Development, Design and Evaluation of the CataPULT; A Mechanical Device for Upper Limb Rehabilitation of Stroke

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2013

Declaration of Authenticity and Author's Rights

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Date:

Acknowledgements

I would like to take this opportunity to express my sincere gratitude to those who have assisted me in the completion of this dissertation, especially:

Andrew Kerr, my dissertation supervisor for his continued support, guidance, patience and thought provoking discussions.

Stephen Murray, my workshop technician for his guidance and creative assistance in the development of the device.

Kevin Wilson, my student mentor for his constant mentoring, encouragement and support throughout the year and especially in this final stage of my project.

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Abstract

The purpose of this project was to design and evaluate a mechanical training device for the upper limb rehabilitation of stroke survivors. The importance of this issue is widely acknowledged, particularly given the rising number of stroke patients presenting with rehabilitation challenges. Therefore a feasible and clinically effective solution for rehabilitation of the upper limb is needed.

A critical review of literature examined theory and concepts pertaining to complications of general, stroke, rehabilitation of the upper limb, device design, testing processes and benefits and challenges of existing devices.

A three-phased approach was adopted towards the design and evaluation of the device named CataPULT; Development of device specification, Production of the device, and Testing of the device on a single healthy subject. Testing involved three assessments; Isolated range of motion; Elastics load capacity; and Functional movement.

CataPULT demonstrated the capacity for engaging three modes of operation; between 'Elastic', 'Free', and 'Locked' modes which are interchangeable within clinical environments with appropriate tools. Findings highlighted that CataPULT has the potential to support the arm and provide assisted movement through a functional range of motion to facilitate upper limb rehabilitation following stroke. The elastics enhanced device function by applying forces over the mechanical joints to assist in joint motion, thus reducing the energy required to perform functional activities.

Other advantages of the CataPULT identified in comparison with alternative technologies such as robotic devices were that the device involves a cost effective manufacturing process, components are readily available and inexpensive to replace, and the device is extremely portable at home and in the clinical environment. With further development of the device, additional benefits may be possible and to this end, further opportunities for research have been identified.

Chapter 1 – Introduction

This section provides an introduction to the research topic and ideas explored in this research project.

Stroke can be a severely debilitating condition and is one of the main causes of acquired disability in adults on a global scale (7). Recent advances in healthcare have increased the rate of survival of patients following stroke, which correlates with a rise in the number of stroke patients presenting with rehabilitation challenges. It is reported that 20% of stroke survivors require clinical treatment three months following stroke (8). Therefore there is a need to invest greater focus on the development of cost effective solutions to assist in the rehabilitation of stroke survivors.

The aim of this project is to design and evaluate a mechanical training device for the upper limb rehabilitation of stroke survivors.

In order to achieve the research aim the following objectives have been established:

- Carry out a review of literature to gain insight and understanding of theory and concepts pertaining to stroke rehabilitation, with particular focus on a critical review of existing devices
- Determine a list of desirable attributes that may be incorporated into the development of a comfortable, functional and portable device to assist functional movement of stroke patients
- Design an appropriate methodology for the development and production of the device
- Subject the device to an evaluation process involving a selection of testing phases
- Analyse and evaluate the potential of the device as an appropriate solution for upper limb stroke rehabilitation

The project consists of three phases:

1) Development of device specification,
2) Production of the device, and
3) Device testing on a single healthy subject

The thesis chapters are summarised as follows:

- Chapter one: Introduces the topic and provides rationale for research in this area
- Chapter two: Literature Review provides a theoretical foundation from which knowledge and understanding presented in literature can be further developed
- Chapter three: Methodology presents the method undertaken to achieve the project aim, involving a three-phase process for the development, production and testing of the device
- Chapter four: Results presents the findings obtained from the device testing process
- Chapter five: Discussion provides a discussion and conclusion on issues pertaining to the assessment of the device, research limitations and opportunities for further research

This project makes an original contribution to academia through the investigation, design and testing of a financially viable and clinically effective mechanical device to assist in the recovery of stroke patients. The outcome of this project will contribute towards research which aims to improve current rehabilitation practice in the upper limb rehabilitation of stroke patients.

