24	8	49.42	
Timing belts	317.5 mm (MXL)	11.85	1	11.85	1.96%
	420 mm (MXL)	12.57	1	12.57	
Pulleys	A80W187	19.53	6	117.18	9.40%

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Plug & Socket Connectors & Components	SAMTEC ISDF-07-D Connector Housing, Dual Row, ISDF Series, Receptacle, 14 Ways, 1.27 mm	0.63	15	9.45	2.32%
	SAMTEC CC03L-2830-01-G Contact, TigerEye™, CC03L Series, Socket, Crimp, 28 AWG, Gold Plated Contacts	0.389	50	19.45	
Materials	Aluminium and ABS	300	1	300	24.08%
Total				1246.03	

The selection of key components, such as actuators, sensors and micro-controllers, etc. are based on the balance of both technical requirements and cost-effective solution. The selection process and criteria are detailed in Chapter 4.

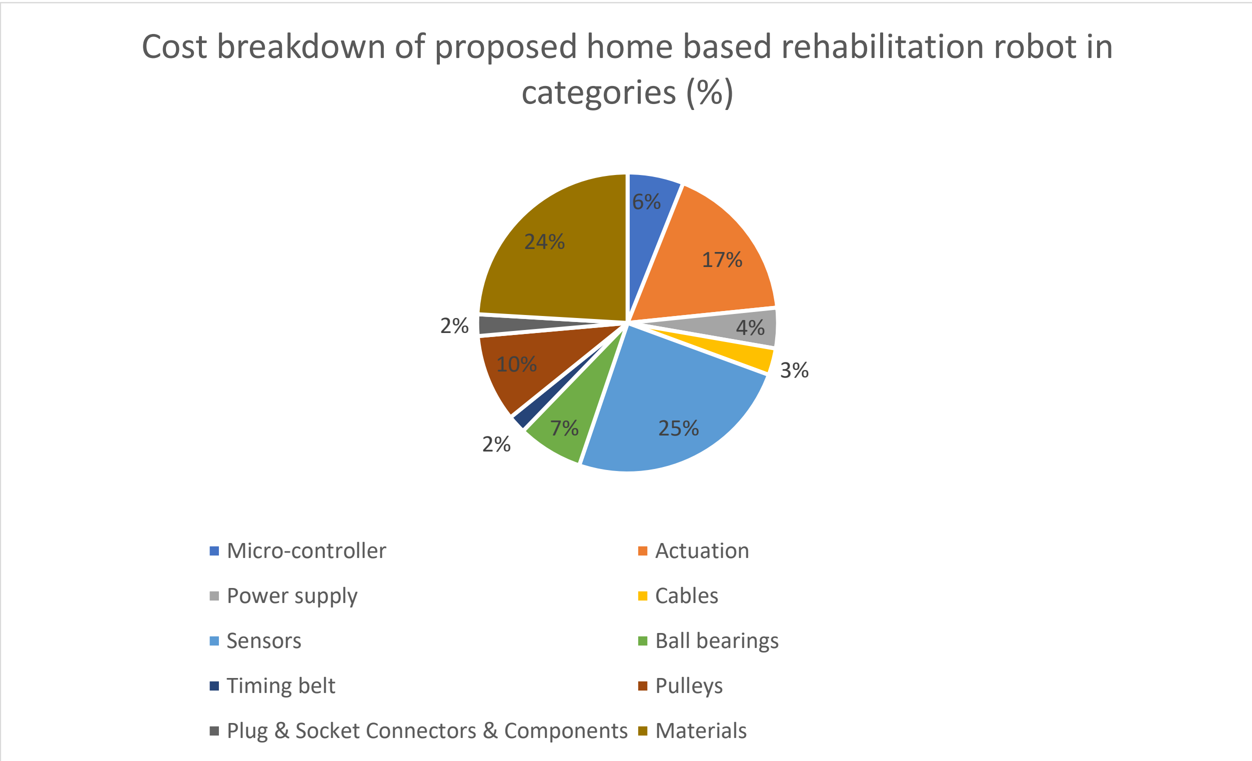

Figure 28. Cost breakdown of proposed home-based rehabilitation robot in categories (%)

6.3.2 Indirect costs associated with the rehabilitation robot

The labour cost represents the estimated costs incurred by the technician executing the manufacturing of the device. As the aim of this research is to develop a cost-effective rehabilitation robot for children with cerebral palsy, a key element is designing for

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manufacture to minimise the assembly costs [107], the next section of this chapter considers this aspect.

Both therapists, representing healthcare providers, and patients want a low-cost device [108], so a strategy is needed to minimise the cost. There are several factors that can reduce the cost of a rehabilitation robot. One of the trends in reducing the cost of rehabilitation robot is additive manufacturing often referred to as 3D printing [109]. In this case, a comparison with traditional manufacturing processes is important, especially for cost comparison.

When comparing costs of producing a part through additive manufacturing and conventional manufacturing, there are several aspects to be considered. The first factor that is varied is the building rate, which is the speed at which the additive manufacturing machine operates. Another factor is the cost. The cost model can be seen in the figure 1 above. The total cost of the build (C) with 3D printing can be split into two categories: direct and indirect cost. From Hopkinson and Dickens cost model, only the material purchase was considered to be a direct cost [110]. The raw material costs are the price ($P_{material}$), measured in GBP per cubic centimetre, multiplied by the volume of entire build in cm^3 (V). The indirect costs are calculated as the total build time (T) multiplied by a cost rate ($P_{indirect}$). The total cost of a build is then represented as:

$$C = P_{material} \times V + P_{indirect} \times T \tag{6-1}$$

Labour and production overhead could be seen as an indirect cost. In this case, labour costs for machine set-up and any required post-processing calculated from technician's annual salary. Production overhead costs incurred due to production, e.g. energy cost. Some cost studies for additive manufacturing, such as Hopkinson and Dickens [110] excluded energy in their reporting, as it contributed less than one percent to the final cost. However, energy consumption is an important factor in considering the cost of additive manufacturing compared to traditional manufacturing. The total required electricity is calculated from the energy consumption rate (1.4 kWh for a 1-hour print). Energy price is taken from reports on average industrial electricity cost in UK. The energy cost (C_{energy}) is represented as

$$C_{energy} = Energy\ price \times Energy\ consumption\ rate \times working\ time \tag{6-2}$$

In additive manufacturing, it contains material that ends up in the final product and wasted material. The wasted material was calculated by the volume of the support material wasted

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over total beds volume. As the volume of support material is varied according to different geometry and printing position of parts. The estimate of material waste is assumed to maximum 20%. The material recycle is not considered in this model.

$$W = \frac{V_{support}}{V_{total}} \tag{6-3}$$

Weight affects the patient's comfort, and the portability and cost of the robot. Therefore, we selected ABS plastic filament as the primary material used for this technology as it is both light weight and has the strength required. The raw material price is £0.35/ cm^3. Table 15 summarizes the costs associated with additive manufacturing.

Table 14. Elements of the unit cost model

Direct cost	Material density	1.05 g/cm^3
	Raw material price	£ 0.35 /cm^3
	Waste factor	0.20 (assumption)
Indirect cost	**Labour cost details**	
	Full annual labour costs	£32,420 /year
	Working days net of holiday	228 days
	Total hours worked per year	1653 h
	Labour cost rate	£19.61 /h
	Production overhead cost details	
	Energy price	8.794 p/kWh
	Energy consumption rate	1.4kW

Seven components of the home-based rehabilitation robot were manufactured by 3D printing when compared with traditional manufacturing. The inclusion criteria of them is difficult to manufacture with traditional method due to their complex geometry. Build time is a significant component in regard to estimating the cost of 3D printing which refers to how long the machine takes for the build. The table 16 below presents a cost breakdown of each 3D printing part. Each component costs 0.33 Labour hours for 3D Printer set up and post-process that contributes to the same labour cost. The total cost of 3D printing estimates £165.37.

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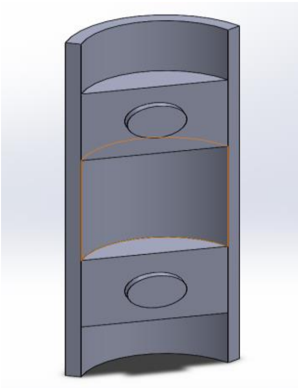
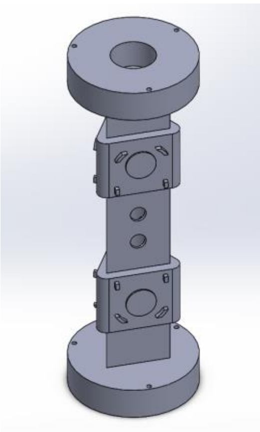
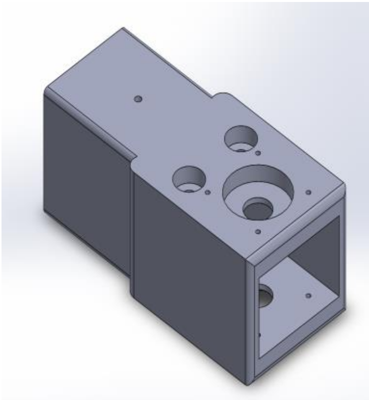
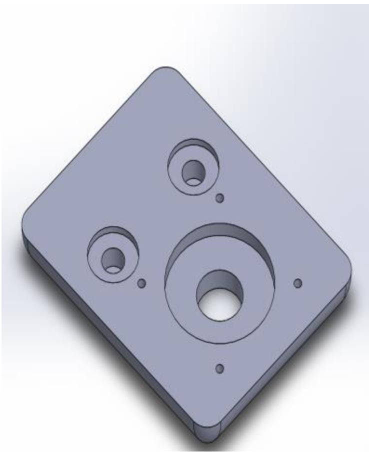
Table 15. Cost breakdown of each 3D printing part

3D printing components	Net build time (hours)	Component material (cm^3)	Support material (cm^3)	Direct cost	Indirect		Total (GBP)
				Material cost (GBP)	Labour cost (GBP)	Energy cost (GBP)	
Shell piece for the handle 	1.01	12.41	2.48	5.21	6.54	0.12	11.87
Handle (main) 	3.37	41.45	8.29	17.41	6.54	0.42	24.36
Pipe connection between handle and handle-base	2.20	27.06	5.41	11.37	6.54	0.27	18.17

							
Joint 	7.81	95.96	19.19	40.30	6.54	0.96	47.80
Cover for joint 	1.29	15.79	3.15	6.63	6.54	0.16	13.33

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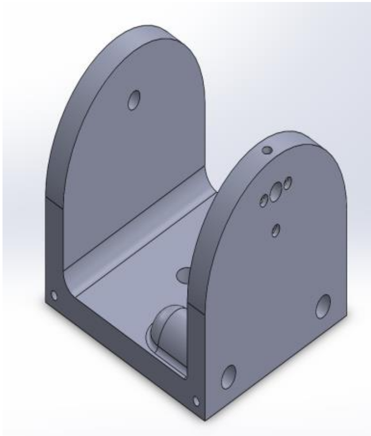
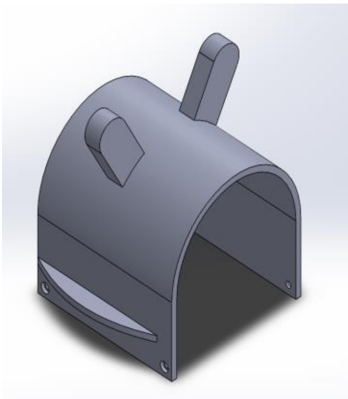
Base structure of handle-arm support sub-system 	4.93	58.85	11.77	24.72	6.54	0.59	31.85
Cover for base structure 	2.16	26.63	5.32	11.18	6.54	0.27	17.99
						Total	165.37

However, there are some parts manufactured by traditional method as their more cost-effectiveness over 3D printing. The reason is that traditional manufacturing are relatively low cost when manufacturing simple geometry and heavy parts, such as shaft and plate. Table 17 below summarizes the cost of parts with traditional manufacturing. The part cost in the table refers to the total cost of materials, manufacturing and energy cost. The total cost of traditional manufacturing for the proposed home-based rehabilitation robot is £269.42.

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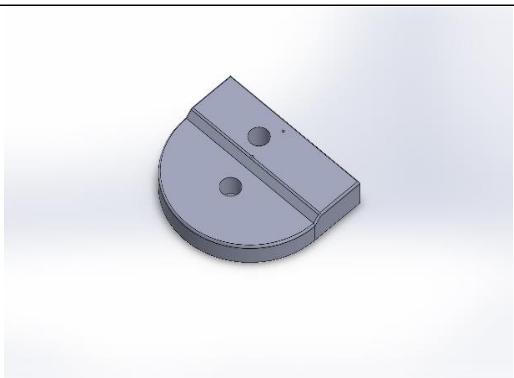
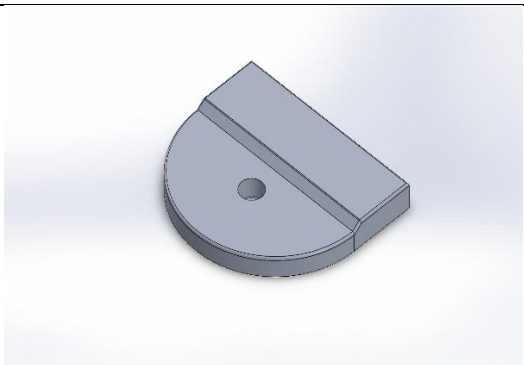
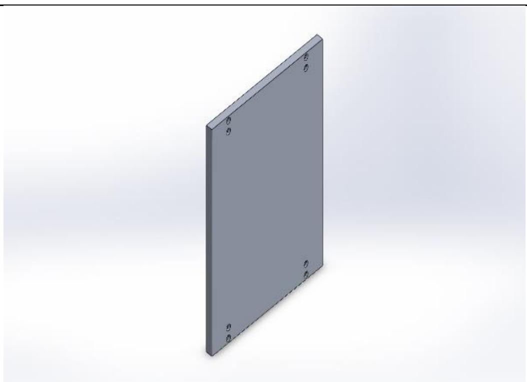
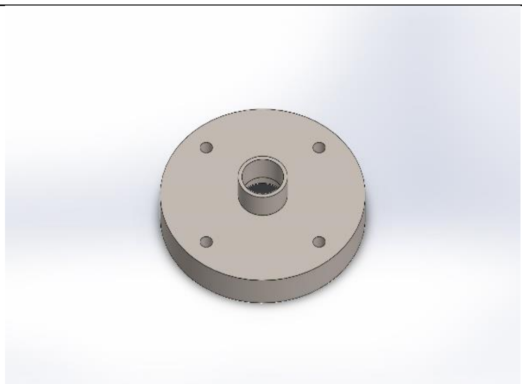
Table 16. Cost breakdown of traditional manufacturing parts

Traditional manufacturing components		Illustration	Quantity	Part cost (GBP)	Total cost (GBP)
Base sub-system	Base (top part)		1	50.41	50.41
	Base (bot part)		1	48.75	48.75
	Base (main)		1	23.00	23.00
	Flange		2	12.05	24.10

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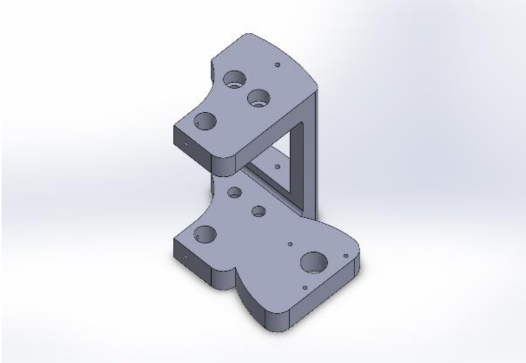
	Shaft		1	10.09	10.09
Joint sub-system	Support structure for motor		1	113.07	113.07
				Total	269.42

6.3.3 Results

Therefore, after combining all costs for manufacturing a home-based upper limb rehabilitation robot, the estimated manufacturing cost is around £1,680 that is much less than most rehabilitation robots on the market. This is only the cost estimation for hardware parts, the total will increase after redesigning and developing the software sections. From the figure 28 below, the direct cost is up to 74% while indirect cost is 26%.

Lu et al [68] conducted an online survey with therapists and asked about how much their hospital would pay for such a robot. All the therapists agreed if the price is around £5000. As the costs of robotic devices not only include the device, but system maintenance, training, and therapist set up time. It could be supposed that most therapists would not choose to use rehabilitation robot unless the costs are dropped dramatically. Therefore, it is necessary to develop a low-cost home-based rehabilitation robot.

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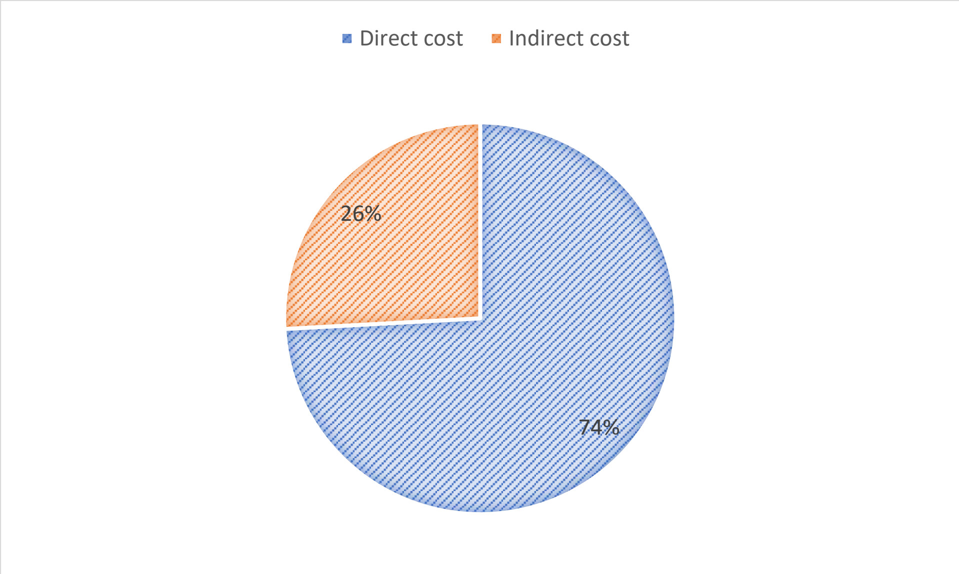

Figure 29. Cost breakdown showing the weight of different activities on the total cost

6.4 Cost comparison between clinical intensive treatment, clinical robot-assisted therapy and home-based robot-assisted therapy

There is evidence that the outcome of robotic-assisted therapy is affected by the number of patients treated in each robotic-assisted therapy session and the time available for the therapist to spend with patients during robotic-assisted therapy sessions [111]. There were 192,000 therapy professionals in UK in 2019, including 62,000 physiotherapists (physical therapists), 51,000 occupational therapists, 19,000 speech and language therapists and 60,000 other therapists [112]. However, the number of cerebral palsy survivors in UK were about 1.2 million, more than 6 times of that of therapy professionals [113]. The huge imbalance between the number of therapy professionals and cerebral palsy survivors has caused a considerable number of patients to fail to receive effective rehabilitation training. In addition, traveling to and from the hospital and home also causes inconvenience for patients and increases in costs and travelling time. Therefore, home-based robotic-assisted therapy is becoming a new trend in cerebral palsy rehabilitation.

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Table 17. Factors impact the cost computations of cerebral palsy rehabilitation

Items	Clinical intensive therapy	Clinical robotic-assisted therapy	Home-based robotic-assisted therapy
Therapists needs	High	Medium	Low
Community service needed	High	Medium	Low
Informal care needed	Low	Low	High
Frequency of patient's travel between home and clinics	High	High	Low
Frequency of therapist's travel to meet patients	High	High	Low
Therapists available time for per patient per week	Low (7.35 hours of physiotherapists; 4.06 hours of occupational therapists) [116]	Medium	Low
General device cost	Not applicable	£64k—213k	Around £5k [68]
Depreciation time	Not applicable	5 years [111]	10 years
Maintenance cost per year	Not applicable	£3.84k-£12.78k (Assumed the depreciation rate is around 6%)	£0.5k (Assumed the depreciation rate is around 10%)
Percentage of people receiving target rehabilitation times	80% [115]	80%	100%
Rehabilitation outcome	Medium	High	High

During the chronic rehabilitation phase, there are many factors impact the total cost of cerebral palsy rehabilitation, including community service, device charges and informal care. For different therapies, these factors have different effects. Table 18 above indicates the detailed factors impact the chronic cost of cerebral palsy rehabilitation in different rehabilitation therapies. For clinical intensive therapy, the cost of therapists, travel and community service take a large portion of total cost; for clinical robotic-assisted therapy, the

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major cost is the robot purchase and maintenance cost. The demand of community services, therapists and travel are low in home-based therapy. In addition, home-based rehabilitation robot has a longer depreciation period due to the relatively low use frequency, which also help more patients receiving more rehabilitation training. The NICE (National Institute for Health and Care Excellence) quality standard stipulates that for adults' patients in the hospital or community, each relevant treatment should last at least 45 minutes, at least 5 days a week [114]. While, only 80% patients can get the target rehabilitation times in clinical settings [115]. Patients choosing the homebased robotic-assisted therapy can guarantee to receive the target rehabilitation times.

The cost comparison between clinical intensive treatment, clinical robot-assisted therapy and home-based robot-assisted therapy that proves the cost-effectiveness of home-based robot-assisted therapy. In the next chapter, a topology optimization method applied to the lightweight design of the rehabilitation robot is presented based on finite element analysis.

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Chapter 7: Mass reduction of prototype home-based rehabilitation robot through topology optimisation

7.1 Introduction

Topology optimisation is a widely used design method for structural design by determining the best distribution of materials within a prescribed design domain to achieve the optimal performance that meets all the design requirements [117]. Due to the high cost and difficulty in manufacturing of complex structure parts [118], most designers prefer taking the lightweight material topology optimization method [119]. Moreover, topology optimization is an ideal design approach in the preliminary design to get the desired structure of the part because it is to seek the suitable material distribution within the optimized area rather than modify the existing part structure [120]. And it is a popular optimal design method that has been widely used in the fields of aerospace, automobile, robot, and so on [121][122].

In this study, lightweight design become a key point in developing a rehabilitation robot, as it has been identified that a key design requirement is for the robot to be low mass so it can be easily manoeuvred in a home environment. Moreover, more lightweight robot components will reduce the burden on actuating motors potentially recuing the cost of the robot and the energy consumption.

In this chapter a topology optimization method applied to the lightweight design of the rehabilitation robot is presented based on finite element analysis. The aim is to identify an optimal mass of the rehabilitation robot whilst ensuring the structural integrity to the expected loading. An additive manufacturing strategy will be utilised to reduce the mass of suitable parts through topology optimisation.