Chapter 2 – Literature review

2.1 – Introduction

The literature review demonstrates an understanding of existing literature pertaining to stroke devices and methods of practice obtained from secondary research. Background research provides a theoretical foundation from which the researcher can further develop key concepts, design and device evaluation, and it is therefore critical to the underpinning of device development suitable for modern rehabilitation. The literature review satisfies the first project objective; to lay a theoretical underpinning for device fabrication, development and testing.

2.2 – Research Design/Approach

An exploratory approach has been adopted in the literature review to satisfy the project aim, as exploratory research can provide insight into areas of current interest, areas requiring further research, and in considering previously explored ideas in a new perspective (9). Critical analysis of existing literature considers the findings of previous studies, their contribution to knowledge, challenges encountered and the value of those findings in relation to the current research project (9, 10).

Tertiary research sources, particularly 'SUPrimo' - Strathclyde University's academic search system were initially used to locate appropriate sources of research articles prior to secondary research being reviewed. Whilst a wide range of literature was reviewed only seventy articles specifically focussed on stroke rehabilitation of the upper limb and of these, forty were central to addressing the first objective. The development of the device has thus been substantiated by a review of literature relevant to stroke rehabilitation devices addressing upper limb complications.

2.3 – Structure of the literature review

An outline of the structure of the literature review is as follows:

2.4 - An initial overview of complications associated with general stroke, and challenges specifically relating to the upper limb.

2.5 - A discussion on stroke rehabilitation of the upper limb; in particular - how upper limb stroke rehabilitation is delivered, its importance and clinical effectiveness.

2.6 - The latter chapter discusses theories and concepts pertaining to device design, prescription criteria and also reviews attempted technological solutions for upper limb stroke rehabilitation. This includes consideration of device challenges and limitations presented in previous findings and overview of the testing and evaluation processes of existing devices.

2.7 – The literature finally provides a summary of literature findings most relevant to the scope of the current project.

2.4 - Overview of Stroke, and upper limb challenges

This section provides an overview of general complications associated with stroke, and focuses on challenges specifically relating to the upper limb in stroke rehabilitation.

Stroke pathology:

A Cerebral Vascular Accident (CVA), or stroke (7, 11, 12), is the occurrence of brain damage resulting from occlusion of oxygenated blood to the brain; subsequent death of brain neurones can induce loss of brain function (13).

Stroke incidence/prevalence and disability:

Due to advances in healthcare, humans are facing an ever aging population with an increasing likelihood of stroke survivors (12, 14), and stroke is thus particularly prevalent in the elderly population (11, 12). In 2010, the prevalence of stroke

among subjects over the age of 20 was 2.8% (15), and of those over the age of 18, "2.7% of men and 2.6% of woman.. had a history of stroke" (15). Woman are at a higher risk of stroke than men (15). In 2009, fifteen percent of all health expenditures in the United States (US) were associated with cardiovascular disease and stroke - the highest expenditure for any major diagnostic group (15). It is projected that by 2030, prevalence of stroke in the US will increase by 21.9% (15).

Throughout all industrialised nations, stroke is the primary cause of disability (11, 12, 16-19). Over fifty percent of stroke victims survive, often with disability (12), and one third of survivors experience severe disability (11, 15).

A disability can be defined as:

> "*difficulty with activities of daily living or instrumental activities of daily living, specific functional limitations (except vision, hearing, or speech), and limitation in ability to do housework or work at a job or business*"(15).

Of particular relevance are difficulties associated with activities of daily living (ADL), and some specific functional limitations. For stroke patients, one of the most prominent goals of rehabilitation is the ability to complete ADL unaided and independently (16).

Symptoms of stroke:

Symptoms of stroke can include loss of sensation, coordination, spasticity, muscle weakness and hemiparesis (5, 11, 15, 20-23). Symptoms occur immediately following stroke (11), and can affect functional activities of daily life (21) long after the onset of stroke (4); twenty six percent depend on assistance for ADL (15). Stroke survivors' arm movements are slower and more reluctant to motion compared to normal subjects, even when faced with a functional task (5). Fifty percent of stroke survivors experience hemiparesis (15), yet difficulties are observed both unilaterally and bilaterally, where bilateral challenges primarily relate to correlated movements between arms (5, 22).

Upper limb deficiencies are present in eighty five percent of stroke survivors (11, 24), and of this population only fifty percent of patients demonstrate functional recovery (11). Hand function deficiencies present in sixty percent of survivors (25), and thirty to sixty six percent do not regain hand or arm function six months following stroke (17, 25). Despite this, rehabilitation of the upper limb is often abandoned following stroke (6), and successful functional recovery is only demonstrated in five to twenty percent of patients (17).