7.2 Methodology

The goal of this chapter is to use topology optimization to improve the original designed components from the preliminary design of rehabilitation robot to achieve a mass reduction. To do this, Solidworks simulation is used to carry out the analysis and topological optimization, which is an Finite Element Analysis add-in produced byBendose [124]. The main rehabilitation robots parts, such as base, joint, links, handle etc. are modelled with Solidworks. The analysis of loading condition was needed before topology optimisation simulation, which is helpful for

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choosing suitable mesh size and the goal of topology study. The selection of mesh size is based on the statistic study result and the computer performance. To guarantee the safety and functionality of this home-based upper limb rehabilitation robotic system, the safety factor and constraint of topology optimisation are set as keeping the best stiffness to weight. After topology optimization, important rehabilitation robot components will be identified through mass reduction when under loading conditions. The iterative optimization process is defined below:

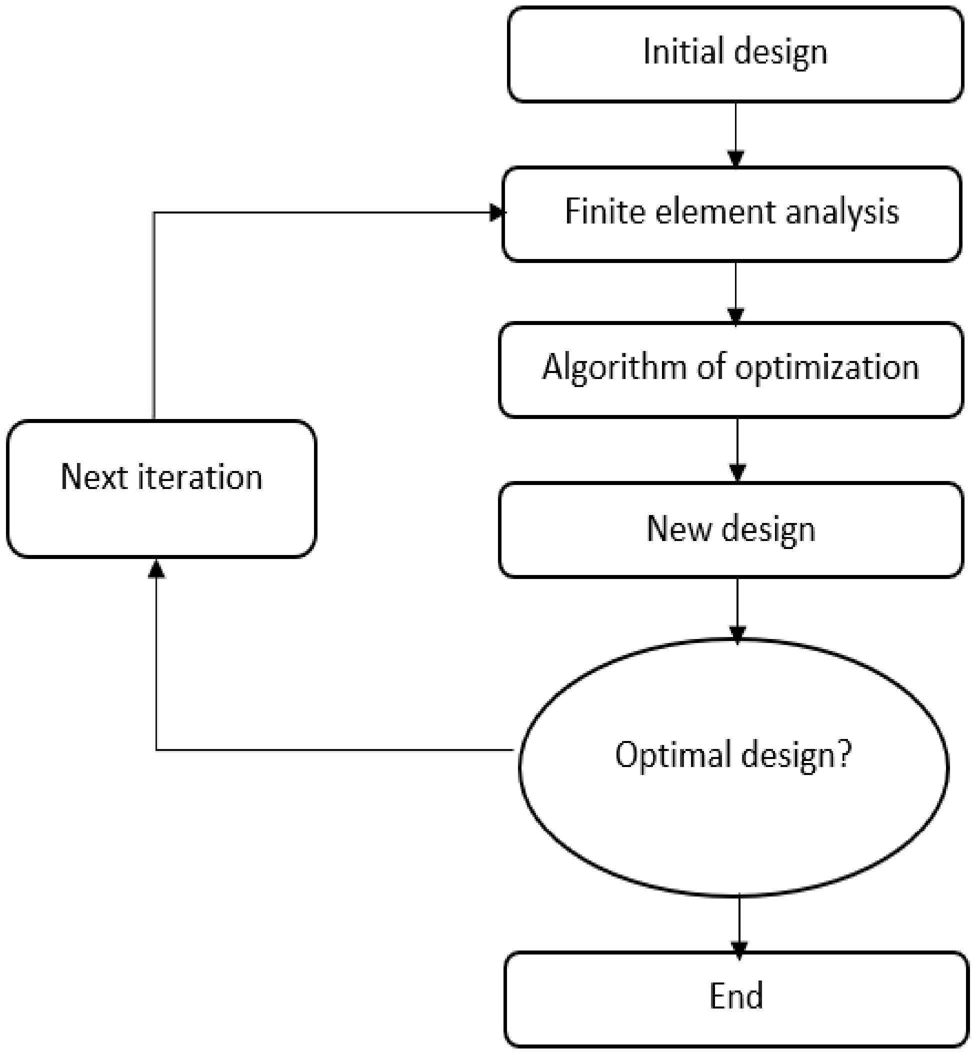

Figure 30. Description of optimization process

The first step to optimization is to model a concept design in Solidworks. This is assimilated by considering the space restrictions surrounding around the existing design as well as

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considering the manufacturing restrictions. The CAD model can then be exported into Simulation add-ins provided by Solidworks for the application of loading conditions. According to the stress and displacement distributions, areas that are supporting little load or not meaningfully playing the role to support the loadings are considered avoidable. Next, a preliminary optimization is operated with minimal shape restrictions. This first optimization is used to minimize the design space and allow for a finer mesh for a second optimization. Once completed, the finalized topology can be exported and generated which adheres to the design rule. Finally, the model is simulated in Solidworks with the same boundary conditions used for optimization. After each separate analysis of sub systems of rehabilitation robots, the optimized mass and original mass is compared showing the mass reduction.

7.3 Mass distribution for the preliminary design of home-based rehabilitation robot

Based on the mechanical structure, the designed home-based rehabilitation robot can be divided in to four sub systems: ‘base’, ‘handle-arm support’, ‘links’, ‘joints’. An overview of the prototype is illustrated below:

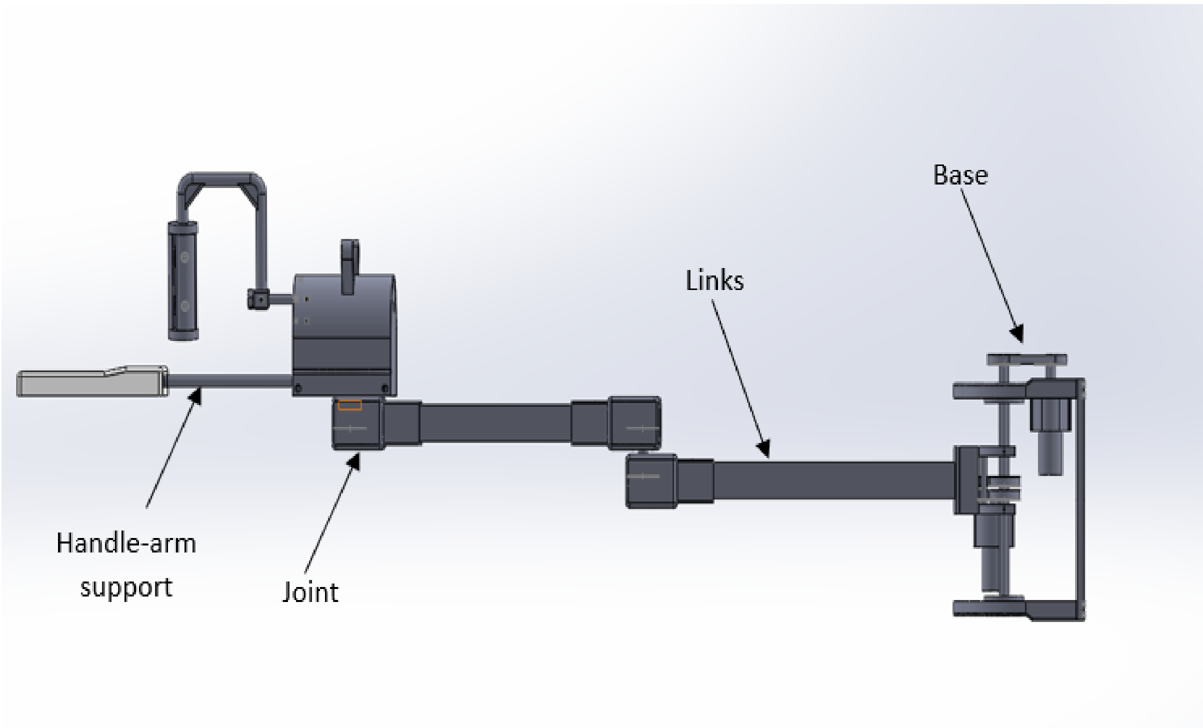

Figure 31. Overview of the rehabilitation robot prototype in Solidworks modelling

According to the Figure 30 above, the base structure is mounted on the table or a fixed horizontal plane that needs to bear the weight of whole rehabilitation robot system. The

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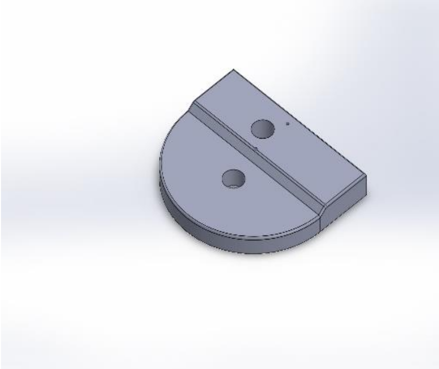
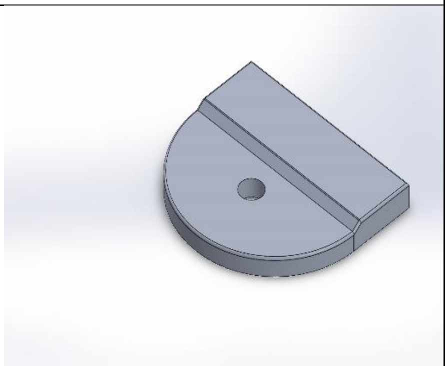
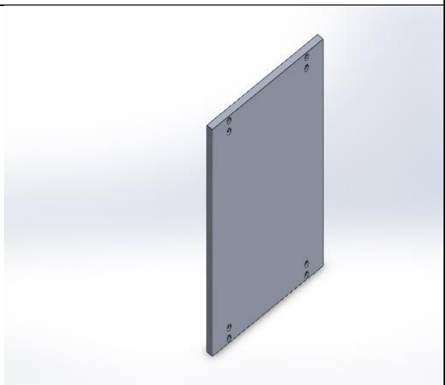
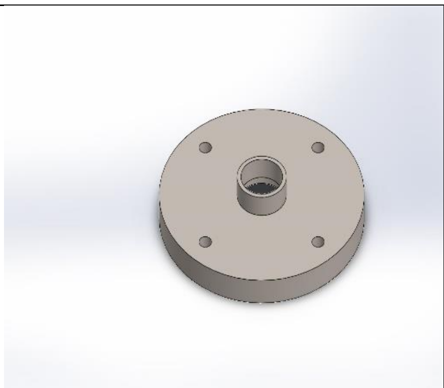
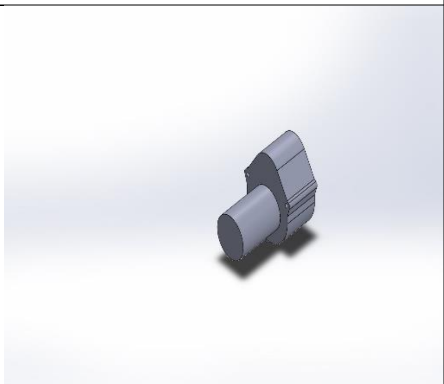
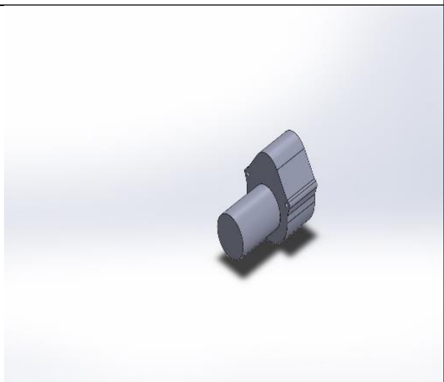
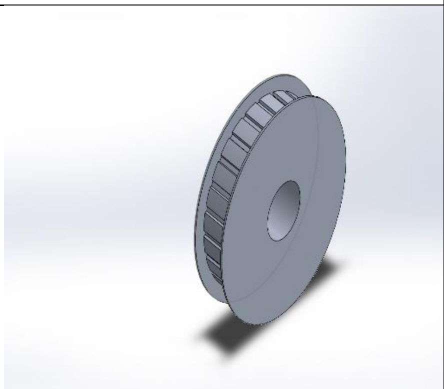
tables below detailed the material, original mass, percentage of total mass of each element in four individual sub system.

Table 18. Mass of key component in base sub system

Component	**Illustration**	**Material**	**Manufacturing method**	**Suitable for optimization**	**Original mass (g)**	**Percentage of total mass in sub system (%)**
Base (top part)		Al alloy	Conventional	Yes	1330.14	26.85
Base (bot part)		Al alloy	Conventional	Yes	1357.58	27.41
Base (main part)		Al alloy	Conventional	No	1344.54	27.15

Flange ×2		Alloy stell	Conventional	No	139.28 (69.64 each)	2.81
Crouzet DC geared motor (82869009)		Mixed motor components	Conventional	No	240	4.85
Crouzet DC geared motor (82869010)		mixed motor components	Conventional	No	239.95	4.85
45 mm driving pulley ×5		Al alloy	Conventional	No	30.03	0.61

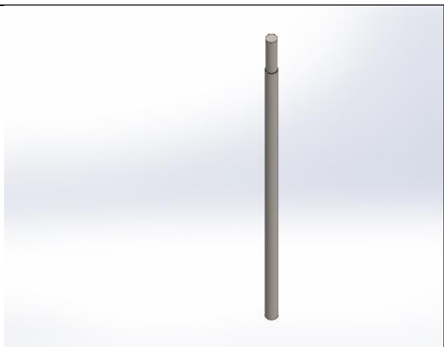
Main shaft		Alloy steel	Conventional	No	271.41	5.48
Total					4953.15	

Table 19. Mass of key component in links sub system

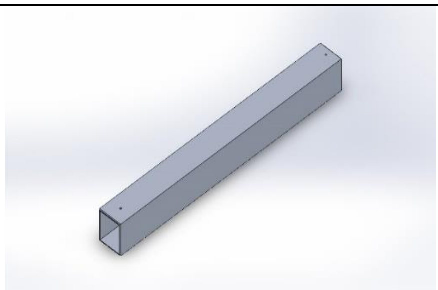
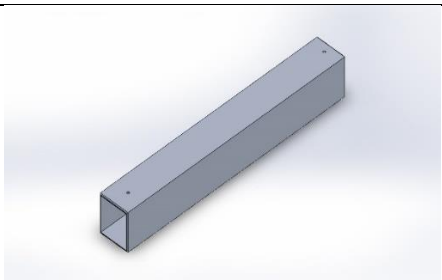
Component	Illustration	Material	Manufacturing method	Suitable for optimization	Original mass (g)	Percentage of total mass in sub system(%)
Aluminum box section (long)		Al alloy	Conventional	No	255.91	57.15
Aluminum box section (short)		Al alloy	Conventional	No	191.86	42.85
Total					447.77	

Table 20. Mass of key component in joint sub system

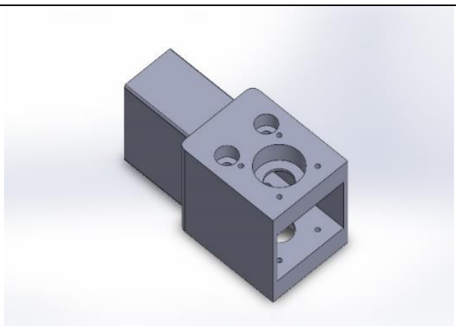
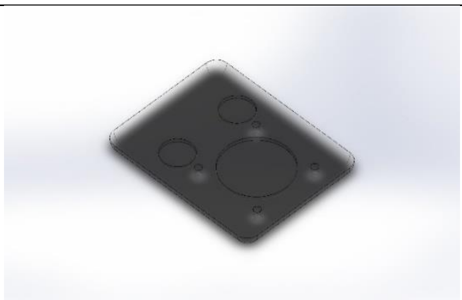
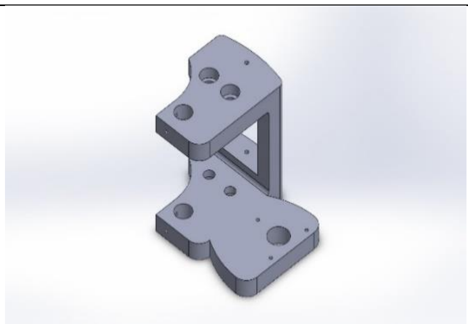
Component	Illustration	Material	Manufacturing method	Suitable for optimization	Original mass (g)	Percentage of total mass in sub system(%)
Joint×3		ABS plastic	3D printing	Yes	241.08 (80.36 each)	18.59%
Cover for joint ×6		ABS plastic	3D printing	No	64.5 (10.75 each)	5.0%
Support structure for motor		Steel alloy	Conventional	Yes	991.50	76.41%
Total					1297.08	

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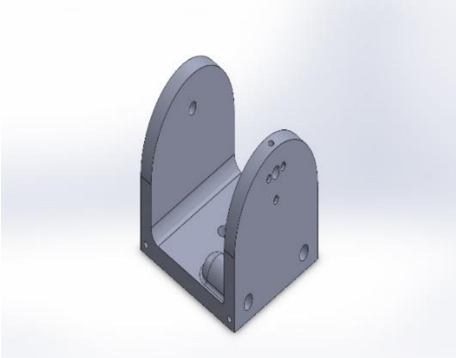
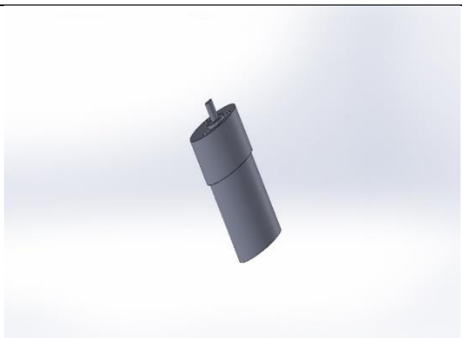
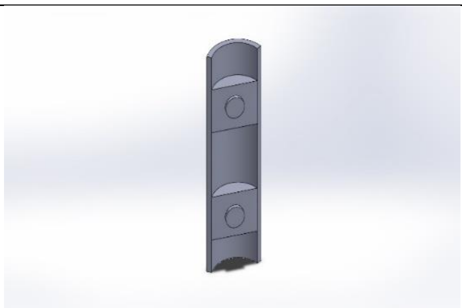
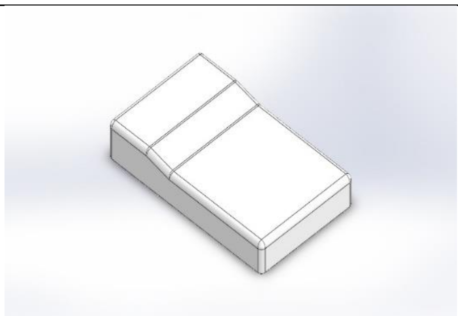
Table 21. Mass of key component in handle-arm support sub system

Component	Illustration	Material	Manufacturing method	Suitable for optimization	Original mass (g)	Percentage of total mass in sub system(%)
Base structure		ABS plastic	3D printing	Yes	630.07	32.27
Crouzet DC geared motor (82862003)		mixed motor components	Conventional	No	120	6.15
Cover for base structure		ABS plastic	3D printing	No	227.67	11.66
Handle connection		ABS plastic	3D printing	No	28.95	1.48

Handle (main part)		ABS plastic	3D printing	No	44.35	2.27
Handle (shell)		ABS plastic	3D printing	No	39.84 (13.28 each)	2.04
Arm support		ABS plastic	3D printing	Yes	640.72	19.16
Link between arm support and base structure		Steel alloy	Conventional	No	487.68 (243.84 each)	24.97
Total					2219.28	

The original mass of the whole rehabilitation robot device is:

$$M_{total} = M_{base} + M_{joint} + M_{links} + M_{handle} = 4952.93g + 447.77g + 1297.08g + 2219.28g = 8917.06g$$

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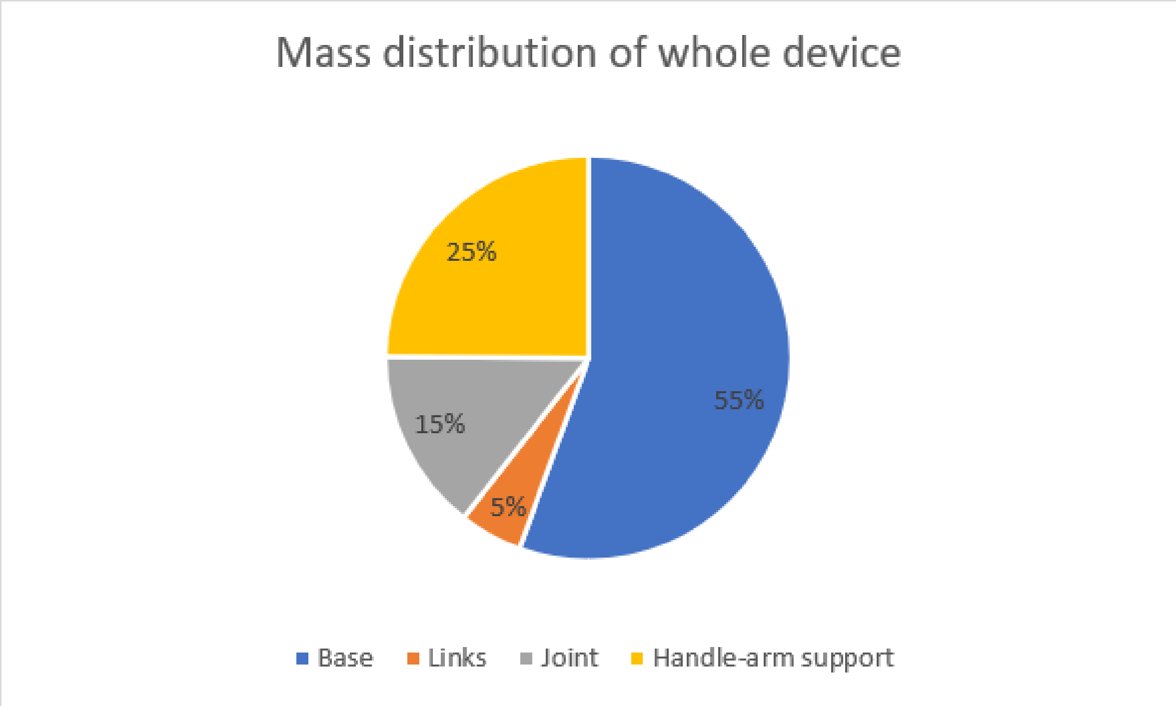


Figure 32. Mass distribution of sub system in the whole device

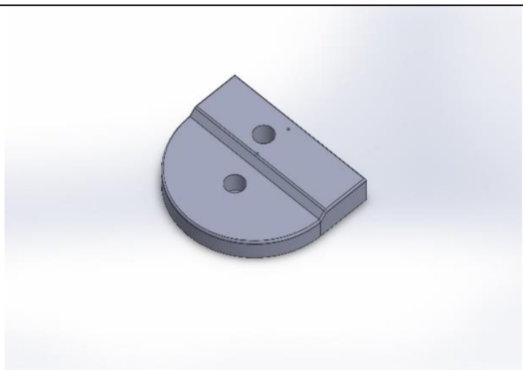
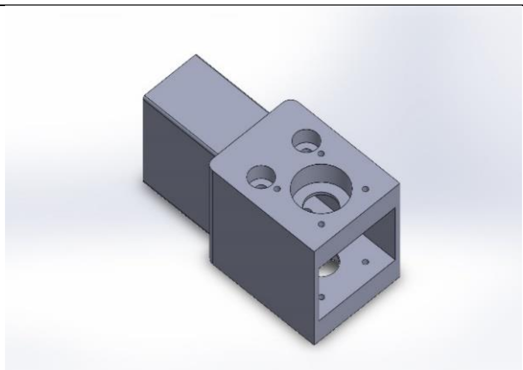
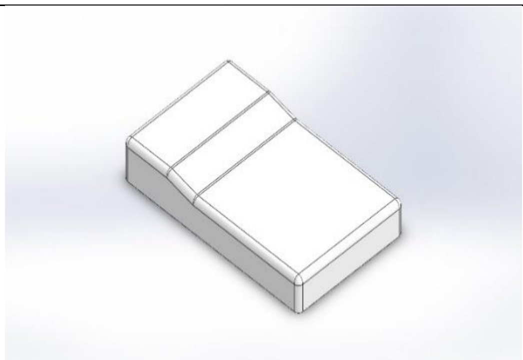
Figure 31 above indicates the original mass of the whole device (8650.75g), the large section is the Base accounting for 55% of the total mass, followed by the handle-arm support (25%), Joint (15%) and links (5%). In order to ensure that the size and quality of the robot are suitable for the home environment, therefore, it is necessary to reduce the mass of the device. The next step is identified which elements will gain from topology optimization, in other word, have most benefit from mass reduction.

7.4 Key components selected for topology optimization

For this rehabilitation robot, the parts that can be optimized are considered having the potential for mass reduction as it is the goal for this topology optimization. Besides, conventional manufactured parts with complex geometry are included for the potential of reducing economic cost. Because if it is conventional manufacture method, then there will be an additional cost associated with optimisation. The more time it takes to manufacture conventional parts the more expensive they will be. Therefore, the optimisation for these parts should be in simple shape and easy to machine to prevent cost increasing.

As a result, the parts selected for this topology optimization are “Base (top part)“, “joint” connection for aluminium box section, ”arm support”, ”support structure for motor”, ”base structure” in handle-arm support subsystem, see in table 23 below. To guarantee the safety and functionality of this home-based upper limb rehabilitation robotic system, the goal and constraint of topology optimisation are set as keeping best stiffness to weight ration and reducing 25% mass of original mass. The mesh size was selected based on the mesh refinement result.

Table 22. Key components selected for topology optimization

Component	Illustration	Manufacturing method	Original mass (g)	Reason for optimization
Base (top part)		Conventional	1330.14	Potential for mass reduction
Joint		3D printing	80.36	complex geometry
Arm support		3D printing	374.19	Potential for mass reduction

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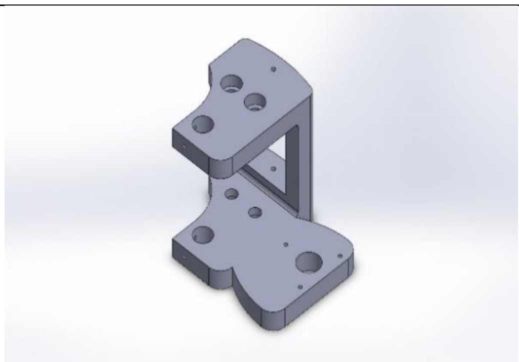
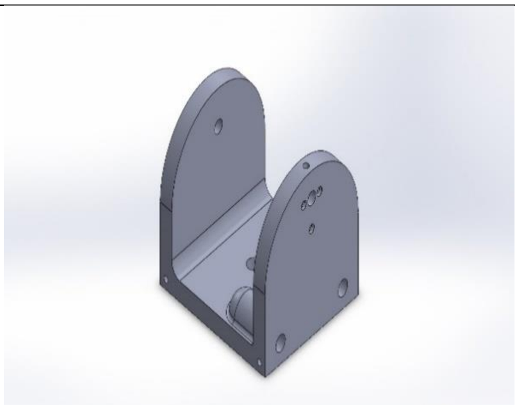
Support structure for motor		Conventional	991.50	complex geometry
Base structure		3D printing	630.07	complex geometry

7.5 Mesh refinement

7.5.1 Static loading condition

Base (top part) was used to find out the suitable mesh size for this computer and assemble due to its simple static loading condition. This part is fixed with Base (main) through bolts. The external loads of this part is gravity only. The value of external load can be calculated through equations below. The loads and constraints are applied in the Solidworks Simulation shown in Figure 32. The red and green arrows represent gravity and fixed area respectively. For the convenience of software calculation, the force was assumed as uniform distribution on the top surface.

$$F_{gravity} = m_{base\ (top\ part)} \times g = 1.33 \times 9.81 = 13.05N \quad (7\text{-}1)$$

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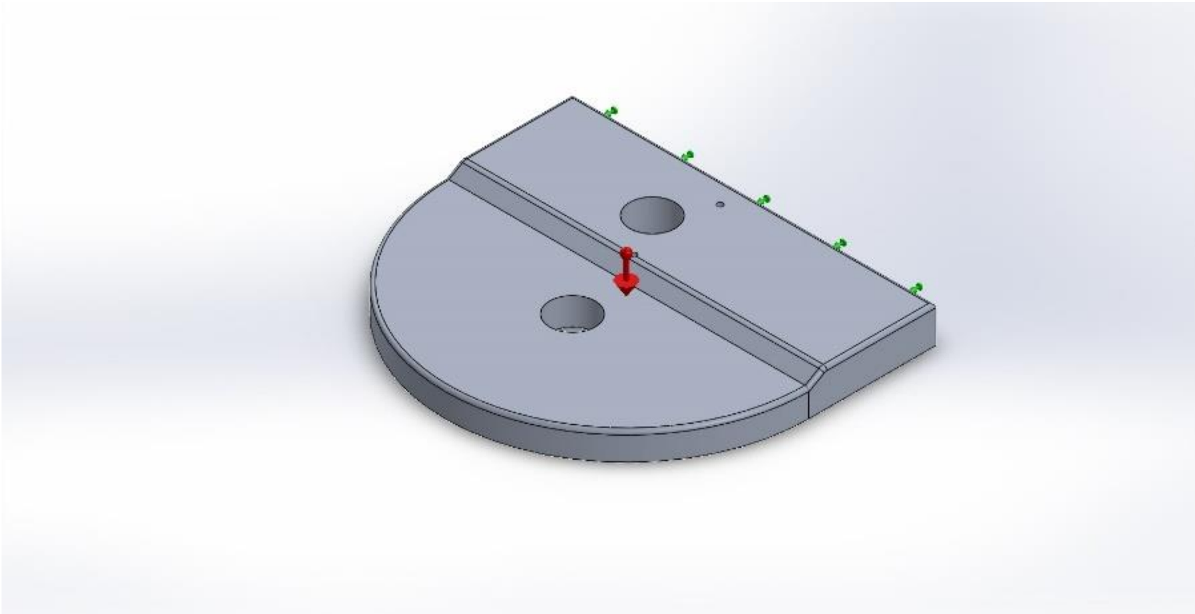

Figure 33. Static loading condition of base (top part)

7.5.2 Mesh refinement simulation results

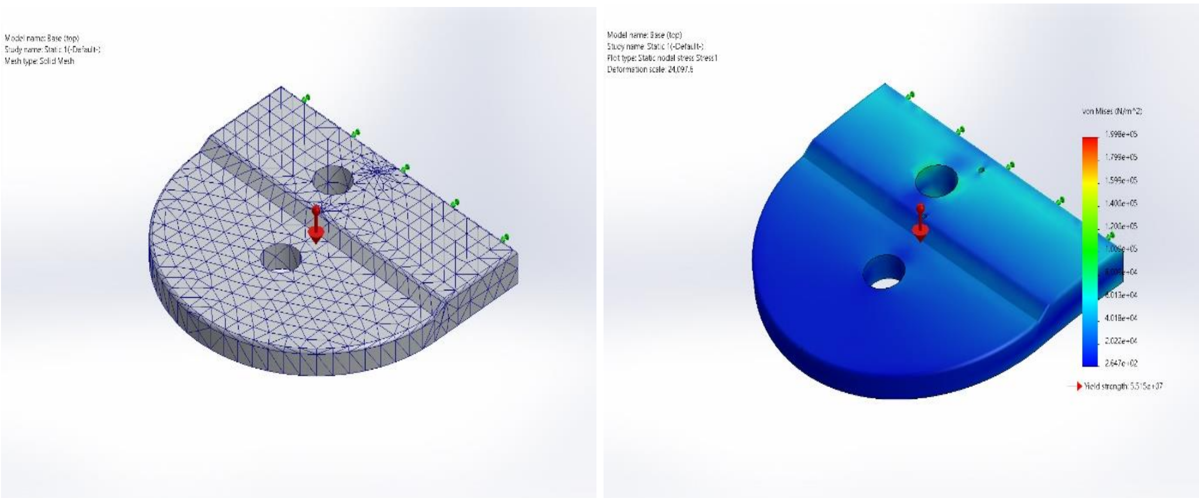

Figure 34. Left, 10 mm mesh size of selected part. Right, Statistic result in 10 mm mesh size.

The table 24 below indicates the mesh refinement simulation results that were produced through 11 statistic studies in SolidWorks. The initial mesh size was determined as 10 mm (see Figure 33) when considered the geometry of selected part. The mesh size varied from 10mm to 2.5mm; number of element varied from 6303 to 200,198; result of maximum stress applied on the component varied from 1.998e+05N/m2 to 1.231e+05N/m2 ; most studies were in fine mesh density and few studies in medium mesh density.

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Table 23. Statistic study result with various mesh size

Mesh size (mm)	Total elements	Elapsed time	Statistic result (N/m^2)
10	6303	0''	1.998e+05
7	13487	1''	1.962e+05
6	19779	1''	2.036e+05
5	30412	2''	2.061e+05
4.5	42635	2''	2.030e+05
4	53495	3''	2.106e+05
3.5	79837	4''	2.095e+05
3.25	100683	6''	2.114e+05
3	121704	6''	1.203e+05
2.75	160004	8''	1.157e+05
2.5	200198	11''	1.231e+05

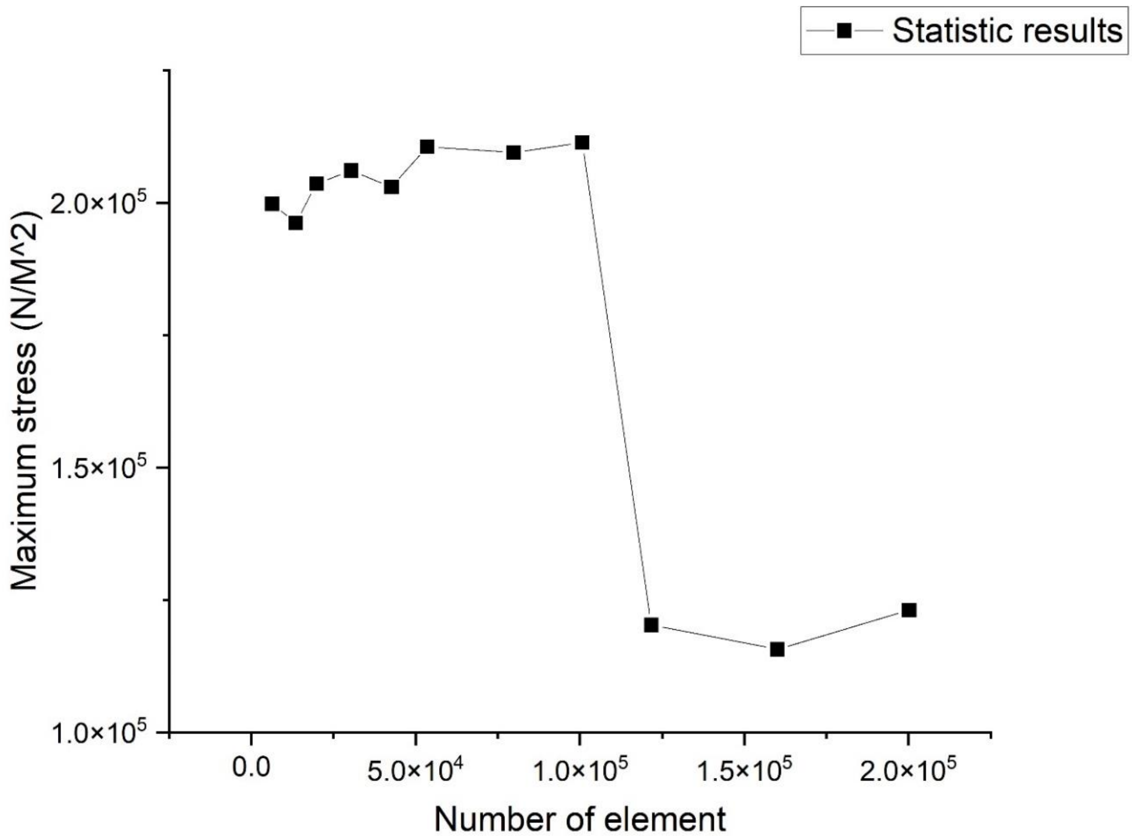

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Figure 35. Maximum stress with different mesh size for the selected part

In the typical mesh refinement study, result error initially decreases as the mesh size decreases, and then stabilizes. When the mesh is too small, the error will become large as the grid is refined. From Figure 34 indicates there is a huge drop of simulation result at 3.25mm mesh size, and then stabled between 1.203×$10^5 N/m^2$ to 1.231×$10^5 N/m^2$. Within this stress range, the simulated mesh size varies from 2.5mm to 3mm. Due to the solving efficiency is based on the mesh refinement and computer performance, the 3mm mesh size was selected for this research according to computer condition and accuracy of statistic study result.

For my rehabilitation robot, parts that can be optimized are “Base (top part)“, “joint” connection for aluminium box section, ”arm support”, ”support structure for motor”, ”base structure”. To guarantee the safety and functionality of this home-based upper limb rehabilitation robotic system, the goal and constraint of topology optimisation are set as keeping best stiffness to weight ration and reducing 25% mass of original mass. The mesh size was selected as 3mm based on the mesh refinement results.

7.6 Topology optimisation

7.6.1 Base (top part)

As mentioned before, by applying the loads and boundary conditions, the topology optimisation was developed by Solidworks. The initial simulation result of base (top part) by reducing 25% mass of original mass is shown below (figure 35).

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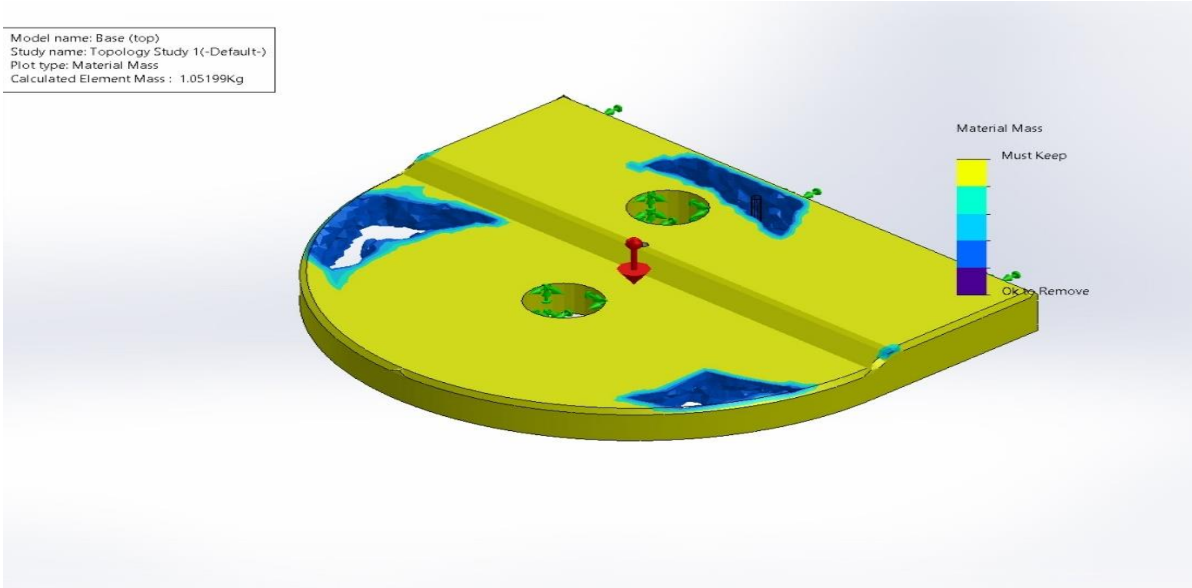

Figure 36. Initial topology optimisation simulation result of base (top part)

As the material of this part is aluminium alloy, and it is manufactured by conventional manufacturing method, machining. To prevent cost increasing and keep the geometry boundary, simple machining is considered to improve the part. The final design is shown below Figure 36. After topology optimisation, the mass will reduce to 1139.13g (previous 1330.14g) and maximum stress will increase from to 1.203e+05$\mathrm{N/m^2}$ to 1.408e+05 $\mathrm{N/m^2}$. Although the maximum stress increased, it still below the yield strength, 5.515e+07 $\mathrm{N/m^2}$.

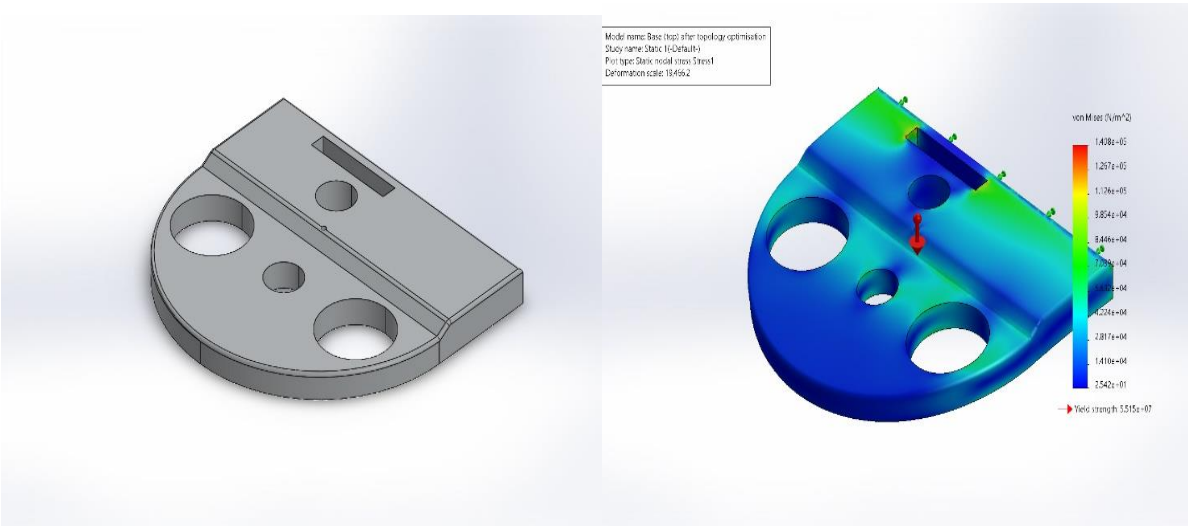

Figure 37. Final design of base (top part) and statistic simulation result after topology optimisation

7.6.2 Arm support

Similar topology optimisation simulation process was developed on “arm support” part. This part is fixed with “base structure” in “handle-arm support” sub-system by two steel alloy bars,

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that can be seen from figure 30. The external loads of this parts are gravity and the weight of user's arm. From figure 37, purple arrow is external load that was assumed as uniform distribution on top surface, green arrow is fixed area and red arrow is the gravity of arm support. The user's forearm weight can be calculated based on the Zatsiorsky's study [8]. The body segment mass can be calculated by the equation:

$$m_{body\ segment\ mass} = B_0 + B_1 \times M_{body\ weight} + B_2 \times H_{body\ height} \quad (7\text{-}2)$$

and the whole upper limb weight is

$$m_{upper\ limb} = m_{forearm} + m_{hand} + m_{upper\ arm} \quad (7\text{-}3)$$

Considered the weight of children's arm and safety factor, the force is set as 20N.

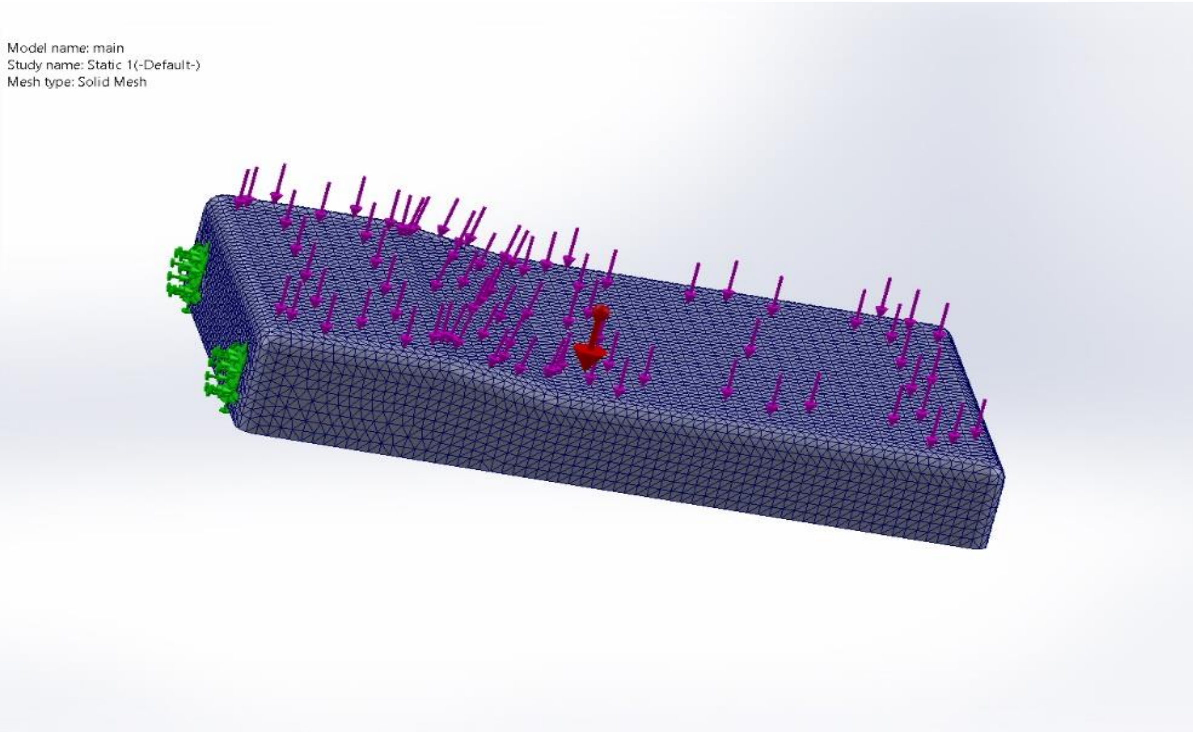

Figure 38. Loading condition and mesh illustration of arm support

The statistic simulation result before topology optimisation is shown below (Figure 38), the mesh size is 3mm. The maximum stress is 4.048 e+07 $\mathrm{N/m^2}$ and the original mass is 640.72g.

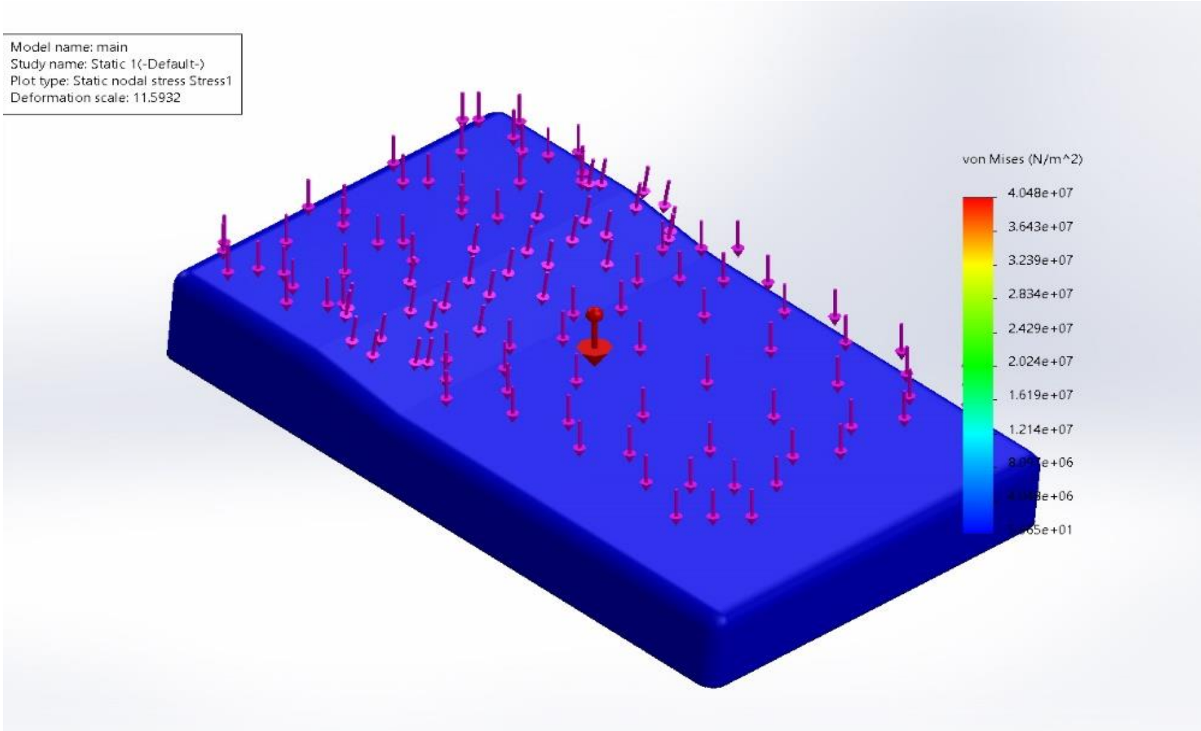

Figure 39. Maximum stress before topology optimisation

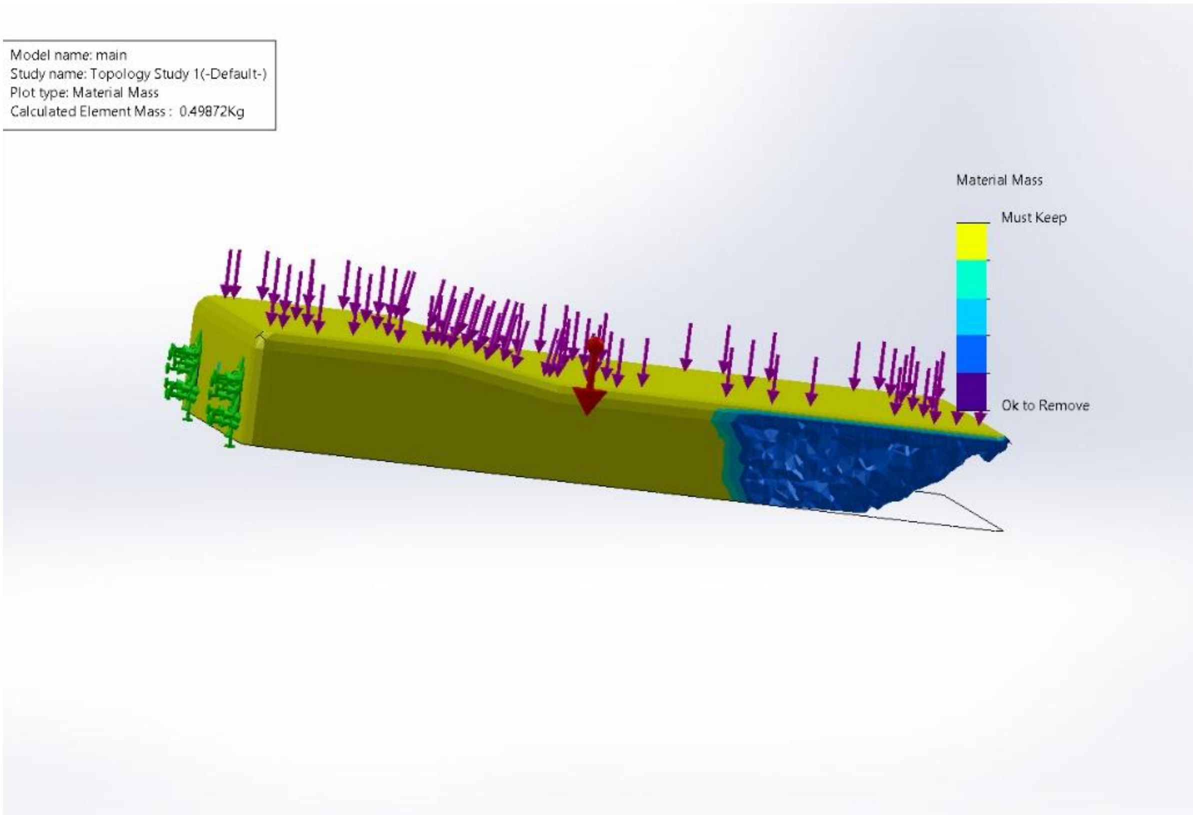

Figure 40. Initial topology optimisation of arm support

The arm support was manufactured by 3D printing method, therefore, the goal of mass reduction is not related to complex geometry. After topology optimisation, the mass will reduce to 543.01g and maximum stress will reduce from 4.048 e+07 $\mathrm{N/m^2}$ to 2.399 e+07 $\mathrm{N/m^2}$ (Figure 7.40).