2.5 – Rehabilitative practice of stroke, and of the upper limb

The following discussion is based on literature pertaining to the practice of stroke rehabilitation of the upper limb. It has a particular focus on how rehabilitation is implemented, the importance of rehabilitation to recovery following stroke, and presents evidence of the clinical effectiveness of such rehabilitation.

Rehabilitative goal:

The goal of physical rehabilitation of the upper limb is to provide the "*best possible motor, cognitive and functional recovery*" (12).

Rehabilitation has traditionally been delivered on the premise that significant recovery of motor skills can only be obtained within the first year following stroke (4, 19); however more recent rehabilitative literature has concluded that intensive rehabilitation can introduce significant recovery to motor skills and to activities of daily living even after the first year following stroke (4). This supports the importance of rehabilitation to patients even after long periods of time since the stroke incident, and may disqualify previous doubt regarding the effectiveness of stroke rehabilitation.

Home discharge:

Table 2.1 below presents an analysis of stroke survivors' discharge destinations from hospital stay in the USA:

Discharge destination of stroke survivors	
Discharged home	~45%
	Of this group, 32% of patients continue use homecare services
Inpatient rehabilitation following discharge	24%
Skilled nursing facilities following discharge	31%

Table 2.1 has been created from a synthesis of data (15).

Table 2.1 reiterates the importance of independent or semi-independent rehabilitation following the occurrence of stroke. In 2010, it was reported that patients benefit from only 6.1 days in hospital prior to discharge (15). Giving consideration to the statistic that thirty to seventy percent of patients lack functional ability in their affected arm at point of discharge, a stay of 6.1 days in hospital appears to be a very narrow window of opportunity for assistance during this potentially traumatic time.

It is particularly notable that forty five percent of stroke patients are discharged to home, where rehabilitation is most likely an individual process. While at home, patients may gain aspirations to resume a normal functional daily life in the familiar comfort of their home. However, far from the hospital environment, rehabilitative staff and equipment, patients may feel isolated from assistance and guided rehabilitation therapy. While some patients are capable of such independence, and thus can feasibly recover at home, others may be more dependent on rehabilitative equipment, and are arguably at a disadvantage.

Conventional rehabilitation may have benefits over robot-assisted therapy for functional activities at home (26); unlike robotics, conventional rehabilitation may provide an easier method of integrating therapy into activities of daily living. This

may support alternatives to robot-assisted therapy for functional improvements of activities of daily living.

Psychology implications of stroke:

Should the patient find independence from guided rehabilitation particularly challenging, discharge to home may incur feelings of depression and of a lack of hope of rehabilitation for the patient involved. Post-stroke depression affects one third of stroke patients (15). Independent rehabilitation at home is particularly challenging because of the physical difficulties associated with stroke; this often results in reduced compliance in following home rehabilitation regimes (27).

The stages of motor relearning requires several key aspects from the patient, notably active participation, attention and motivation (11, 28, 29). This implies that consideration must be given to the patient's perseverance and willingness to work with staff and equipment to undergo rehabilitation. Thus, it is essential that rehabilitative equipment is designed to encourage assiduity and motivation in rehabilitation.

Independence vs shortages in clinician-patient time:

The prospect of patients training independently is highly important in modern rehabilitation. Limitations in healthcare funding often results in restrictions in the amount of time clinicians can spend with patients (27). It has been reported that shortages in clinical time dedicated to individual patients is the reason compliance with evidence-based guidelines have not been successfully implemented in therapy (14, 17, 30). Increases in clinician-patient time may therefore not be a feasible solution for improving stroke rehabilitation. Recent research has demonstrated that a reduction in therapist time can be compensated with appropriate technology, without compromise to the effectiveness of treatment (6). Thus, an alternative

solution suitable for providing independent rehabilitation is required to improve rehabilitation of stroke patients.

Whilst rehabilitation without the presence of a therapist is possible, exercises at home is often particularly challenging for patients who struggle to hold their arm against gravity, or who lack hand dexterity; such difficulties may lead to reductions in compliance at home (27).