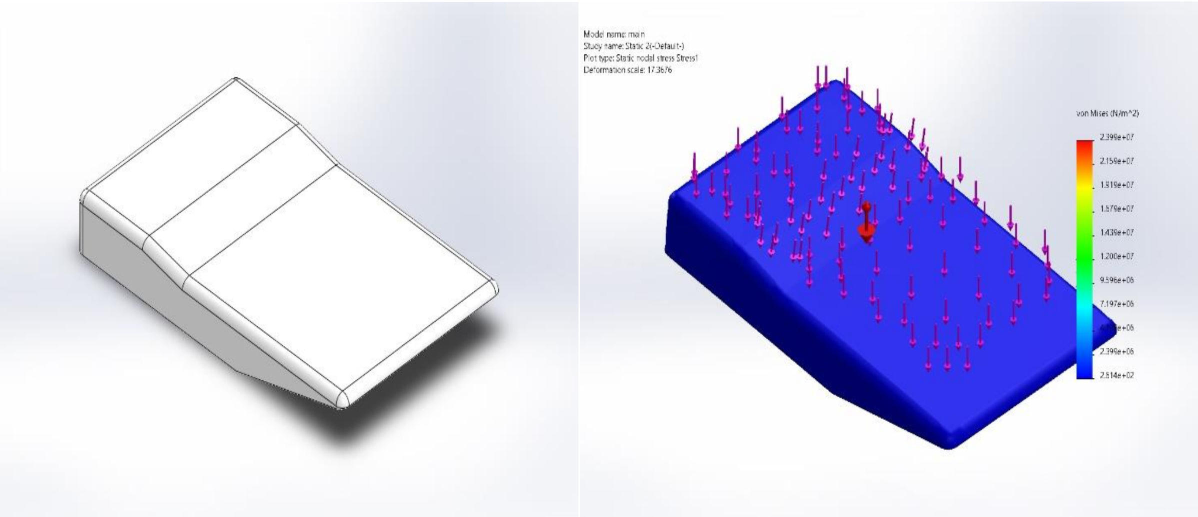

Figure 41. Final design of arm support and statistic simulation result after topology optimisation

7.6.3 Joint

Joint is a 3D printing component that connect to aluminum box section through bolts and on the one side. On the other side, two joints are connect together through shaft and bearings. The loads applied on joints are gravity, bearing load from bearing and motor rotation (5.4N) and force from other components and user's arm (140N), see Figure 41.

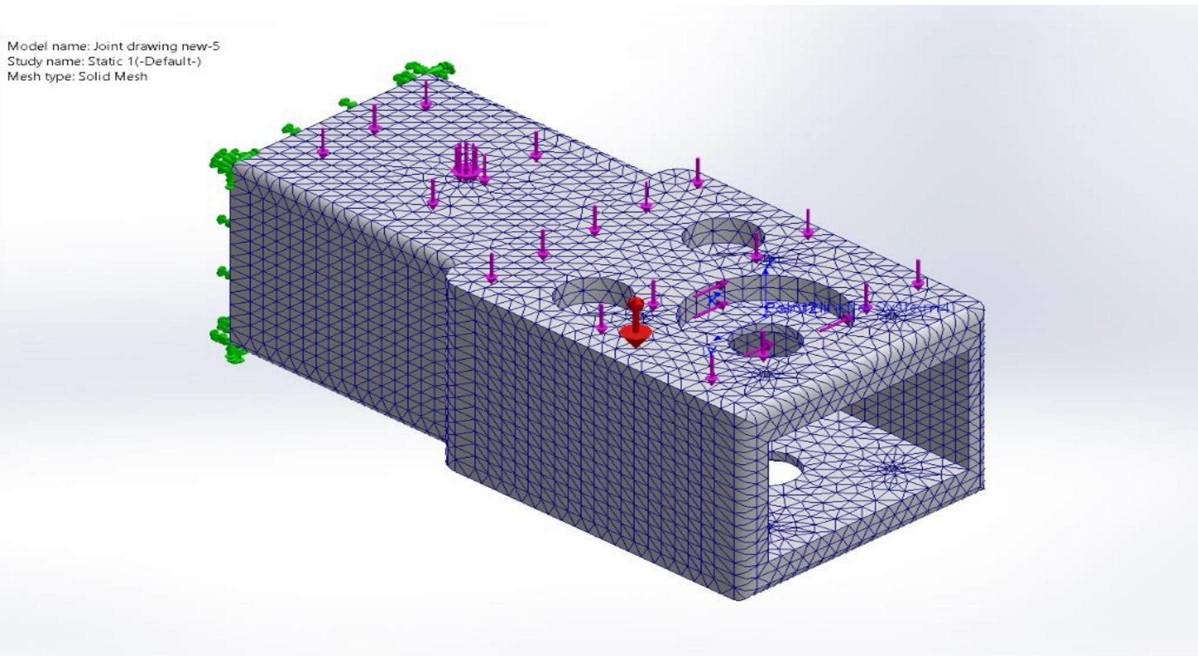

Figure 42. Loading condition and mesh illustration of Joint

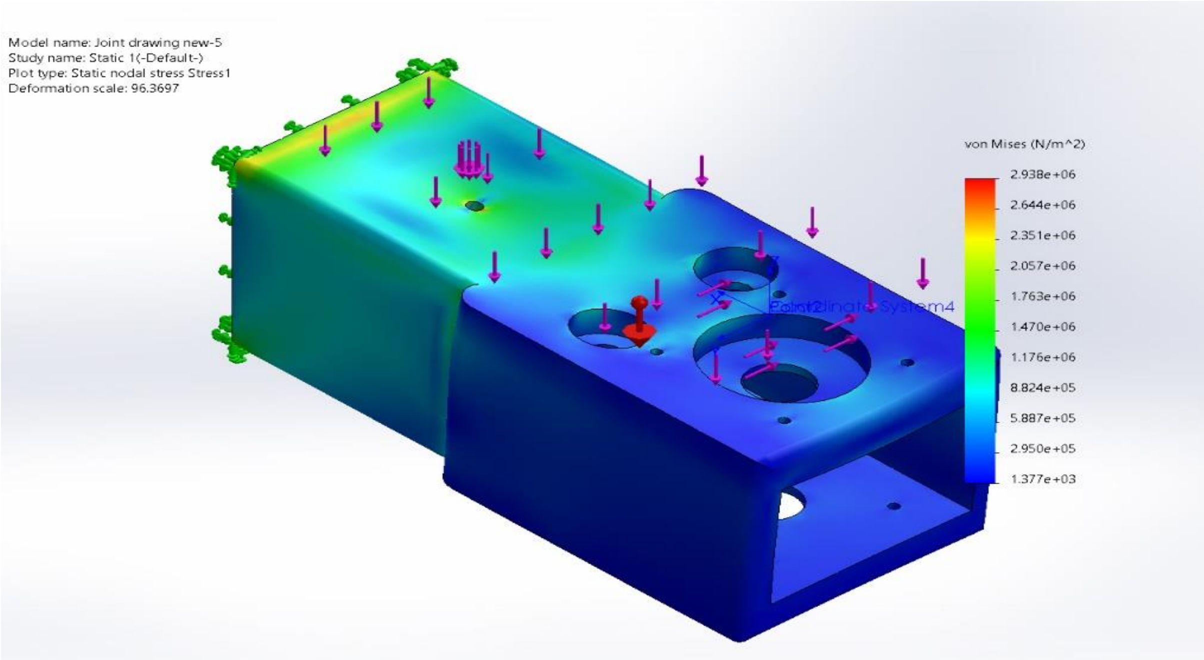

Figure 43. Maximum stress before topology optimisation

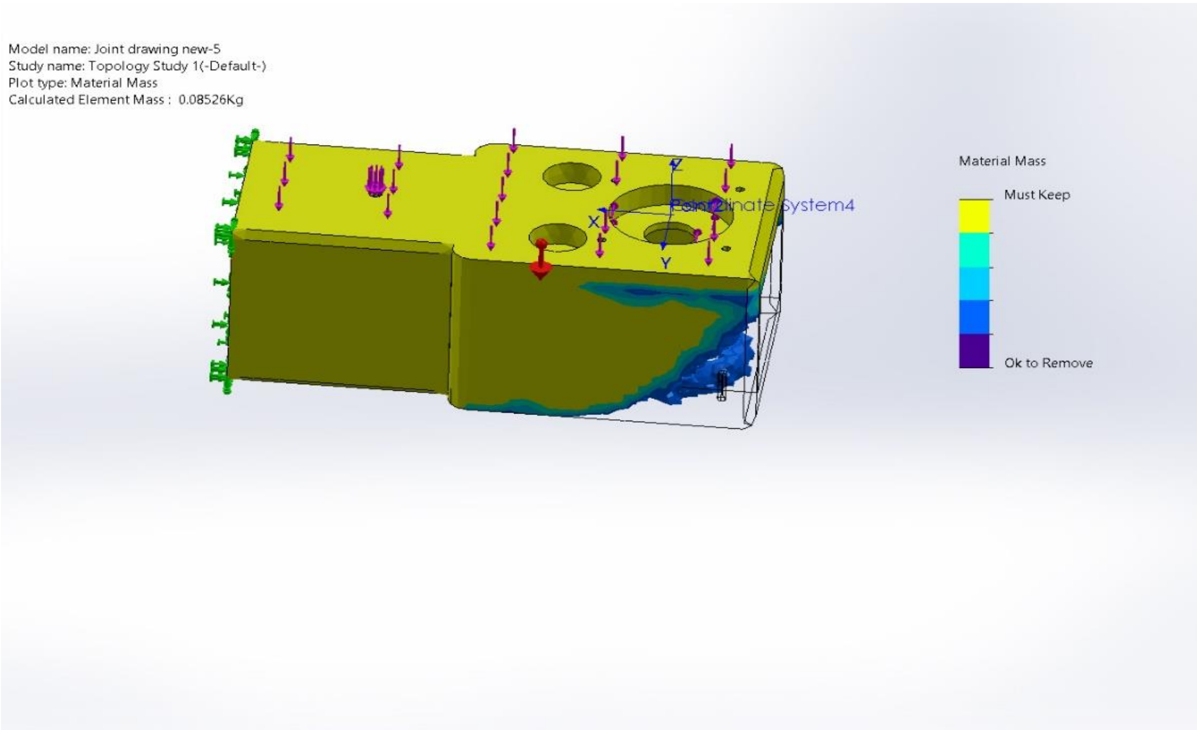

Figure 44. Initial topology optimisation simulation result of joint

By considering the maximum stress and topology optimisation simulation result and geometry of joint, it is impossible to achieve the goal of topology optimisation by reducing 25% mass of original mass while keeping the functionality of this component.

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7.6.4 Support structure for motor

"Support structure for motor" is a key component in the "base" sub-system. On the one hand, it connects to one motor with bolts. On the other hand, it is the connection between "link" and "base" sub-system. The external load of this part is gravity, load from motor (2.35N) and force from user's arm and other components (100N). From Figure 44, the maximum stress is 3.371e+06 $\mathrm{N/m^2}$, the yield strength is 6.204e+08 $\mathrm{N/m^2}$ and the original mass is 991.50g.

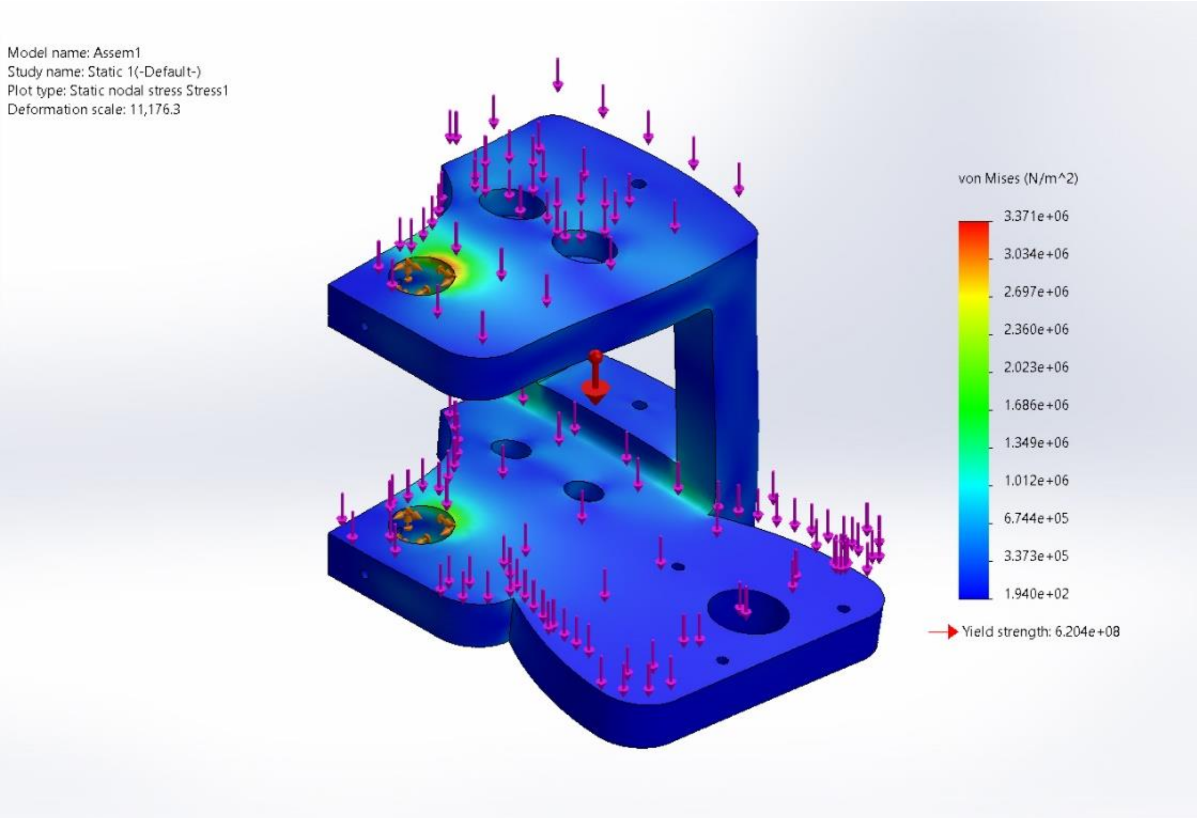

Figure 45. Loading condition and maximum stress before topology optimisation

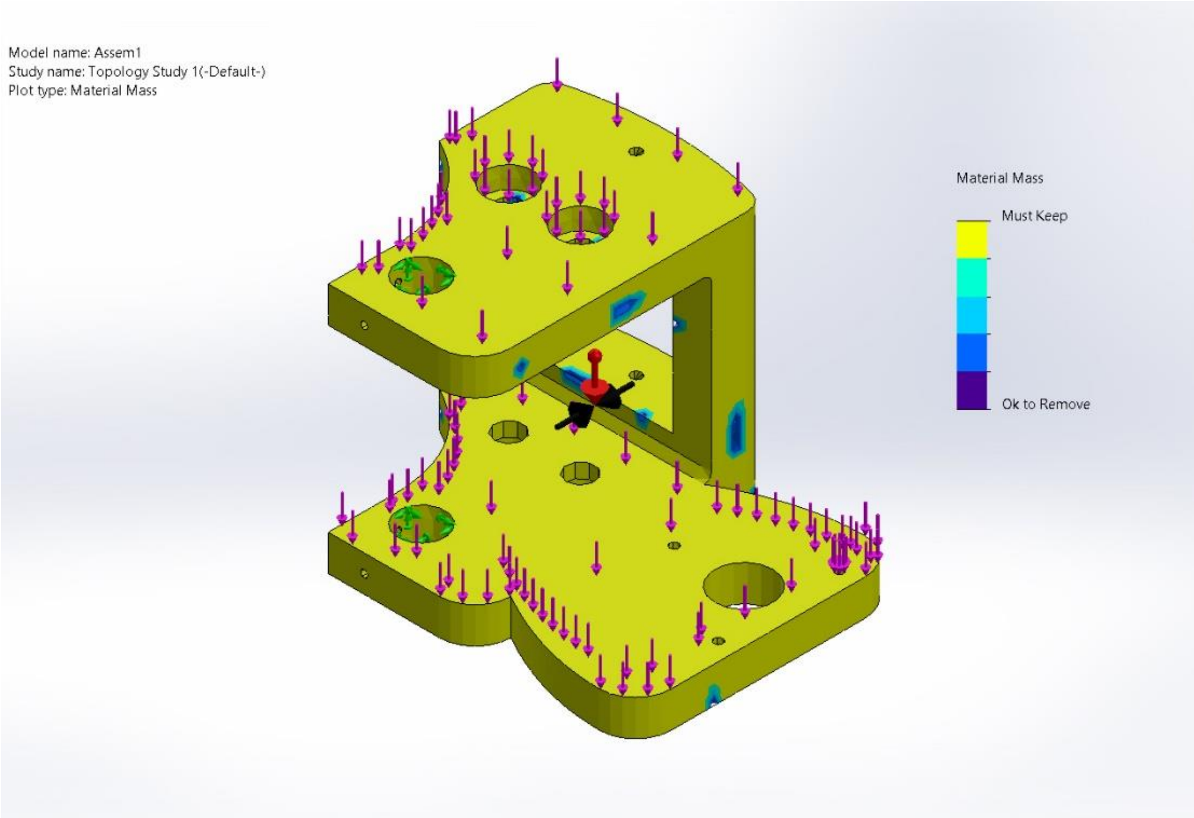

Figure 46. Initial topology optimisation simulation result of support structure for motor

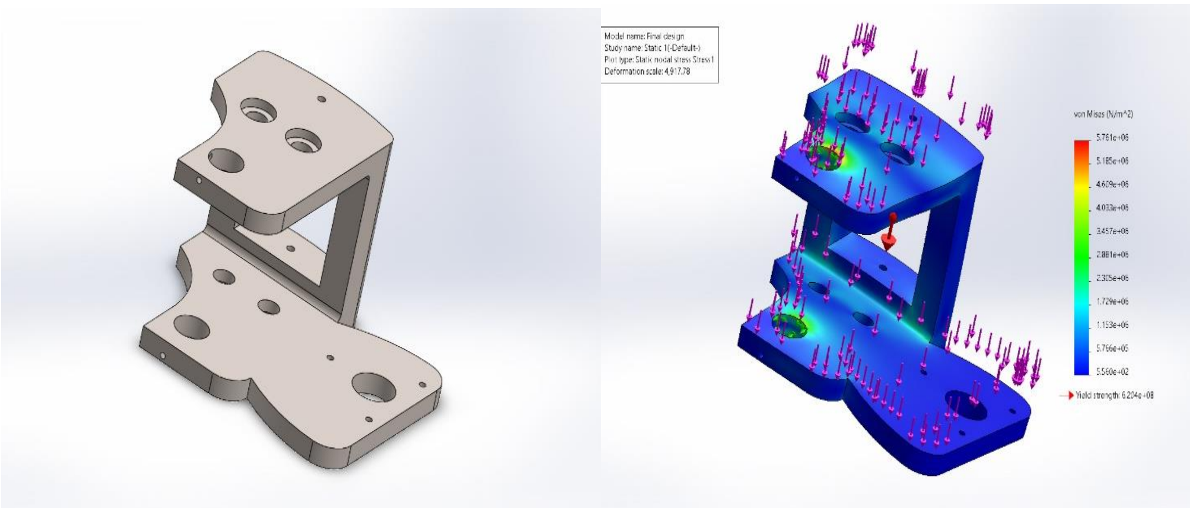

Figure 47. Final design of support structure for motor and statistic simulation result after topology optimization

As the material of components is steel alloy and manufactured by conventional manufacturing method, the more complex the geometry the bigger the costs it is in manufacturing. From the topology optimisation simulation result (Figure 45), the mass reduction of this component is achieved by reducing the thickness of walls. In the final design (Figure 46), the walls are reduced from 10mm to 7mm and the maximum stress is 5.761e+06 $\mathrm{N/m^2}$ in statistic simulation result. After topology optimisation, although the maximum stress increasing from 3.371e+06 $\mathrm{N/m^2}$ to 5.761e+06 $\mathrm{N/m^2}$, it is still below the yield strength 6.204e+08 $\mathrm{N/m^2}$. As the result, the mass reduced from 991.50g to 753.22g.

7.6.5 Base structure

The "base structure" is basically in the "handle-arm support" sub-system. It connected with arm support by two alloy steel bars. On the bottom of base structure, it connects with joint by shaft and bearings. The loading condition of this component are force from user's arm and arm support (20N), its gravity and other components, motor (1.18N) and cover for base structure (2.23N), see Figure 47. The maximum stress of the part before topology optimisation is 2.194e+04 $\mathrm{N/m^2}$.