Difficulties in upper limb rehabilitation:

Despite the debilitating impact stroke can have on the upper limb, delivery of rehabilitation to the upper limb is commonly abandoned (6). Functional recovery of the upper limb is more difficult than that of the lower limb, due to the complexity of upper limb function (11, 28). Yet other authors state that unilateral rehabilitation of ADL is more time consuming, more challenging, and equipment is more cumbersome, when compared to bilateral rehabilitation (6). Upper limb functional activities include "*locating a target, reaching (transport of arm and hand), grasping an object (grip formation and release) and postural control*" (11); normal functional activities of the upper limb require recovery of these tasks [Ashburn, 2009, cited in (11)].

Following stroke, patients quickly depend on the unaffected arm to perform activities of daily living, and dependency on the affected arm is reduced (21). For some patients, rehabilitation may therefore be a process of promoting recovery of the affected arm, while reducing habitual use of the sound arm.

Challenges in measurement of rehabilitative success:

One hindrance in measuring rehabilitative success, particularly when measuring the success of robot-assisted therapy, is that following stroke patients not only experience physical challenges, but also challenges in cognitive ability (21). As such, difficulty in the completion of a task with the assistance of a device may be a result

of either a deficit in the device's performance, or in cognitive limitations in addressing the task.

Rehabilitation and activities of daily living:

Activities of daily living requires a multitude of specific motor functions, including skills in hand dexterity and arm coordination (21). However, whilst ADL require motor skills, improvements to motor skills do not necessarily induce improvements to performance in ADL (25). As such, improvement to ADL requires the practice of ADL in addition to improvement to motor skills.

Rehabilitation of the wrist and hand is important in the ability to manipulate objects, which in turn is vital to most ADL (21).

Consideration to functional tasks in rehabilitation is vital to performance improvements in ADL (21, 25). Functional activity training and consideration to ADL, in combination with motor training such as robot-assisted therapy, is more effective than motor training alone (21).

Unilateral and bilateral rehabilitation:

ADL often require bilateral activity (21) however stroke patients often have major challenges with both unilateral and bilateral movements (5, 22). Abnormal synergy between the arms tend to occur during voluntary movement, however this finding is more applicable to the proximal arm rather than the whole arm (22). Bilateral complications exist due to abnormal muscle activation, and "*reflex response, voluntary movement, or both*" (22). One study concluded that unilateral rehabilitation is more effective than bilateral training (6); yet this may be due to the complex nature of synchronisation between the affected arm and the unaffected arm. Functional tasks involving bilateral coordination is a basic constituent of ADL; activities of ADL can range from simple symmetrical motions such as catching a

large ball (5), some cooking tasks (21), to complex, asymmetric motion such as the operation of drawers (5).

Conversely, research has highlighted that unilateral training alone does not suffice for restoration of bilateral function (5). Bilateral training not only requires unilateral motor skills, but also the involvement of crossover signals on either side of the brain, as both arms interact together (21). Bilateral rehabilitation should therefore involve simultaneous motion of both the affected and unaffected arm in order to stimulate crossover signals in the brain and ultimately improve bilateral function.

Successful approaches to rehabilitation:

A number of investigators recognise that intensive rehabilitation can significantly improve the recovery of stroke patients (4, 11, 17, 18, 27). Intensive therapy may not be applicable to severely affected patients, who may lack sufficient levels of motivation and thus require additional encouragement from a therapist (6, 26).

It is also recognised that repetitive rehabilitation assists in the reorganisation of neural structures in the brain, enhancing recovery (25, 26). Even simple repetitive rehabilitation may be more effective than other types of therapy in patients less affected by stroke (26).

In 2012, Hwang et al. found that upper limb rehabilitative therapy was dose dependant; suggesting that higher doses of rehabilitation induce greater recovery (25).

Intensive rehabilitation requires that therapy is delivered for extended periods of time, or for particularly stimulating or rigorous therapy sessions, yet the optimal amount of intensity required is generally unknown (21, 24). Rehabilitation timescales can range from only thirty to sixty minutes, delivered three times a week, to increased intensities in excess of ninety minutes provided five times a

week (21). Nine hundred cyclic repetitions of tasks is considered low, compared to 2,700 to 3,600 (21).

Current state of field and need for improvements in rehabilitation:

Whilst the etiology and risk factors concerning stroke are well recognised throughout the literature, there is a great necessity for further improvement in the recovery of stroke patients (11). The focus of rehabilitation has been on the recovery of functional independence, and as such, therapy focusing on functional recovery specifically of the paretic upper limb is commonly abandoned "in favour of [upper limb] compensation strategies" (6). This is driven by reductions in dedicated clinician-patient time, and rehabilitation adopting the understanding that the unaffected arm can compensate for affected arm deficits in functional ability (6).