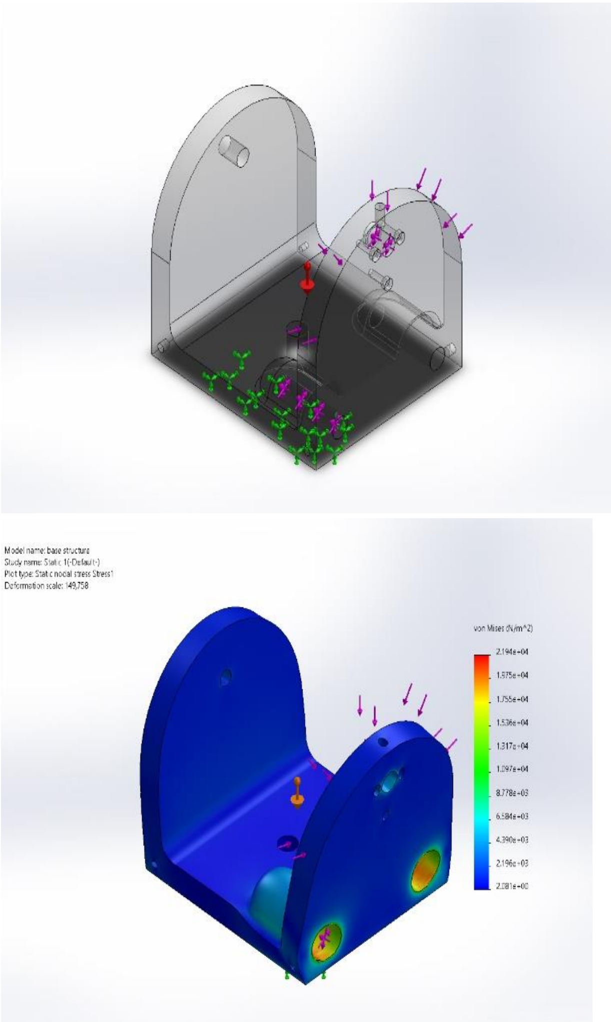

Figure 48. Statistic loading condition and maximum stress of part before topology optimisation

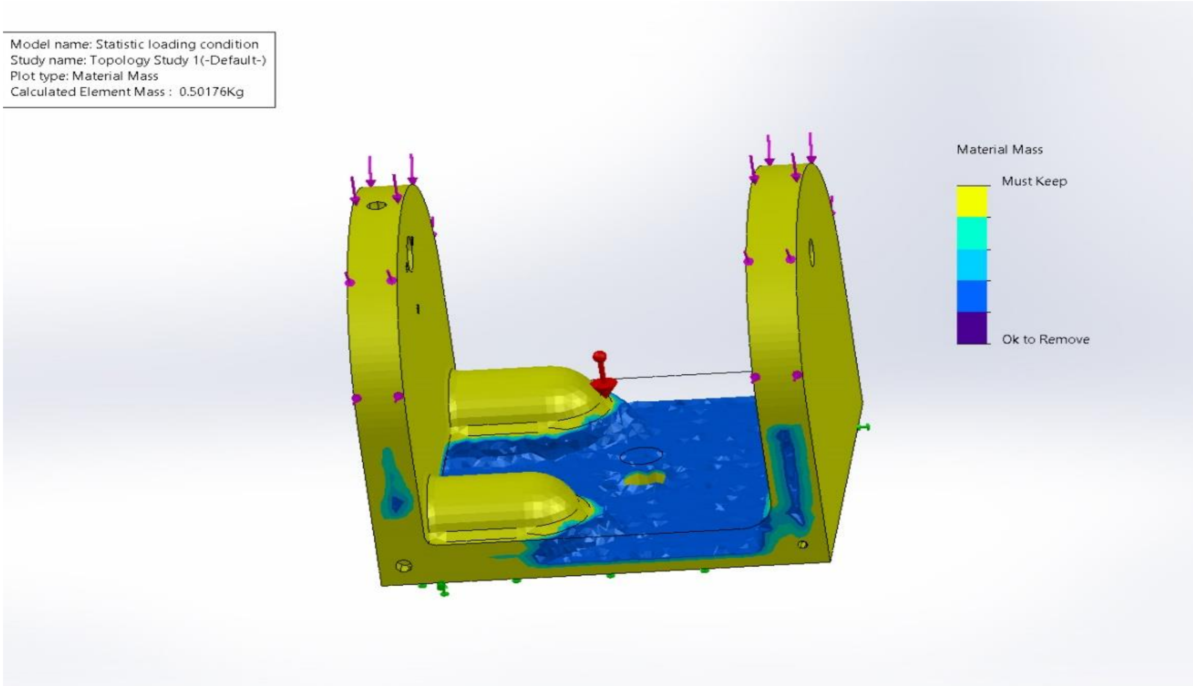

Figure 49. Initial topology optimisation simulation result of base structure

From the topology optimisation simulation result (Figure 48), this component will reduce mass by removing some bottom part and decreasing the thickness of side wall. In the final design, the thickness of side wall and bottom part were reduced 4mm and 7.5mm respectively. That results the mass reduced from 630.07g to 511.18g. The statistic simulation result for the final design is shown below, Figure 49. As the result, the maximum stress increased from 2.194+04 $\mathrm{N/m^2}$ to 2.238+04 $\mathrm{N/m^2}$.

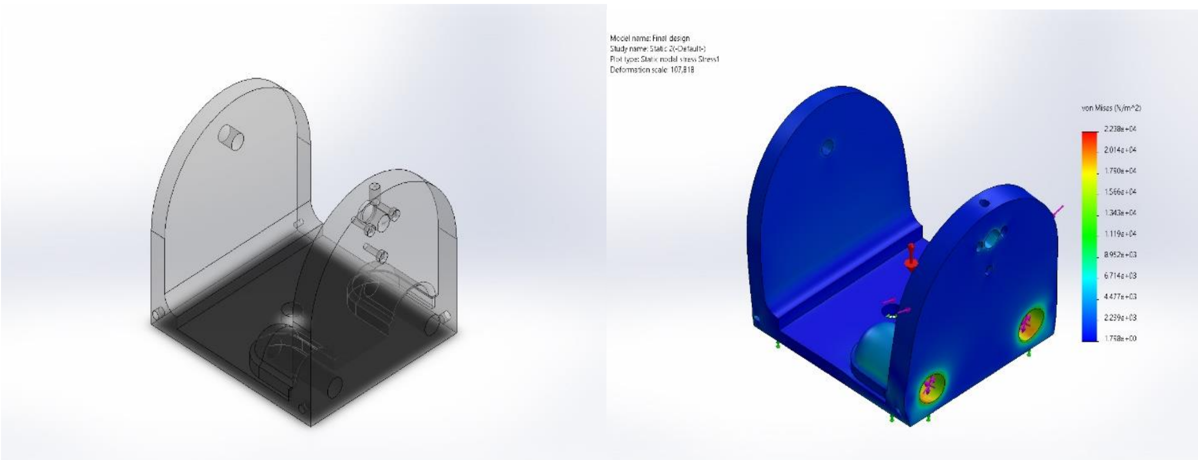

Figure 50. Final design of base structure and statistic simulation result after topology optimisation

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7.7 Results and summary

Table 24. Robot component mass comparison before and after topology optimisation

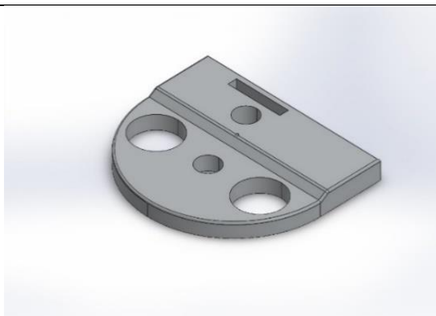
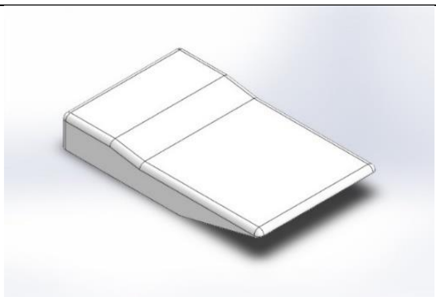
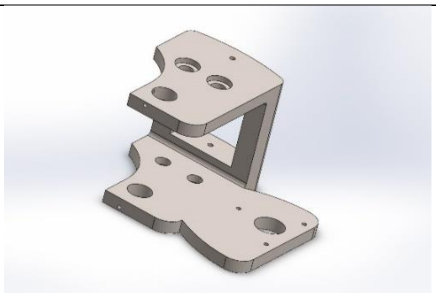
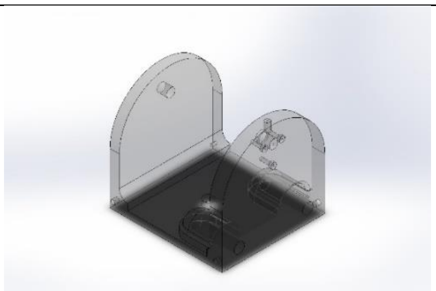
Components (final design)	Illustration	Manufacturing method	Original mass (g)	Optimised mass (g)	Mass reduction (%)
Base (top part)		Conventional manufacturing	1330.14	1139.13	-14.36%
Joint	Not applicable				
Arm support		3D printing	640.72	543.01	-15.25%
Support structure for motor		Conventional manufacturing	991.50	753.22	-24.03%
Base structure		3D printing	630.07	511.18	-18.87%

Table 25 above indicates the estimate mass change before and after topology optimisation. For parts that will be manufactured by conventional manufacturing method, the mass optimisation are achieved by simple machining for example, drill some holes, such as "Base

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(top part) and “Support structure for motor”. The reason is the more complex geometry the bigger cost in manufacturing process.

For parts that will be 3D printed with ABS (such as “arm support” and “base structure”), the mass will change slightly. However, “joint” part is not applicable on this topology optimisation, as it cannot reduce the mass while keeping its functionality. In order to reduce the total mass of the home-based low-cost upper limb rehabilitation robotic system while maintaining its functions, the shaft and joint diameters are increased. Although the mass of the shafts have increased slightly, the mass of the whole system has decreased. After structure optimisation, the final mass of the whole device is estimated about 8300g, reduced the 6.95% mass of original design.

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Chapter 8: Evaluation of prototype cost-effective home-based rehabilitation robot with stakeholders

8.1 Focus group study

After finishing the final prototype of home-based upper limb rehabilitation robot, the testing and evaluation are needed. To make sure this robot is useful for rehabilitation of children with cerebral palsy, focus group study with therapists and children with cerebral palsy will be arranged. Focus group is one of the qualitative data collection methods [130]. A focus group is a group of deliberately selected people who participate in a facilitated discussion to obtain consumer perceptions about a particular topic or area of interest [130]. The purpose of the focus group in this research is to gather information from users (patients and therapists) to evaluate the prototype design, refine the features, specifications and user interfaces for an upper limb rehabilitation robot.

8.1.1 Method

Focus group will be conducted with a broad range of therapists having experience of cerebral palsy therapy and patients with cerebral palsy. Ideally 5 therapists and 5 patients will be conducted for this, the total time of focus group will lasting around 2 to 3 hours (or longer if the participants are open and willing to talk for longer). The focus group ideally take place in the university's buildings where participants feel comfortable and secure with. Before the focus group begins, participants should provide informed consent and where appropriate be informed of compensation procedures. Data collected from the literature will be analysed to develop strategic questions for the focus group sessions. These questions, as well as the prototype will be presented to the participants for further advice. For more information on the structure of the focus group, see below.

8.1.2 Participants

The participants include therapists (physiotherapists and occupational therapists) and patients diagnosed with cerebral palsy and their upper limbs are affected. The age range of patients will be at least 9 and up to 16 years old. Where possible, the focus group will cover a mixture of gender. Participants of therapists involved in the study have to have at least two

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years of experience working with upper limb rehabilitation with patients with cerebral palsy. Participants are required to review and sign the information and consent form (appendix 5).

8.1.3 Focus group discussion guide

The focus group discussion guide is not intended to provide a rigid structure for the focus group as the priority is to allow the participant to express their opinions and experiences freely. It was based on the study's aims and objectives and also reflected questions posed in previously published research. The interview will be carried out with a clinical staff (therapist, neurologist and clinic nurse) and patient with cerebral palsy who will use an earlier prototype of the robotic aid to explore areas to generate possible topics and gain experience in interview technique.

The topic guide included the following: expectations of the robotic aid; acceptability of treatment protocol; design of the robot; use of robotics to enhance motivation; and opinion of having a robotic device at home. Rather, it is used as a prompt to focus the data collection and ensure that all relevant topic areas are explored during the interview. The details of interview topic are below:

- Check that the participant is still happy to be involved in the research
- Check that participant is OK with being recorded.
- Indicate length of interview.

General perceptions of robot and expectations

Prompts: Initial impression
Expectation
Comfort
Pain
Satisfied
Safe
Confusing

Perceptions of the treatment protocol

Prompts: Too long, too short
Challenging
Meaningful/Functional

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Any changes

Design of robot

Prompts: Appearance

Comfort

Ease of setting up and attachment

Any changes

Motivational Aspects?

Prompts: Help with motivation to persist with practice?

Feedback:

Helpful?

Understandable?

Sufficient?

Computer games:

Opinion on using computer games in stroke rehabilitation

Enjoyable? Interested?

Virtual Reality

Use of Robot in Different Environments

Prompts: Using the robot at home:

Barriers (assistance, size etc)

Benefits Outpatient setting

8.1.4 Questionnaire to therapists

In order to understand the general requirements of quality cerebral palsy therapy from the perspective of therapists, as well as the requirements for a home-based rehabilitation robot that would be able to deliver the same level of quality care as would a therapist, a self-customized questionnaire was designed based on an occupational therapist with 10 years of experience working in neurorehabilitation. The questionnaire was specially targeted at home-based rehabilitation robot and was divided into 4 sections: therapists background and treatment approach, facilitation of robot movements, potential attributes of a rehabilitation robot and reasonable cost of a home-based rehabilitation. Most questions were either closed-ended questions (multiple choice), or questions based on a five point Likert scale, which gauged level of agreement (‘strongly disagree’, ‘disagree’, ‘neutral’, ‘agree’, or ‘strongly

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agree’). Open questions are available for each sections. Results from the questionnaire will be used to inform future research.

Part 1. Background and Treatment approach

1. What is your profession?
   - ☐ Occupational Therapist
   - ☐ Physical Therapist
   - ☐ Rehabilitation Nurse
   - ☐ Other, please specify:____

2. What credential (s) do you hold?
   - ☐ BA or BS
   - ☐ MSPT, MSOT, MA
   - ☐ DPT, DOT, PhD
   - ☐ Other, please specify: ____

3. What methods of stroke treatment do you practice? Please select all that apply:
   - ☐ Neurophysiological/Neurodevelopmental Treatment
   - ☐ Constraint-Induced Movement Therapy
   - ☐ Motor Relearning Program
   - ☐ Electrical stimulation
   - ☐ Robot assisted rehabilitation
   - ☐ Electromyographic biofeedback
   - ☐ Mental practice with motor imagery
   - ☐ Repetitive task training
   - ☐ High intensity/practice
   - ☐ Splinting or orthosis
   - ☐ Other, please specify: ____
4. How long have you been working with stroke clients?
   - ☐ <1 year
   - ☐ 1-5 years
   - ☐ 6-10 years
   - ☐ >10 years
5. What population (s) do you work with? Please select all that apply:
   - ☐ Children (0-10yrs)
   - ☐ Youth (11-18yrs)
   - ☐ Adults (19-64yrs)
   - ☐ Senior Adults (65+yrs)
6. In what settings have you worked with stroke clients? Please select all that apply
   - ☐ Acute care (inpatient)
   - ☐ Rehabilitation hospital
   - ☐ Long-term care facilities
   - ☐ Outpatient Clinic
   - ☐ Home care

Other, please specify: ____

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Part 2. Facilitation of movement, please watch the video and choose your answer

5. The therapist should guide the patient how to use the robot?
   Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

   ____

   ____

   ____

6. Patients can improve arm function by using this system?
   Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

   ____

   ____

   ____

7. This robot should promote movement in the transverse plane (pronation and supination)?
   Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

   ____

   ____

   ____

8. This robot can promote useful exercise of the elbow?
Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

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9. This robot can promote useful grasping movement?
Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

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Part 3. Rehabilitation robot device

1. The robot will be most useful in the patient's home?
Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

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2. Patients will be satisfied with the appearance of the robot?
Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

3. The robot would be safe for patients to use by themselves?
Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

4. Patients can use robot in a seated position?
Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

5. The robot provides suffieicent arm and hand support?
Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

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6. It is important for the robot to record usage and provide to therapists?
   Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

Part 4. Cost

1. How much would patient be willing to pay for an upper limb rehabilitation robot?
   - ☐ **<£1000**
   - ☐ £1000-£4999
   - ☐ £5000-£9999
   - ☐ >£10000

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2. The NHS should loan rehabilitation robots to patients in the acute phase of recovery?
   Strongly disagree ☐ Disagree ☐ Neutral ☐ Agree ☐ Strongly agree ☐

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8.1.5 Results

After finishing the final prototype of home-based upper limb rehabilitation robot, the testing and evaluation are needed. However, due to the covid-19's restrictions on university lockdown, travel and in-person gathering, the focus group was cancelled. To make sure this robot is useful for rehabilitation of cerebral palsy survivors, focus group study with therapists and stroke survivors will be arranged in a future study.

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Chapter 9: Discussion and conclusions

9.1 Discussion

9.1.1 Interpretation and implications of research

From the literature review (Chapter 2), I found over 120 upper limb rehabilitation robots have been developed [45]. Among these rehabilitation robots, 110 are still at the prototype stage, 10 are commercially available and in use in hospitals or clinics, even and only 3 devices are being utilised in the home environment [45]. Key factors that limit the development of rehabilitation robots include a lack of clinical evidence [123], cost constraints [68], safety issues [124] and functionality limitation [125]. There are two main types of rehabilitation robots, exoskeleton-based and end-effector-based. From the functionality aspects, end-effector-based rehabilitation robots generally have less functionality than exoskeleton-based as they have two or three DoFs, limiting how the device is able to simulate ADLs, while exoskeleton-based rehabilitation robots have more flexibility and range of motion. However, most exoskeleton-based rehabilitation robots are large in footprint and complex for the user to don in the home environment. Considering a number of patients may not receive the target rehabilitation due to the inconvenience of travelling to and from hospital and home as well as the limited number of clinical rehabilitation robots, therapists and rehabilitation centres. Therefore, developing a home-based end-effector rehabilitation robot is the aim of our research.

The scoping review I undertook in chapter 4, identified the clinical and technical requirements of home-based upper limb rehabilitation robots, reflecting the actual needs and development trends for children with cerebral palsy and their therapists. Four main design requirements were identified: functionality, usability, software and safety. A home-based upper limb rehabilitation robot needs to enable the practice of movements and tasks related to ADL; be suitable for a wide range of users and settings but provide personalised therapy, be safe, easy and appealing to use, and be small, easy to store, and inexpensive. These findings form the design requirements for developing a novel low-cost home-based upper limb rehabilitation robot. The significance of the research I have presented provides clear guidance for designers and researchers about real-world needs for home-based upper limb rehabilitation robots enabling them to develop new systems which are fit for purpose. Designing a home-based rehabilitation robot which meets the user requirements, and is also yet be cost effective was a challenge .

In Chapter 4, I adopted a user-centred design methodology for the development the home-based rehabilitation robot. It is telling that most of the design requirements related to functionality and usability as it is essential that these needs are met if the device is to be adopted and used. The lack of user involvement has resulted in many medical devices which are not fit for purpose [12]and has been highlighted as a factor contributing to their lack of uptake. Users involved in the medical device design phase can also reduce the design time and modifications. By ensuring we understood users' needs and preferences we have designed a concept which addresses the main requirements and barriers to use, however challenges remain. Minimising cost is always desirable but has to be balanced with meeting other functional requirements. I have endeavoured to make the device as easy and intuitive to use as possible but cannot completely negate the need for assistance for some users. The size and 'movability' of home-based robots are also important but challenging. Thus, a device needs to be as small as possible and to be easy to pack away and move out of the way when not in use, but this needs to be balanced against the need for the device to be big and heavy enough to be stable and to produce full range movements. For most, existing home rehabilitation robots are too large and heavy to be easily used or moved [45]. Patients are unsupervised by the therapists when using home-based devices. Therefore, safety is an important characteristic for rehabilitation robots. I have determined an evidence-based method to determine safety limits, which can be used in the design of other devices. The workspace should be no more than 650mm × 280mm when considering safety factor. Furthermore, unlike other upper limb rehabilitation robots, we have carefully considered the movements the device needs to produce/assist. We are aware that to ensure carry-over into everyday function, the same movements need to be practiced in the robot as are used in functional activities, so we used a well-designed measurement tool of upper limb function (the ABILHAND) to identify important everyday tasks and worked with therapists to identify, and then prioritise the movements involved [97]. Consequently, we are confident that the device will maximise functional improvements by practicing the most relevant and important movements.

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In Chapter 5, I promoted the development of an end effector that measuring grip strength and setting appropriate challenge's within the software which change as a function of time. As end effectors are an important part of the design, they must be designed in conjunction with therapists to determine the types, sizes, and shapes of necessary for rehabilitation. For this reason, a customized end-effector has been developed, which can measure forces in three principal directions using six thin film force sensing resistors (Flexiforce sensor). To measure the axis of maximum grip force and directionality of interaction forces between the user and the handle during rehabilitation therapy, measuring force in at least three directions is necessary. The end-effector is incorporated into the home-based rehabilitation robot, to enable real-time monitoring of grip strength for the purposes of assessment and determination of rehabilitation efficacy. The developed end-effector has further examined the ability of Flexiforce sensor as a force sensor to reduce friction felt by the user when interacting with a robot. Further focus groups are necessary to refine this portion of the design.

In Chapter 6, I investigated the economic aspects of home-based rehabilitation robotics. The cost of current commercial rehabilitation robots is relatively high and makes them unaffordable for many families. For example, the price for one of commercial rehabilitation robot InMotion2 (version 2010) is £61,822. However, it is still more cost effective to buy a rehabilitation robot rather than employ a therapist for highly intensive therapy [126]. Both patients and therapists want a low-cost home-based rehabilitation robot, so cost reduction strategies were needed. It not only covers the cost of equipment, but also includes maintenance, such as motors and sensors need to be maintained regularly to insure the normal operation of the devices. Typically, the cost of rehabilitation robot increases with the increase of the DOF. From the cost analysis of the developed prototype of home-based rehabilitation robot, the estimated manufacturing costs (including the direct costs and indirect cost) is £1,680.

In Chapter 7, a topology optimization method applied to the lightweight design of the rehabilitation robot is presented based on finite element analysis. The aim was to identify an optimal mass of the rehabilitation robot whilst ensuring the structural integrity to the expected loading. An additive manufacturing strategy was utilised to reduce the mass of selected parts through topology optimisation. The mechanical structure optimisation was produced by topology simulation in SolidWorks. The statistic simulation was developed before structure optimisation, which is helpful for choosing suitable mesh size and the goal of topology study [117]. For this rehabilitation robot, the parts that can be optimized are considered having the potential for mass reduction as it is the goal for this topology optimization. Besides, conventional manufactured parts with complex geometry are included for the potential of reducing economic cost. Because if it is conventional manufacture method, then there will be an additional cost associated with optimisation. The more time it takes to manufacture conventional parts the more expensive they will be. Therefore, the optimisation for these parts should be in simple shape and easy to machine to prevent cost increasing. Five parts of the whole rehabilitation robot were selected for topology optimisation simulation, which were the "Base (top part)", "Joint", "Arm support", "Support structure for motor" and "Base structure". Among these parts, "Base (top part)" and "Support structure for motor" were manufactured by conventional methods. The mass optimisation of these parts was achieved by simple machining, e.g. drilling holes and reducing thickness some walls. For parts that will be 3D printed with ABS (such as "arm support" and "base structure"), the mass will change slightly according to the topology optimisation simulation result. However, "joint" part is not applicable on this topology optimisation, as it cannot reduce the mass while keeping its functionality. After structure optimisation, the final mass of the whole device is estimated about 8300g, reduced the 6.95% mass of original design.

9.1.2 Limitations of this research

There are some limitations to the research presented and in this paragraph, I will reflect on these, identifying areas for future work. The first limitation of this work which need to be considered are that the sample size of participants is small (4 participants for investigating the design requirements of a home-based rehabilitation robot) , although we included 2 therapists with a wide range of backgrounds and experience, involving more therapist may have yielded different results. Secondly, participants for testing the robot is not sufficient due to covid-19 pandemic that limited physical engagements with stakeholders. These important stakeholders will be involved in the future stages of the device's development. Another limitation is the budget, that limited the prototype redesign and re-manufacturing process.

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Although I choose the cost-effective materials and manufacturing methods for this robot, the cost will increase due to manufacture and maintenance. This still needs to be solved in the future research of home-based and low-cost upper limb rehabilitation robot. Besides, although we have identified the home-based rehabilitation robot is much more cost-effectiveness than clinical therapy. There is evidence indicating that the cost for robotic-assisted therapy is lower than traditional therapy in the long term [127]. A three month trail indicated that robotic-assisted therapy had a lower total cost (£9,265.50) relative to the usual care (£13,956.34) when there is no significant difference of upper limb functional improvement between them [128]. However, the detailed statistic analyse is needed in future research. Finally, this developed low cost home-based rehabilitation robot focused on children with cerebral palsy rather than adults.

9.1.3 Novelty and contribution to knowledge

The aim of this research was to: design, develop and evaluate a low-cost home-based rehabilitation robotic system integrating hand grasping, elbow flexion/extension and forearm pronation/supination movement assistance for children with cerebral palsy. The table below lists the research objectives summarising if they have been met.

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Table 25. Completion met of objectives of this research

Objectives	Identify a design specification of rehabilitation robotic systems through both a literature review and stakeholder (therapists, engineers) engagement.	Designs and manufacture a novel low-cost home-based rehabilitation robotic system which meets the design specification considering functionality (hand grasping, elbow flexion/extension and forearm pronation/supination), manufacturability and cost.	Evaluate the prototype robotic system with stakeholders and its mechatronic performance.	Identify areas the robotic system should be refined and future research areas.	Publication
Completion met	Fully met	Fully met	Partially met Note – user engagement limited by covid-19.	Fully met	A scoping review of design requirements for a home-based upper limb rehabilitation robot for stroke

The research I have presented in this thesis compliments existing research in this area and makes the following novel contributions:

1. Developed a journal paper involving 4 themes and 63 design requirements from therapists and patients for a home-based rehabilitation robot (has been submitted to the journal of topics of stroke rehabilitation and under reviewing).
2. The first analysis of human upper limb joint usage in 21 high frequency ADLs to inform what a home-based upper limb rehabilitation robot should do.

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3. Designed and manufactured a prototype of a novel low-cost home-based rehabilitation robot with 5 DOF’s. Current home-based rehabilitation robots are limited to 5 degrees of freedom.
4. Designed the first force sensing handgrip for a home-based rehabilitation robot which can measure real-time grip strength and promote useful exercise.

9.2 Conclusions

9.2.1 Summary of key findings

In conclusion, low cost home-based rehabilitation robot could be a useful tool for both therapists and patients with cerebral palsy. Therapists surveyed in a focus group desired a low cost and portable device that could be used in home environment [129] . Also, the participants in the focus group wanted it to be used with minimal supervision to perform repetitive rehabilitation therapy.

This research has identified what a home-based rehabilitation robot should do and has provided a reasonable, effective and cost-effectiveness solution for home-based upper limb rehabilitation for children with cerebral palsy. This low-cost home-based rehabilitation robot has met patients’ and therapists’ needs and requirements, practicing movements and tasks that are important in daily life; are suitable for wide age range of children (7-17 years old) with cerebral palsy and can provide individualized therapy, and are safe, easy and appealing to use. It is helpful for increasing users’ motivation and efficiency of post rehabilitation and reducing the stress on clinical and therapists. These should be considered in future robot design and development. After cost analysis, the ideal rehabilitation robot should have 5 DOF’s, weight less than 10kg and cost under £5,000.

9.2.2 Recommendations for future work

It is recommended that further design and assessment be incorporated into the development of this rehabilitation robot. I make the following recommendations:

1. Increase the length of links to increase the workspace area, so it will be suitable for adults as well as children, this may increase the potential market size for the robot and improve the economic justification for development.

2. Investigate the economic aspects of low-cost rehabilitation robots potentially reducing the cost of healthcare provision. A detailed analysis is needed including the costs of physios traveling to people's homes the expansion in the case load i.e. number of patients a physio can care for at any point in time.
3. Develop an interactive user interface. The system interface shall be easy for users to understand how to use and the system shall be easy to operation.
4. Construct different arm supports to comfort users. Materials of forearm support shall be comfortable and do not cause chafing of users' skin. The length of forearm support shall be adjustable to accommodate different forearm length (length adjustment range is ±15% of healthy children forearm length). Device shall be used by both right and left side affected users.
5. Shrink the device further based using topology optimisation so that it is more portable and lower cost.

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Appendix

Appendix 1. A scoping review of design requirements for a home-based upper limb rehabilitation robot for stroke

Lutong Li[1], Qiang Fu[2], Sarah Tyson[3], Nick Preston[4], Andrew Weightman[5]*

Address: [1] lutong.li@manchester.ac.uk, School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, M13 9PL, UK. [2]qiang.fu-2@postgrad.manchester.ac.uk, School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, M13 9PL, UK. [3]sarah.tyson@manchester.ac.uk, School of Health Sciences, The University of Manchester, Manchester, M13 9PL, UK. [4]N.Preston@leeds.ac.uk, Academic Department of Rehabilitation Medicine, The University of Leeds, Leeds, LS1 3EX, UK. [5]andrew.weightman@manchester.ac.uk, School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, M13 9PL, UK.

* Correspondence to andrew.weightman@manchester.ac.uk

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Abstract

Background: Home-based robotic therapy is a trend of post-stroke upper limb rehabilitation. Although home-based upper limb rehabilitation robots have been developed over several decades, no design specification has been published.

Objectives: This paper aims to identify and synthesize design requirements considering user and technology needs for a home-based upper limb rehabilitation robot through a scoping review.

Method: Studies published between 1st January 2000 to 10th June 2020 in Scopus, Web of Science and PubMed database regarding design requirements for upper limb rehabilitation robotic devices from of stroke survivors or therapists were identified and analysed.

Results: Nine studies were selected for review. They identified 42 requirements regarding functionality (11, 26.2%), usability (16, 38.0%), software (14, 33.3%) and safety (1, 2.4%). The main implementation barriers with respect to adherence and monitoring were space, operation and cost.

Conclusion: This is the first research to summarize the design requirements for home-based upper limb rehabilitation robots for people with stroke. The need for a safe, comfortable, easy to use device which can be individualized and promote specific movements and tasks emerged. The result of this paper provides designers and researchers guidance about the real-world needs for home-based upper limb rehabilitation robots for stroke.

Keywords: Home-based; upper limb; rehabilitation robot; design requirement; implementation

Barriers

Background

Stroke is one of the most common and disabling health care problems in the world [1]. Annually approximately 33 million people suffer a stroke worldwide [2, 3]; more than 1 million people suffer from stroke in Europe and 100,000 in the United Kingdom (UK) [4]. Up to 85% of stroke survivors suffer upper limb weakness and recovery is often limited [5-7]. Therefore, improving functionality of the upper limb is a major aim of post-stroke rehabilitation. The most effective intervention to improve upper limb recovery is high repetition task-specific training [8-10], however this is difficult to achieve as healthcare systems are resource limited, especially for stroke survivors who are unable to move their limb without assistance. One way to increase the intensity of practice is to use robotic devices to provide this assistance [8, 11].

Since the first use of MIT-MANUS in the clinical environment in 1994, robotic-assisted therapy has entered a new era [12, 13] and several upper limb rehabilitation robots have been developed including

the Mirror Image Motion Enable (MIME) and Automatic Recovery Arm Motility Integrated System (ARAMIS) [14-18]. However, the evidence of the effectiveness of robotic-assisted therapy is mixed [17, 18] and they have not as yet been widely adopted into clinical practice. One reason for this may be the logistics of their use. Patients for whom a rehabilitation robot is indicated are severely disabled and so regular clinic visits for treatment are difficult; expensive; time consuming and fatiguing and patients only receive relatively low doses of therapy. Post-hospital rehabilitation is now-a-days primarily delivered in patients' home [19]. Thus, to be integrated into clinical practice, upper limb

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rehabilitation robots need to be suitable for deployment in patients’ homes which will allow unlimited access to assisted therapy enabling higher frequency and higher intensity.

Several researchers have designed and shown the potential benefit of home-based rehabilitation robots, such as MARIONET, Bi-Manu-Track and hCAAR [20-22]. Although some studies collected or analysed stroke survivors’ or therapists’ requirements for rehabilitation robots [23-25], there is no systematic analysis of design requirement for home-based upper limb rehabilitation robots. The aim of this scoping review is to identify the clinical and technology design requirements and the implementation barriers for home-based rehabilitation robots. The results of this research will help designers and researchers understand the real-world needs for home-based upper limb rehabilitation robots enabling them to develop new systems which are fit for purpose.

Method

Search strategy

Scopus, Web of Science and PubMed were searched using the following search categories: “stroke”, “upper limb”, “home-based”, “rehabilitation robot”, “user”, and “requirement”. The search terms used were (design or speci* or require* or consideration or need) AND (robot* or rehab* system or rehab* technology) AND (upper limb or upper extremity) AND (user or clinic* or patient or stroke survivor) AND (home based or setting or environment) AND (stroke).

The titles, abstract and then full texts were screened for papers which met the following selection criteria:

1. Related to a robot device or robotic assisted system for stroke survivors with upper limb impairments.

2. Including mechanical or medical device design requirements, specification or consideration for a home-based upper limb rehabilitation robot.

3. Including patients’, therapists’ or users’ requirements on home-based rehabilitation robot.

4. Published from 1st January 2000 to 10th June 2020, because there was no research on design requirements of home-based rehabilitation robots before January 1, 2000.

Exclusion criteria were:

1. Not written in English.

2. Describing an exoskeleton device.

3. Describing wheelchair-based devices, as this type device assists movement of disabled arm

rather rehabilitation.

Results

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From 737 studies identified through the initial database search, nine were included in the final scoping review. Studies were omitted, and additional papers included, through the processes given in Figure 1.

(Figure 1)

Among the nine selected studies, five research designs were used: observation [26-28], interview [26, 28-31], questionnaire [26, 28, 32, 33], focus group [27, 30] and literature review [25, 29-31] involving 144 stroke survivors, 379 rehabilitation professionals, 43 informal caregivers and three technological experts (Table 1).

Data extraction and presentation

The information related to design requirements and implementation of a home-based rehabilitation robot was extracted and tabulated, then key themes were identified through thematic content analysis (Table 1).

(Table 1)

Classification and synthesis of requirements and implementation barriers

Forty-two design requirements of home-based upper limb rehabilitation robots were identified from the nine selected studies (Table 1). After reviewing the design requirements, we categorised them into four main themes; Functionality (n=11, 26.2%), Usability (n= 16, 38.0%), Software (n=14, 33.3%) and Safety (n=1, 2.4%) (Table 2). 'Functionality' requirements needed to support users' motor relearning; 'Usability' requirements ensured the robot would be feasible and acceptable to use in the home; 'Software' requirements included everything about programming such as recording or measuring the users' performance and the game design and 'Safety' requirements included relevant requirements to ensure safety of robot and to fulfil all relevant medical device regulations.

(Table 2)

Functionality requirements

Effective motor re-learning after stroke depends on three main factors: task-specific training, intensity of practice and that the practice is challenging (but not overwhelming) for the patient [8, 34, 35]. Therefore, providing repetitive, intensive, challenging, adjustable goal-oriented exercise is one of the basic functions of an upper limb rehabilitation robot [25, 26, 31, 33]. By 'task-specific', stroke survivors and therapists meant that to be effective, the exercises and movements produced by the robot should be related to those used in Activities of Daily Living (ADL) [26, 28, 30, 31] - motions such as grasping a spoon, holding a cup, shaving etc. should be considered. Upper limb movements in daily life are three-dimensional, so the robot should promote upper limb movement in multiple planes [27, 28, 32]. As the robot needs to offer active assistance to patients who are able to produce little or no movement themselves, an active device was preferred to a passive system [25, 29].

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Usability requirements

Usability requirements ensure the robot will be feasible and acceptable to use in the home by people with a wide range of sizes, disabilities and environments. Adjustable features of the robot were a frequent priority for therapists and stroke survivors, such as providing different handles to promote different grips [25, 29] and adjustability for different upper limb sizes [28, 31], so that the device can be adjusted for individual's needs. Users also preferred devices with simple installation and setup [25, 26, 31]. Small size, lightweight, portability and easy storage of the robot are also important features to make a home-based upper limb rehabilitation robot more acceptable to users [25, 28, 31].

Software requirements

A user-friendly interface was required for home-based rehabilitation systems, including clear and simple introduction and operating instructions [25-28, 31]. Providing multiple games was important to maintain users' motivation to exercise [26, 32]. However, as a device needs to accommodate a wide range of levels of ability, games with a wide range of difficulty and assistance are needed [25, 28, 30, 31, 33]. Recording users' performance and device usage (i.e. the dose of treatment) and making it available to users and therapists was a frequent feature for home-based upper limb rehabilitation robots. This was so therapists could evaluate stroke survivors' progress based on performance feedback [25, 32], and to increase patients' motivation with graphical or audio feedback when tasks or games were completed [26-28, 30, 33].

Safety requirements

Safety is always paramount for a medical device; general safety requirements should be met for every medical device such as including an emergency button and warning messages, avoiding sharp edges and possible finger traps, and protecting users' skin [28, 29, 31]. In additional, as a commercial medical device, it should meet all safety regulations [25], such as ISO standard, CE marking and IEC standard [36-38].

Implementation barriers

We identified four main barriers which need to be overcome for successful implementation of upper limb rehabilitation robots at home, namely "operation", "adherence and monitoring", "space" and "cost" (Table 3).

(Table 3)

Operational barriers related to installation and usability of a rehabilitation robot at home, such as device installation, system set up and operation. Many stroke survivors are elderly and may not be familiar with technology [25, 33]. Furthermore, many suffer from cognitive, communication and visual problems, as well as motor impairments which means they will need assistance from others (such as informal caregivers or family members) to operate rehabilitation robot at home [39]. These issues may have an impact on the feasibility of, and users' motivation to use a home-based rehabilitation robot.

Adherence and monitoring barriers included the possible detrimental effect of the lack of direct supervision from a therapist at home, which may mean that patients lack confidence, or motivation,

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or do the robot mediated exercises in an ineffective way. Feedback to the patients' and therapists about the device's usage (i.e. the dose of treatment) and the patients' performance was considered important to monitor progress, and to maintain communication and motivation [26].

Lack of space could act as a barrier to using rehabilitation robots in a home setting. Many stroke survivors have little spare space in their home to accommodate a rehabilitation robot. Consequently a robot needs to be small, portable and easy to store when not in use. Furthermore, to be used in everyday life, the robot needs to be compatible with existing furniture such as suitable table or chairs. It also needs to be suitable for use in different settings, for example some users may want to use the robot in their living room or bedroom but store it elsewhere.

Cost barriers relate to the cost for rehabilitation robot (which needs to be as low as possible) and needs to consider the cost of usage (electricity and any other resources) and maintenance in addition to the cost of purchase or leasing [25, 33].

Discussion

This research has identified the design requirements and implementation barriers, for a home-based upper limb rehabilitation robot through a scoping review. The results of this research will be important to guide the design of acceptable, user-friendly, effective home-based upper limb rehabilitation robots.

Promotion of upper limb function is the basic requirement for a rehabilitation robot. We are aware that for training to carry-over into everyday function, the same movements need to be practised during robot training as those used in functional activities (i.e. three-dimensional movement of multiple joints) [26, 28, 29, 31]. However, most existing research home-based rehabilitation robots are limited to planar movement of only a few (sometimes only one joint such as elbow flexion/extension), such as Bi-Manu-Track and hCAAR [21, 22]. This limited functionality may have been chosen to minimise costs, however if the movements produced by the robot are not those needed to promote recovery, the home-based robot is unlikely to be effective or adopted however inexpensive.

Customisation features are another high priority design requirement. Stroke survivors with different level of upper limb weakness will required different level of assistance [25, 30, 32]. The robot system should allow users to choose the most suitable games, adapt the game difficulty and amount of assistance provided as the patient progresses. It also needs to record and monitor users' performance, and provide feedback to therapists and users. Therapists can then evaluate usage and progress and update the patient's training accordingly. In addition, users' motivation for using a home-based rehabilitation will depend on the choice for games, initial setting of the interface or program, and simplicity of operation. Complicated operating procedures will reduce the users' motivation, leading to abandonment of the robot.

The majority of stroke survivors are elderly [40] and may not be familiar with using computers (although this will change with time), and many have multiple system impairments [41-43]. Any home based rehabilitation robot should therefore be as intuitive to use as possible. However some users

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may, inevitably require assistance from others to either set up or operate the robot. Minimising the amount of physical assistance required and the technical know-how needed to do so are important priorities.

Minimising the size and maximising the portability and storage of home-based robots are important but also a challenge. Many homes have limited space to accommodate robotic devices. Thus, a device needs to be as small as possible, easy to move and to 'pack down' to minimise storage space when not in use. However, this needs to be balanced against the need for the device to have sufficient power, stability and functionality for a wide range of abilities [44].

Limitations

This paper presents the design requirements identified by therapists and stroke survivors but we have not ranked them. This will be addressed in future publications along with the engineering requirements, i.e. technology capabilities and limitations. These issues are important to find a balance between robot function and cost.

Conclusion

This scoping review identified the clinical and technical requirements of home-based upper limb rehabilitation robots, reflecting the actual needs and development trends for stroke survivors and their therapists. Four main requirement themes were identified; functionality, usability, software and safety. Four barriers to implementation have been detailed, namely operational details; adherence, space and cost. A home-based upper limb rehabilitation robot needs to enable practice movements and tasks related to ADL; be suitable for wide range of users and settings but provide personalised therapy, be safe, easy and appealing to use, and small and easy to store, and inexpensive. These findings form the basis for the next stage of the authors' research; designing and developing a novel low-cost home-based upper limb rehabilitation robot which meets these requirements. The significance of the research we present provides clear guidance for designers and researchers about real-world needs for home-based upper limb rehabilitation robots enabling them to develop new systems which are fit for purpose.

List ofabbreviation

ADL: Activities of Daily Living

MIME: Mirror Image Motion Enable

ARAMIS: Automatic Recovery Arm Motility Integrated System

Declarations

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Tables1. Overview of selected studies

	Methodology	Participants or/and studies involved	Aim	**Main findings** A home-based upper limb rehabilitation robot ne
.al,	Observation; interview; questionnaire	5 stroke survivors (average 4 years after stroke; 3 had a right hemiplegia and two on the left))	To design and develop a upper limb workstation by collecting users' perceptions	**Functionality requirements:** provide repetitive m be usable in seated, standing or recumbent positi promote movement related to ADL; promote fing movements; promote whole upper limb moveme **Usability requirements:** be easy to set up; usable easy to don and off. **Software requirements**: have a user-friendly app have a graphical performance outcome which mo users; have multiple games to enhance users' mo **Barriers**: A home-based robot may reduce the fre timeliness of communication between stroke surv therapists; how to provide efficient and suitable r therapy at a users' home (should stroke survivors treatment time at home be designed as a trial wit duration, or should they be based on stroke survi progress?)
011	Questionnaire	233 therapists (72% physiotherapists, 27% occupational therapists); most based in Australia (48%) and Canada (28%); over half had more than 10 years' experience; most worked in clinical settings and 42% worked in the stroke survivors' home	To identify the therapist's requirements and preference for upper limb rehabilitation robot	**Functionality requirement:** be usable in any posit (seated, standing or recumbent); facilitate arm m in multiple planes (transverse and sagittal); **Usability requirement**: provide arm and hand sta provide different handholds; be easy to transfer/ store in users' home; be compact size; suitable fo environment; be adjustable to individual needs; k stable; include all device accessories for installatio up **Software requirement**: virtual ADL specific activit resistance and alignment based on users' perform provide fun games; provide feedback to users and therapists; provide separate interfaces for users a therapists; provide predefined functions.
ach	Literature research; semi-structured interview	9 studies related to application of technology in upper limb rehabilitation of stroke survivors; 7 therapists mean experience >18 years in the Netherlands (6 worked in stroke rehabilitation, 1 worked in children's rehabilitation)	To identify and provide guidance on rehabilitation technology criteria	**Functionality requirement:** accommodate individ training goals based on to the patient's ability; pr task-oriented ADL-related training; provide intens repeatable training; **Usability requirement**: provide quick hardware in and software setting; be portable or transferable stable; be ergonomically acceptable; easy to oper **Software requirement**: provide variable type of, a difficulty of training or games; provide feedback o performance to users and therapists; include gam motivate users; be easy and intuitive to use; have introduction; be customizable to individual needs pre-programmed training based on therapists' su a system which can save individual therapy settin users' data; be human-friendly

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				Safety: include an 'emergency stop' button; provi warning messages
t.al, 0]	Interviews; focus group; observation	9 stroke clinicians for interviews (4 medical doctors, 2 occupational therapists, 2 physiotherapists and 1 nurse); 11 therapists for focus group; 9 stroke survivors for observation	To identify the requirements for computer games for upper limb rehabilitation	**Functionality requirement**: include a workspace v users' safe range of movement **Usability requirement**: be easy to use; **Software requirement**: actively involve the user; tasks or games with different levels of challenge; feedback of users' performance; involve games th simple and easy to understand, fun, fulfil the reha goals and relate to ADL; monitor users' usage; the should include clear introduction;
t.al, 9]	Literature research; Interviews	10 studies related to ADL tasks required for hand rehabilitation; 5 sub-acute stroke survivors (> 3 months post-stroke); 3 neuro-rehabilitation experts (1 movement scientist, 1 physiotherapist, 1 occupational therapist); 3 technology experts (1 biomechanical engineer, 1 medical devices developer, 1 prosthetics orthoptist)	To identify the users' requirements for a hand rehabilitation device	**Functionality requirement:** promote hand functio provide active power support for hand and upper movements within the safe range of speed and m for each patient; only provide the required assista each individual; train cylinder grasp **Usability requirement**: easy to don and doff so pa can do it independently; be comfortable and prot users' skin; be lightweight; promote smooth move wireless; be low-cost. **Safety**: avoid any sharp parts; have a back driveab mechanism; easy and quick to stop and move in a emergency situation;
t.al, 7]	Observation; focus group	11 rehabilitation professionals (detailed information of therapists was not provided)	To develop a bimanual upper limb rehabilitation platform through User Centred Design	**Functionality requirement:** promote hand mover both horizontal and vertical planes **Usability requirement**: To be simple to use; low c **Software requirement**: provide enough introduct simple and easy to use; provide sufficient feedbac users; include a set up menu;
.al,	Observation; interview; questionnaires	Therapists (the number of participants was not specified)	To identify the clinical and technology requirements for upper limb rehabilitation robot	**Functionality requirement:** promote upper limb movement close to ADL; allow users to move in th dimensional space; keep the trunk stable; be usab seated position; promote task-oriented training; r joint alignment **Usability requirement**: be adjustable to individua and abilities; easy to transport; easy to use; stable **Software requirement**: provide feedback to thera

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				patients; include customisable game settings (dur time); include a redefined menu; involve a modul **Safety**: be safe for both patients and therapists to
018	Systematic review of users' needs of assistive technologies for upper limb rehabilitation after stroke	9 studies (published from inception to August 2017; related to users' perspective for assistive technologies of rehabilitation; with the involvement of stroke survivors or professionals)	To identify the users', need for upper limb assistive technology after stroke	**Functionality requirement:** provide task-oriented repetitive and intensive exercise; provide active s promote upper limb function **Usability requirement**: should be easy to don and lightweight; adjustable for users; easy to use; low easy to set up and maintain; comfortable to use; s portable **Software requirement**: motivate users; provide fe include introductions; include adaptable system s and programmes; save individual user's data; pro individualized levels of support and game difficult a modular system **Safety**: meet safety regulations **Barriers**: Users may be unfamiliar with technolog financial support if the device is incompatible wit existing furniture; data privacy needs to be maint
.al,	Questionnaire	125 stroke survivors (average 30.6 months after stroke, 81% with cognitive impairments, 84% with physical impairments, 48% with aphasia); 43 informal care givers (mean age = 58 years); 105 health professionals (41% physical therapist, 15% psychologist, 47% physician); 75% worked in rehabilitation centre, 34% worked in general hospital and 10% worked in health centre in primary care; 79% had more than 10 years' work experience)	To identify users' requirements for e-rehabilitation after stroke	**Functionality requirement:** Provide functional ex **Usability requirement**: Provide tailored system; u most common home environments; **Software requirement**: require no internet conne quick to log in; record data on users' performance health status; provide a customisable system inte including adjustable background and font; provide feedback; require no other webpage; avoid comp options; provide video introduction of device/syst to patients and therapists; provide frequently ask question menu and system helpdesk; monitor use performance (duration time, use frequency); prov online agenda option; provide communication fu with other stroke survivors; provide general infor stroke and stroke rehabilitation **Barriers**: Technology adaptability (users may be u with technology or find the system too complicat use); compatibility with space; cost

Table 2. Design requirements for home-based upper limb rehabilitation robots

Requirements	Source
Functionality requirements	
1. Provide repetitive exercise	[25, 26, 31, 33]
2. Provide intensive exercise	[25, 31, 33]
3. Provide goal-oriented exercise	[25, 28, 31, 33]
4. Movements produced to relate to ADL	[26, 28, 29, 31]
5. Apply assistive forces to aid practice of therapeutic movements	[25, 29]
6. Can be used in a seated position	[26, 28, 32]
7. Suitable functional workspace to ensure users' safety	[30]
8. Suitable and safe movement speed of each joint	[28, 29]
9. Provide arm weight support and arm stability	[32]
10. Keep trunk stability / Ensure compensation stability	[28, 32]
11. Enables arm movement in all planes (three-dimensional movement)	[27, 28, 32]
Usability requirements	
12. Intuitive to use	[25, 27, 28, 30, 31]
13. Quick and simple to set up	[25, 26, 31, 32]
14. Quick and easy to install	[31, 32]
15. Easy to maintain	[25]
16. Provide different handholds for different users' needs	[26, 29, 32]
17. Easy to store	[32]
18. Easy to transport/portable	[25, 28, 29, 31, 32]
19. Adjustable to patient's arm size	[25, 28, 31, 33]
20. Comfortable	[25, 29]
21. Easy to don and doff	[25, 26]
22. Suitable for the home environment	[26, 33]
23. Stability of device base	[25, 28, 31]
24. Reliability	[25]
25. Compact size	[28, 32]
26. Lightweight	[25, 29]
27. Low-cost	[25, 27, 29]
Software requirements	
28. User friendly interface	[26, 30]
29. Simple operation system	[31, 33]
30. Provide visual or audio feedback on handle movement and performance for patients	[25-28, 30, 33]
31. Provide feedback on users' performance to therapists	[25, 28, 30-33]
32. Monitor usage	[25, 31]
33. Customisable system, adjustable initial settings	[25, 28, 31, 33]
34. No internet connection requirements	[33] [33]
35. Multiple levels for assistance to accommodate differing patients' needs	[25, 30, 32]
36. Simple and clear instructions for use	[25, 27, 28, 30, 31, 33]
37. Multiple games with differing levels of difficulty to accommodate patients' needs	[25, 30-32]
38. Have menu with frequently asked questions	[27, 28, 33]
39. Provide online agenda option for patients and therapists to arrange the appointment	[33]

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40. Save individual users' data	[25, 33]
41. Modular the rehabilitation exercise (split the exercise into several small tasks)	[25, 28, 31]
Safety requirements	
42. Meet all safety requirements	[25, 28, 29]

Table 3. Implementation barriers of home-based upper limb rehabilitation robots

Implementation barriers	**Derivation and supplement**
Operation	
Lack of technology knowledge	Stroke survivors are often elderly and may not be familiar with using a computer and other technology [25, 33].
Need assistance	Many stroke survivors with severe upper limb weakness need help to set up and don and off a rehabilitation robot at home [39].
System operation	Some systems (games) may be too complicated to stroke survivors to operation [25, 33].
Device installation and system set up	A cumbersome installation and setup procedure will be difficult for stroke survivors or their families, resulting less motivation to use the robot [26].
Adherence and monitoring	
Lack of motivation	Stroke survivors may not persist with regular exercises [26].
Lack of therapists' guidance	Rehabilitation at home involves less direct contact with therapists which may lead to the patients performing exercises less effectively than if they were directly supervised [26].
Data privacy	Personal data privacy needs to be maintained [25].
Space	
Storage space for device	Many stroke survivors do not have spare space in their homes for a large rehabilitation robot [25, 33].
Suitable table or chairs	Home-based rehabilitation may not compatible with users' furniture, such as the height of a table or chairs [25].
Cost	
Cost of device	Some stroke survivors may need financial support to buy or rent a home-based rehabilitation robot [25, 33].

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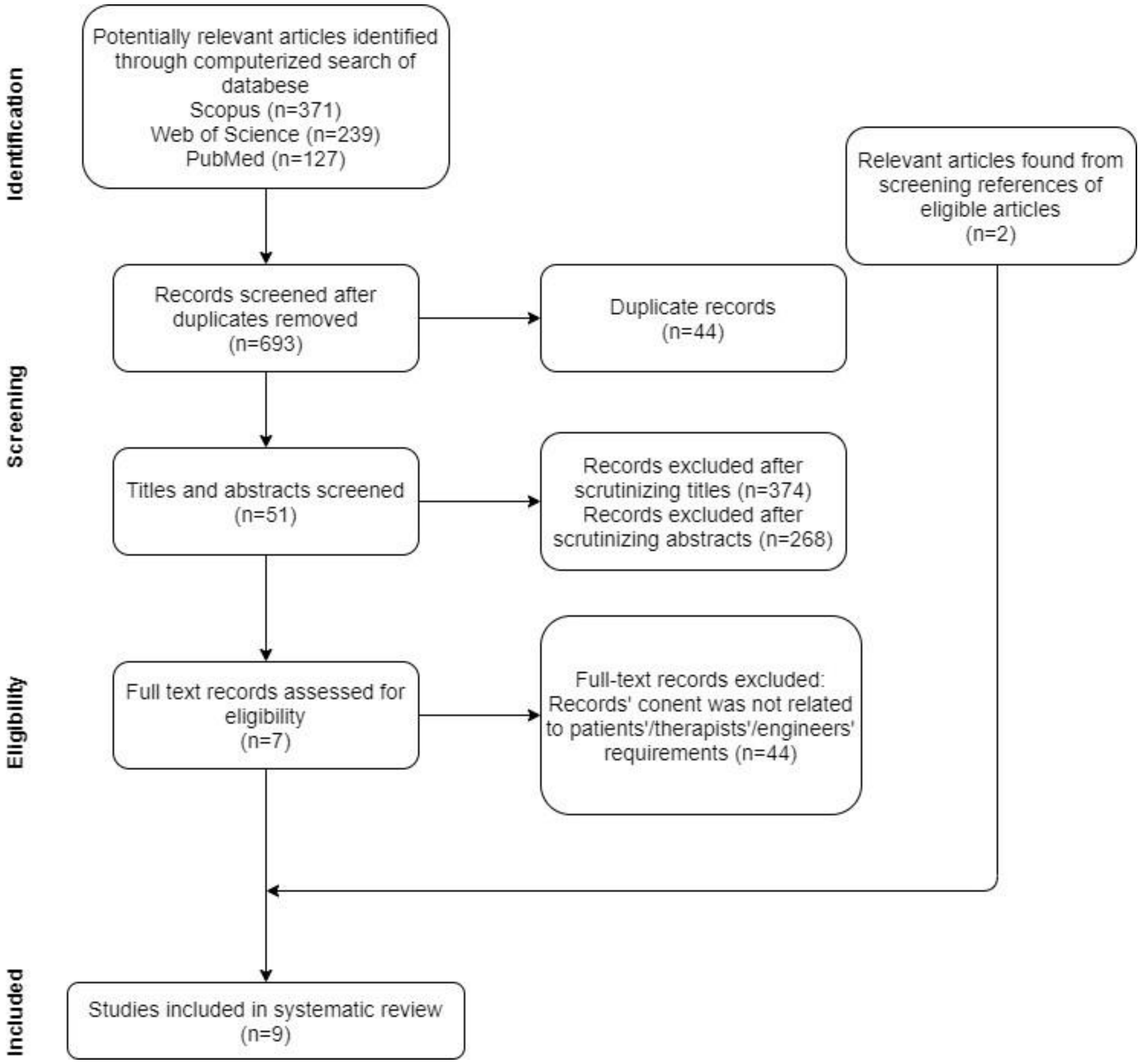
Figure 1. Flowchart of study select



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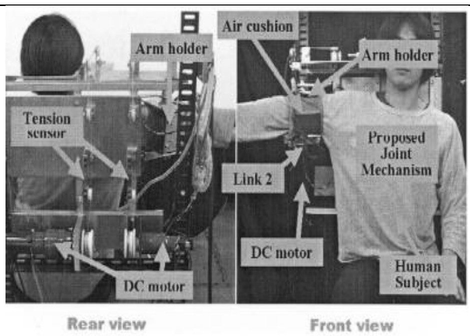
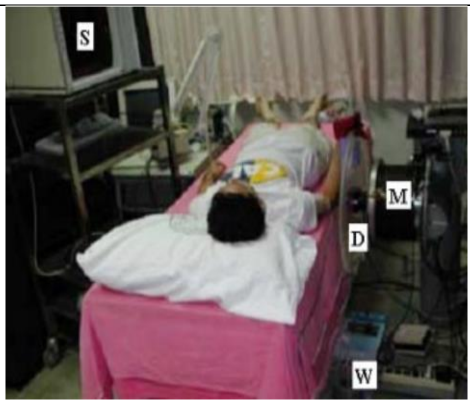
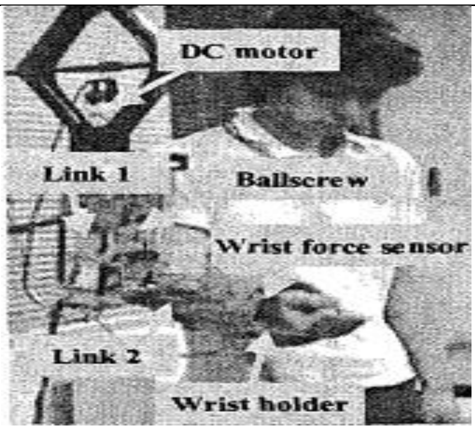
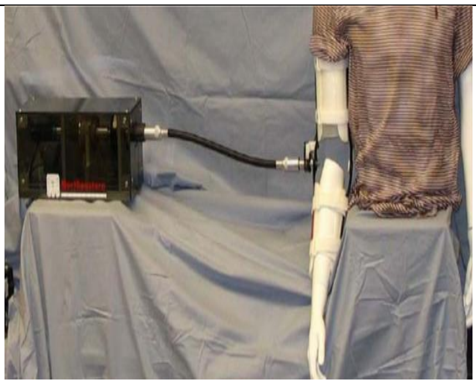
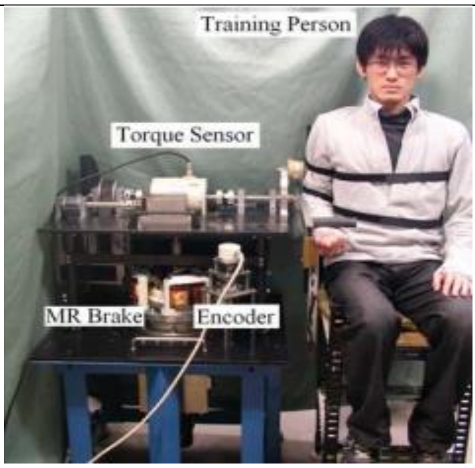
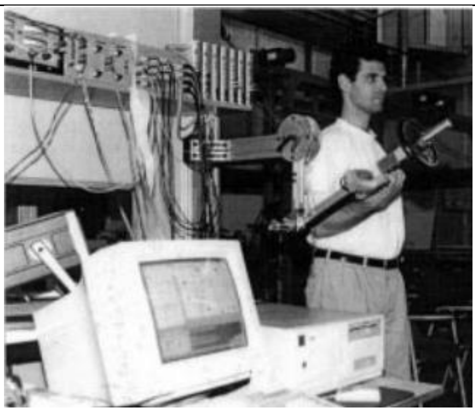
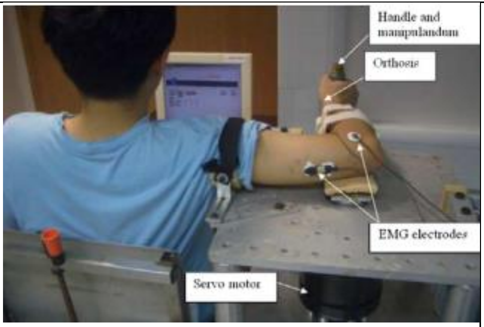
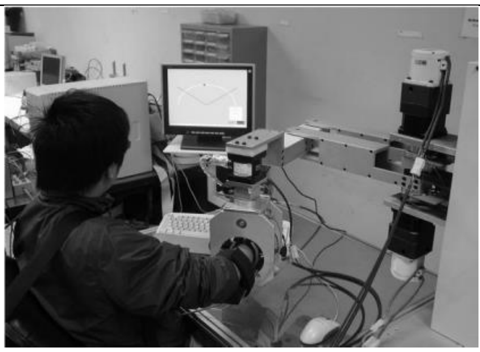
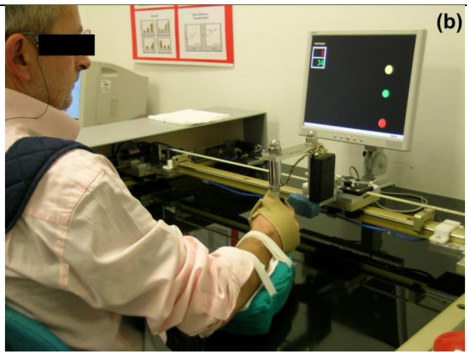
Appendix 2. Hand grasp analysis of current developed rehabilitation robot

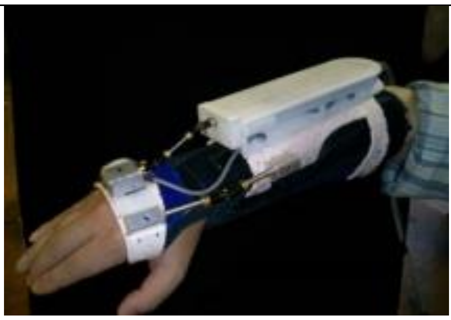
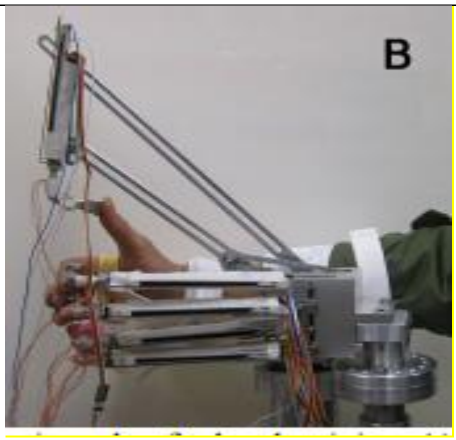
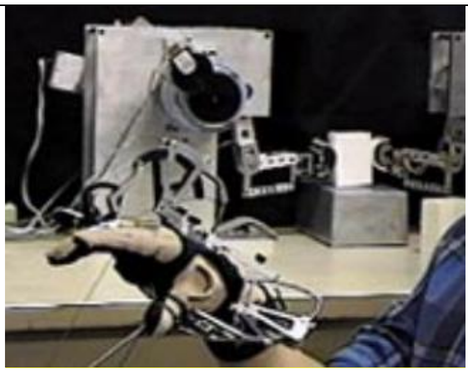
The table below involved over 120 rehabilitation robots have been developed (based on Maciejasz's review paper). According to the table above, pinch/key grip is second highest frequency movement in ADL, therefore, we focus on whether current developed robots cover hand grasp functions. As the result, 11 over 128 robots have pinch/key grip, and all of them are exoskeleton based.

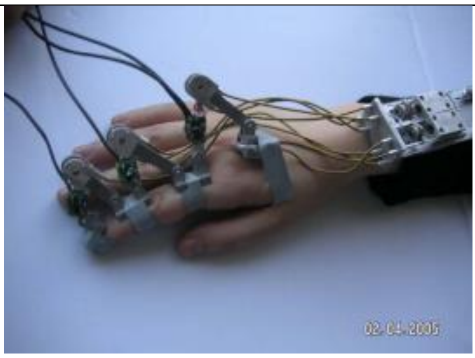
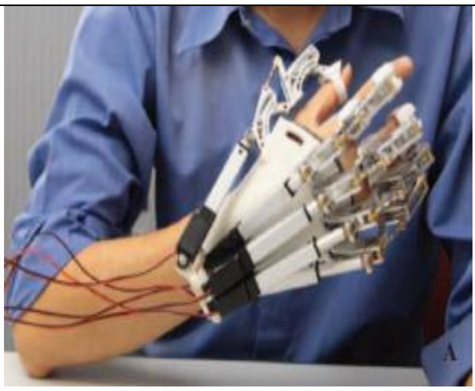
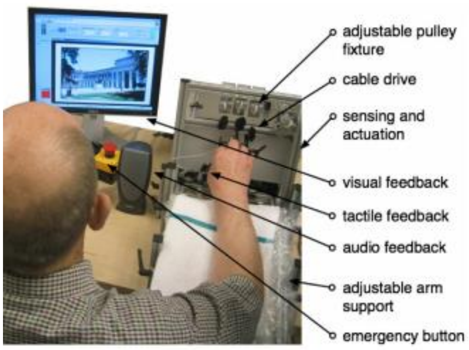
Robot	**Figure of the robot**	**Does the robot cover the following hand grasp? (X- doesn't, √-does)**			
		Grasp grip	**Pinch/key grip**	**Pencil grip**	**Hook grip**
Kiguchi		×	×	×	×
Cheng		×	×	×	×
Cozens		×	×	×	×

Kiguchi		√	×	×	×
MARIONET		√	×	×	×
Mavroidis		×	×	×	×

MEM-MRB		×	×	×	×
Myomo e100		×	×	×	×
Ögce	**Not applicable**	×	×	×	×
Pylatiuk		×	×	×	×
Rosen		×	×	×	×

Song		√	×	×	×
Vanderniepen		×	×	×	×
Kung		×	×	×	×
ASSIST		×	×	×	×
Colombo		√	×	×	×
Hu	**Not applicable**	×	×	×	×

Loureiro		×	×	×	×
PolyJbot		×	×	×	×
Chen		√	√	×	×
Cyber Grasp		√	√	×	×

<table>
<tr><td>Ertas</td><td></td><td>×</td><td>×</td><td>√</td><td>×</td></tr>
<tr><td>Fuxiang</td><td></td><td>×</td><td>×</td><td>×</td><td>×</td></tr>
<tr><td>Hand of Hope</td><td></td><td>√</td><td>×</td><td>×</td><td>×</td></tr>
<tr><td>Hand CARE</td><td>
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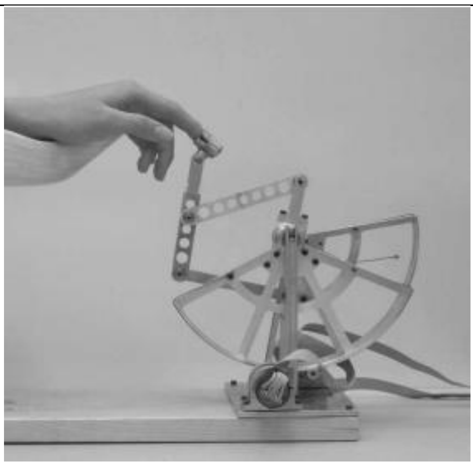
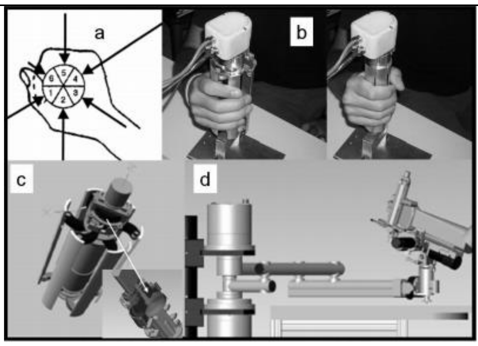
HEXORR		√	√	×	×
HIFE		×	×	×	×
InMotion HAND		√	×	×	×
Kline		√	×	×	×
Lucas		×	√	×	×

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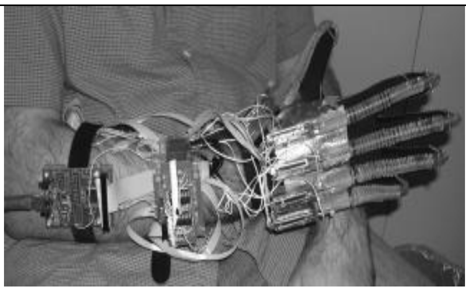
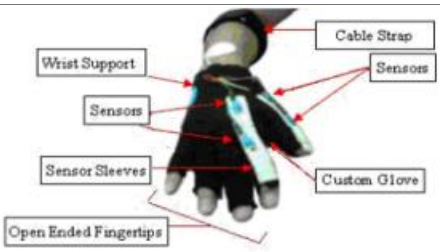
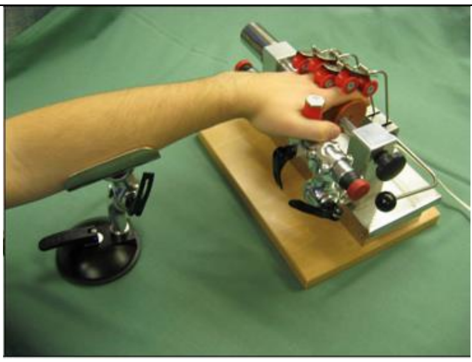
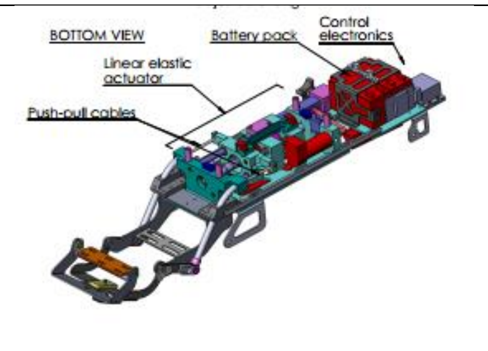
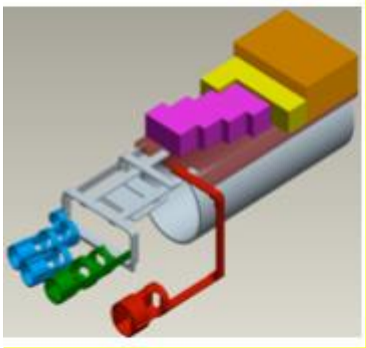
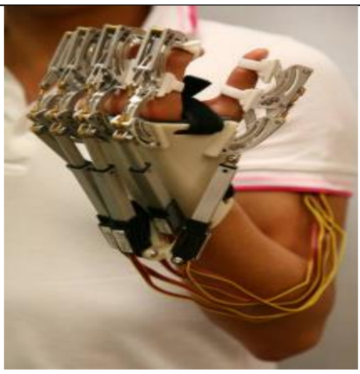
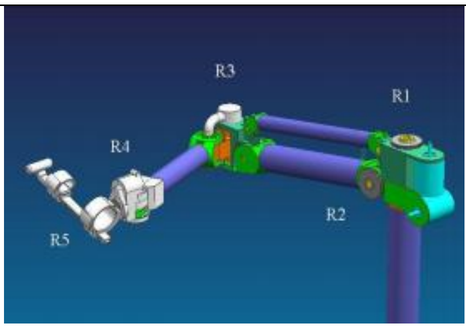
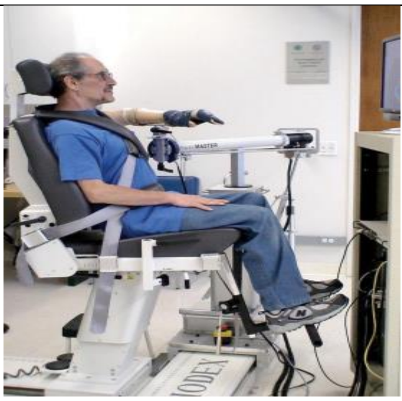
MR_CHIROD v.2		×	×	×	√
MRAGES		×	×	×	×
Mulas		√	×	×	×
Nathan		√	×	×	×
Reha-Digit		×	×	×	√

Rosati		√	×	×	×
Rotella		√	√	×	×
Rutgers Master II-ND		√	×	×	×
Salford Hand Exoskeleton	**Not applicable**	×	×	×	×
Tong		√	×	×	×

TU Berlin Finger Exoskeleton		×	×	×	×
TU Berlin Hand Exoskeleton		×	×	×	×
Worsnopp	**Not applicable**	×	×	×	×
Xing		√	×	×	×
ACRE		×	×	×	×
ACT 3D		×	×	×	×

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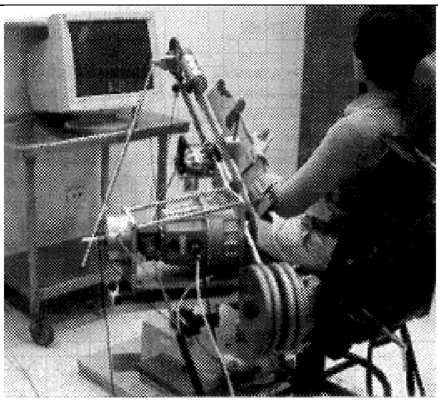
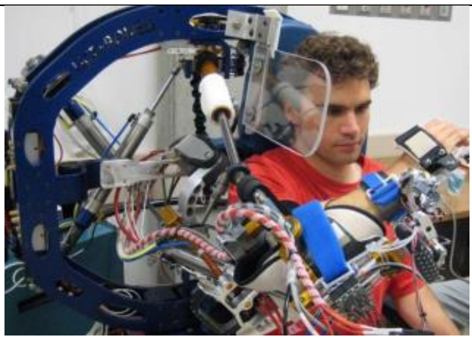
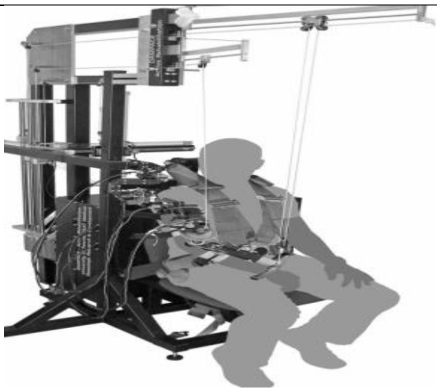
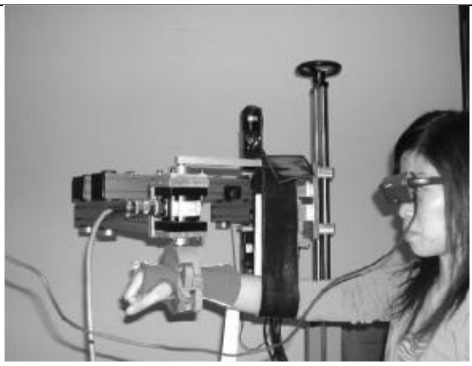
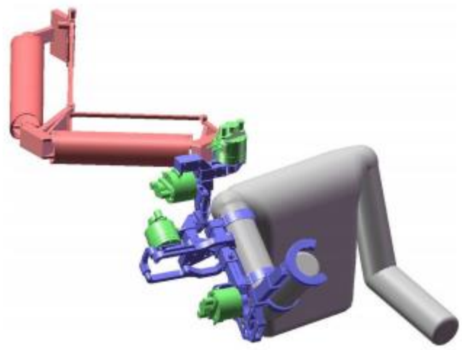
ARC-MIME		√	×	×	×
ARM Guide		√	×	×	×
BFIAMT		√	×	×	×
BONES		√	×	×	×

Dampace		√	×	×	×
Freeman		√	×	×	×
InMotion 2.0		√	×	×	×
Ju		√	×	×	×
Kiguchi		×	×	×	×

Kobayashi		×	×	×	×
Limpact		×	×	×	×
MariBot		×	×	×	×
MEMOS		√	×	×	×

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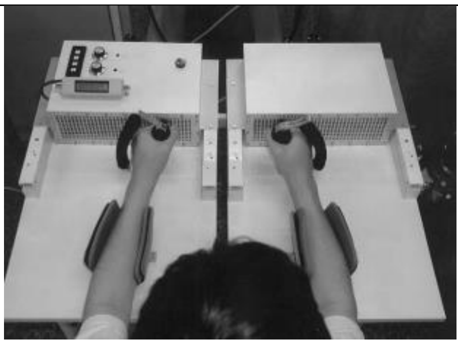
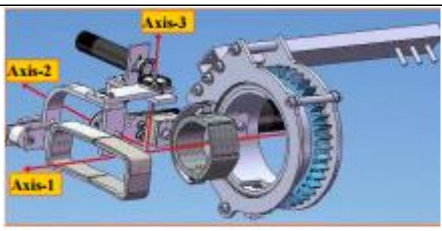
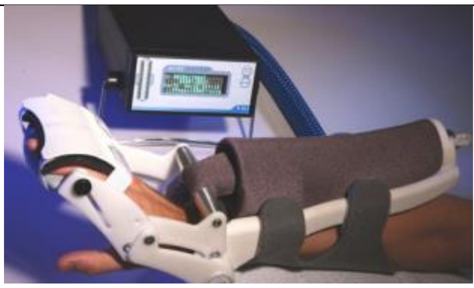
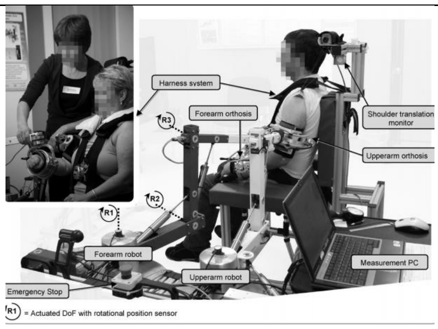
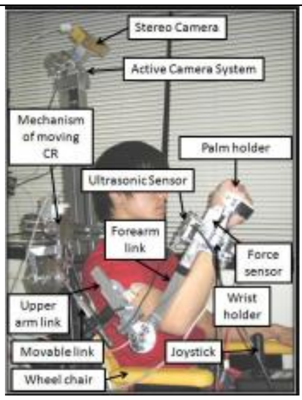
MIME		×	×	×	×
Moubarak		×	×	×	×
NeReBot		×	×	×	×
REHAROB		×	×	×	×

Bi-Manu-Track		√	×	×	×
CRAMER		√	×	×	×
InMotion 3.0		√	×	×	×
Supinator extender (SUE)		√	×	×	×

Takaiwa		√	×	×	×
W-EXOS		√	×	×	×
AMES		×	×	×	×
Hand Mentor™		×	×	×	×
HWARD		√	√	×	×

My Scrivener		×	×	×	×
ADLER		×	×	×	×
ARAMIS		×	×	×	×
Gentle/S		×	×	×	×

iPAM		×	×	×	×
Kiguchi		×	×	×	×
L-Exos		×	×	×	×
MGA		√	×	×	×

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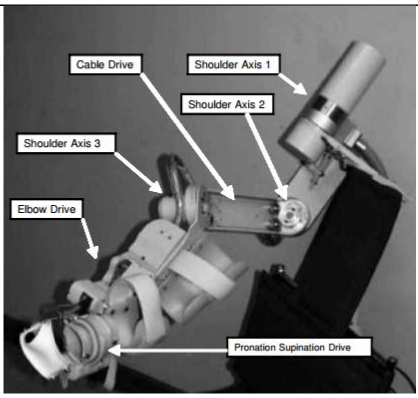
<tr><td>MULOS</td><td>
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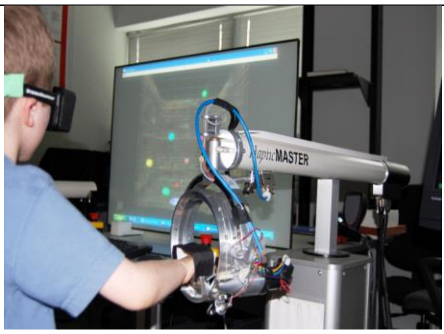
<tr><td>NJIT-RAVR</td><td>
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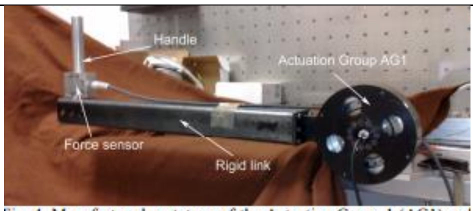
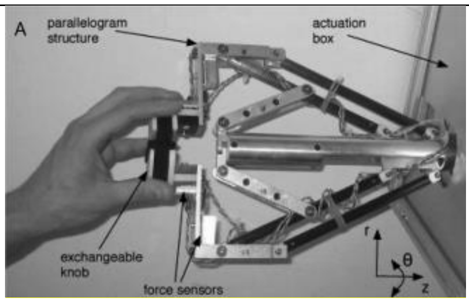
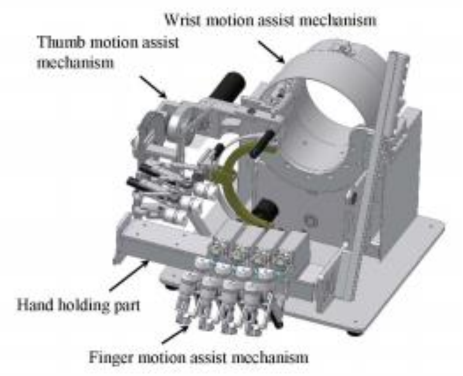
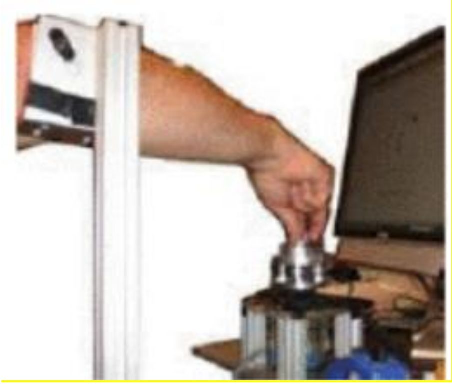
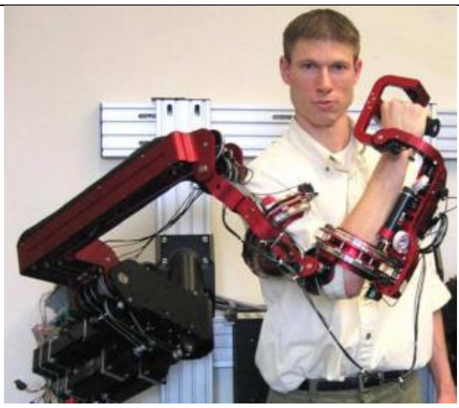
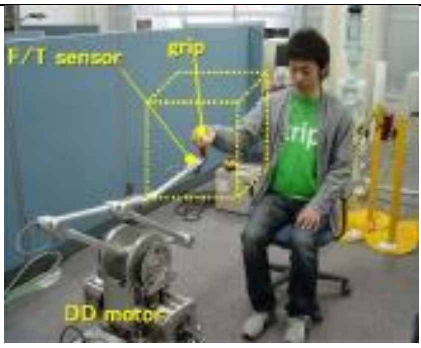
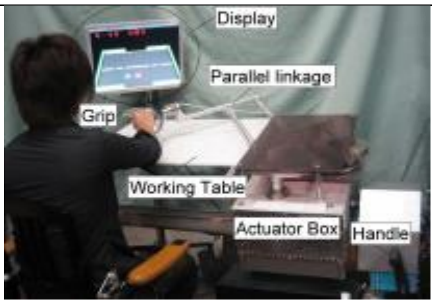
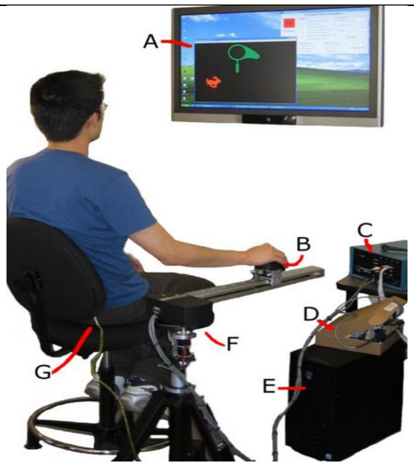
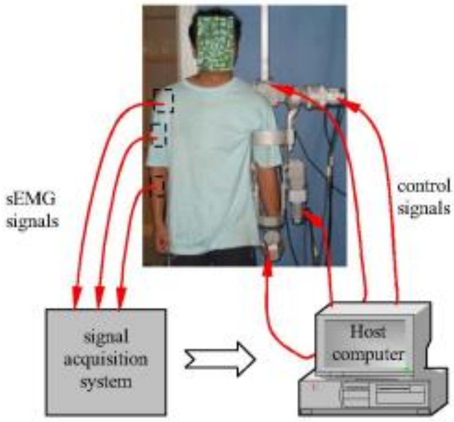
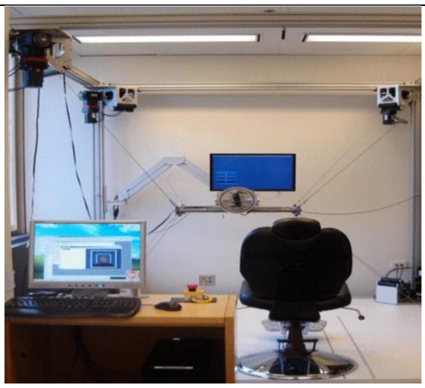
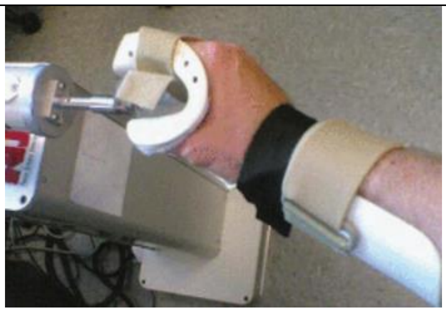
<tr><td>RehabExos</td><td>

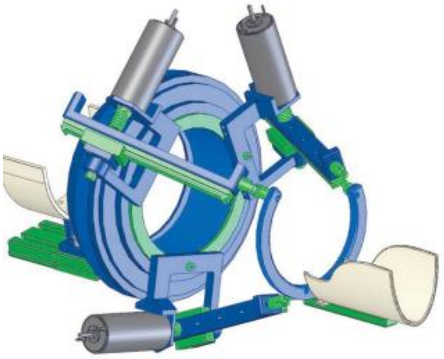
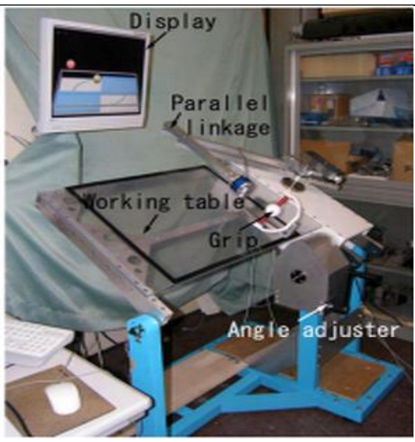
Fig. 4 Manufactured prototype of the Actuation Group 1 (AG1) and</td><td>√</td><td>×</td><td>×</td><td>×</td></tr>
<tr><td>Pneu-WREX</td><td></td><td>√</td><td>×</td><td>×</td><td>×</td></tr>
<tr><td>T-WREX</td><td></td><td>√</td><td>×</td><td>×</td><td>×</td></tr>
</table>

Ding		×	×	×	×
MAHI		×	×	×	×
WOTAS		√	×	×	×
Haptic Knob		√	√	×	×
Hasegawa		√	√	×	×

Kawasaki		√	×	×	×
Scherer		×	√	×	×
Braccio di Ferro	**Not applicable**	×	×	×	×
CADEN-7		√	×	×	×
Denève		√	×	×	×

EMUL		√	×	×	×
ESTEC exoskeleton		×	×	×	×
Furuhashi		√	×	×	×
Hybrid-PLEMO		√	×	×	×

Lam		×	×	×	×
Li		×	×	×	×
MACARM		×	×	×	×
Mathai		√	×	×	×

MIME-RiceWrist		×	×	×	×
PLEMO		√	×	×	×
Robotherapist		√	×	×	×
RUPERT IV		√	×	×	×

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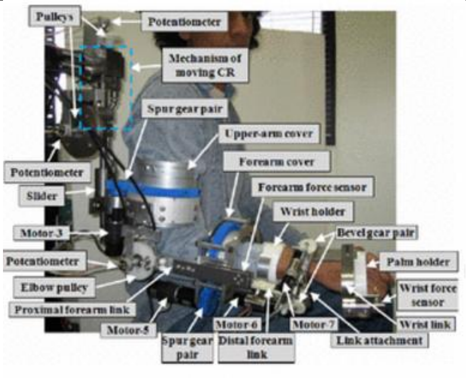
Salford Arm Rehabilitation Exoskeleton		√	×	×	×
Sophia-3	**Not applicable**	×	×	×	×
Sophia-4	**Not applicable**	×	×	×	×
SUEFUL-7		×	×	×	×
Takahashi		×	×	×	×
Tanaka	**Not applicable**	×	×	×	×

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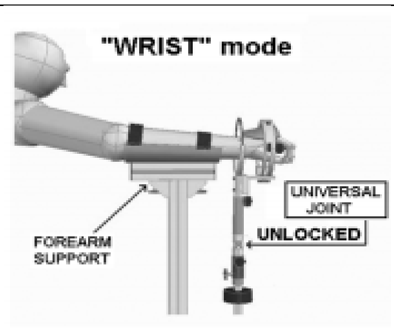
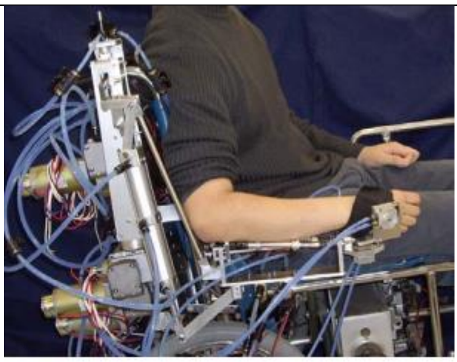
UHD		√	×	×	×
Umemura		×	×	×	×
UMH		√	×	×	×
Xiu-Feng		√	×	×	×

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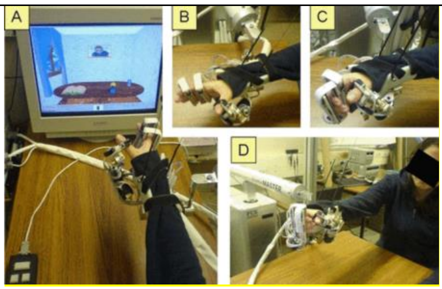
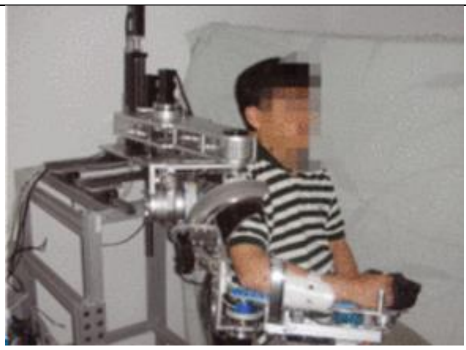
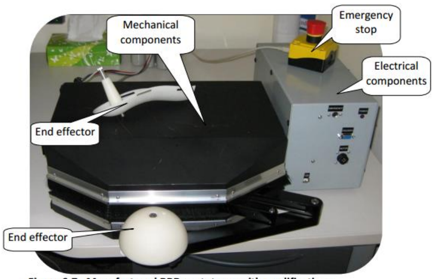
ArmeoPower		√	×	×	×
ArmeoSpring	**Not applicable**	×	×	×	×
ARMOR	**Not applicable**	×	×	×	×
Gentle/G		√	√	×	×
HEnRiE		√	×	×	×
IntelliArm		√	×	×	×

MUNDUS		√	×	×	×
ReoGo	**Not applicable**	×	×	×	×
Lu	 Figure 6-7. Manufactured RRD prototype, with modifications	×	×	×	×

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Appendix 3. Anthropometric data of children (males and females) upper arm and forearm length from 2 to 19 years

Data from: 'Anthropometry of infants, children, and youths to age 18 for product safety design'

Upper arm length (cm)

Age group	Number	Mean	s.d.	Min	95th	Max
2.0-3.5	211	18.5	1.4	15.0	20.9	22.3
3.5-4.5	228	20.3	1.2	17.7	22.3	23.6
4.5-5.5	263	21.9	1.3	18.5	23.9	27.1
5.5-6.5	217	23.3	1.3	18.8	25.5	27.1
6.5-7.5	226	24.7	1.4	20.7	26.9	28.6
7.5-8.5	192	26.0	1.4	22.1	28.4	31.0
8.5-9.5	250	27.5	1.5	23.8	29.7	31.5
9.5-10.5	252	28.6	1.6	24.6	31.6	33.9
10.5-11.5	280	29.8	1.6	24.8	32.3	35.7
11.5-12.5	287	31.0	1.8	26.0	33.8	36.7
12.5-13.5	314	32.4	1.8	27.9	35.5	38.8
13.5-14.5	271	33.5	2.0	28.6	36.7	38.5
14.5-15.5	262	34.5	1.9	30.3	37.6	39.8
15.5-16.5	197	35.1	2.3	29.8	38.5	41.9
16.5-17.5	221	35.2	2.3	29.8	39.0	40.9
17.5-19.0	156	35.8	2.6	31.3	39.6	48.4

Forearm length (cm)

Age group	Number	Mean	s.d.	Min	95th	Max
2.0-3.5	67	13.5	1.1	11.3	15.5	16.0
3.5-4.5	79	14.5	1.2	12.3	16.5	16.8

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4.5-5.5	76	15.7	1.2	12.6	17.6	18.0
5.5-6.5	77	16.8	1.3	14.1	18.8	19.9
6.5-7.5	76	17.7	1.5	14.5	20.4	22.2
7.5-8.5	64	18.6	1.5	15.1	21.1	21.9
8.5-9.5	81	19.3	1.5	16.5	21.9	23.5
9.5-10.5	75	20.3	1.5	15.8	22.6	23.8
10.5-11.5	97	21.0	1.7	16.3	23.5	23.5
11.5-12.5	96	22.4	1.8	18.7	25.4	27.6
12.5-13.5	100	23.0	2.0	19.2	26.4	28.8
13.5-14.5	82	24.1	2.1	19.0	27.7	32.1
14.5-15.5	87	24.2	1.9	19.6	27.0	27.9
15.5-16.5	63	24.9	2.2	20.5	28.0	30.6
16.5-17.5	74	25.0	2.2	20.8	28.3	29.0
17.5-19.0	46	25.1	2.7	20.0	29.5	29.8

Appendix 4. Arduino code for Testing Flexiforce Sensor

sketch_jul06c | Arduino 1.8.3 Hourly Build 2017/05/31 06:33

File Edit Sketch Tools Help

sketch_jul06c §

```
const int FSR_PIN = A0; // Pin connected to FSR/resistor divider

// Measure the voltage at 5V and resistance of your 3.3k resistor, and enter
// their value's below:
const float VCC = 4.98; // Measured voltage of Ardunio 5V line
const float R_DIV = 1000000.0; // Measured resistance of 3.3k resistor

void setup()
{
  Serial.begin(9600);
  pinMode(FSR_PIN, INPUT);
}

void loop()
{
  int fsrADC = analogRead(FSR_PIN);
  // If the FSR has no pressure, the resistance will be
  // near infinite. So the voltage should be near 0.
  if (fsrADC != 0) // If the analog reading is non-zero
  {
    // Use ADC reading to calculate voltage:
    float fsrV = fsrADC * VCC / 1023.0;
    // Use voltage and static resistor value to
    // calculate FSR resistance:
    float fsrR = R_DIV * (VCC / fsrV - 1.0);
    Serial.println("Resistance: " + String(fsrR) + " ohms");
    // Guesstimate force based on slopes in figure 3 of
    // FSR datasheet:
    float force;
    float fsrG = 1.0 / fsrR; // Calculate conductance
    // Break parabolic curve down into two linear slopes:
    if (fsrR <= 600)
      force = (fsrG - 0.00075) / 0.00000032639;
    else
      force =  fsrG / 0.000000642857;
    Serial.println("Force: " + String(force) + " g");
    Serial.println();

    delay(500);
  }
  else
  {
    // No pressure detected
  }
}
```

`

Appendix 5. Consent form

Title of Project: Design, implementation and analysis of a cost effective rehabilitation robot for children with cerebral palsy

Name of Researcher: Qiang Fu

Participant Identification Number for this trial:

Contents	**Please initial box**
1. I confirm that I have read the information sheet for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my medical care or legal rights being affected.	
3. I understand that the information collected about me will be used to support other research in the future and may be shared anonymously with other researchers.	
4. I understand that the information held and maintained by the University of Manchester may be used to help contact me or provide information about my health status	
5. I agree to take part in the above study.	

Name of participant:____

Date:____

Signature:____

If there is any problem, please contact Qiang Fu: Qiang.Fu@manchester.ac.uk