Physiotherapy regimes have often been described as inconsistent and variable among therapists and hospitals (11). This will likely create a barrier for consistency in rehabilitation practice, and thus an increased tendency for variation in rehabilitative success.

2.6 - Review of attempted device designs, technological solutions and challenges associated with upper limb stroke devices

This section discusses theories and concepts pertaining to device design, prescription criteria and also reviews attempted technological solutions for upper limb stroke rehabilitation. This includes consideration to device challenges and limitations highlighted in previous research studies and provides an overview of the testing and evaluation processes of existing devices.

Robotics

One promising technology in the fields of stroke rehabilitation is robot-assisted rehabilitation (6, 21, 28). The main motivators for such research are the need for advancements in upper limb rehabilitation and the significant costs of healthcare (6). Robots may be programmed to perform specific tasks precisely, and can customise rehabilitation to meet individual needs (21). Furthermore, by virtue of the inclusion of electronic equipment robotics may help quantify the effectiveness of treatment (22). Robot-assisted rehabilitation may reduce pressures on healthcare staff, and while robotics may provide a cost-effective method of rehabilitation for some patients, it may be uneconomical for others depending on many variables (6).

Passive mode:

Passive modes are generally modes incorporated into a robotic device by which energy is provided by the robot to move the affected arm; no user input required. Such modes can be useful for movement of the arm in "meaningful ways" (27), possibly in the prevention of muscle contractures as the arm is moved through functional positions, and to remind the patient of the functional capabilities of their own arm, setting aspirations for recovery.

Variation in the effectiveness of robot-assisted therapy:

Literature has shown that patients often demonstrate excellent compliance with robot-assisted therapy (25), and such therapy has great potential (6, 17, 21) especially for subjects with moderate to severe impairment (6). However studies question the effectiveness of robotics, and evidence of its success in literature appears sparse and varied (17). Moreover, there are significant limitations in the validity of literature pertaining to the success of robot-assisted therapy (17).

It has been reported that robot-assisted therapy provides no significant effect (17); yet this conclusion is inconclusive - many studies utilised small sample sizes (17). Sensitivity analysis conducted on such studies showed significant improvement to motor function (17).

It is claimed that robot-assisted therapy can induce significant improvements to motor function of the upper arm (17, 24); however it is unclear as to whether recovery was specific to the arm itself, or whether compensation strategies of the upper limb and trunk were considered (17). It is crucial to differentiate between "*genuine upper limb motor recovery*" and compensation strategies of the upper limb and trunk in the assessment of recovery utilising intervention (17).

Furthermore, many studies claiming to investigate arm recovery have instead investigated recovery of the proximal arm, neglecting the distal arm such as the hand, fingers and wrist (17, 25). Measures of improvement are different for the upper and lower arm, and it is therefore difficult to quantify motor improvement of the upper limb (17).

Whilst robot-assisted therapy can improve bilateral coordination, no solitary robot-assisted therapy provides adequate improvement to bilateral coordination for purposes of functional tasks (5).

<u>Robotics - reductions in effort</u>:

One consequence of providing assistance is a reduction in voluntary effort. However, conventional rehabilitation requires mental stimulation as well as physical stimulation (28). Rehabilitation with the assistance of a robot may in fact reduce the mental and physical stimulation required for recovery, and may subsequently reduce the effectiveness of therapy (27).

<u>Attempts in the measurement of robot's effect on ADL</u>:

From a large systematic review of studies, it has been concluded that robot-assisted devices provided no improvement to unilateral ADL (17). Regarding bilateral ADL,

robot-assisted therapy has not consistently demonstrated improvement (5, 24). However in many studies, valid instruments that measure dexterity of arm and hands were mostly absent (17, 21). It is therefore argued that measurement scales adopted were not representative of normal function; authors note that it is difficult to recreate normal activities of daily living in a clinical rehabilitation setting (21).

Moreover, many measurement scales adopted for the assessment of patient progress fail to take into account the gradual recovery processes of the upper limb following stroke (17) such as neurogenesis (12). This suggests that such measurement scales consider only whether the ADL activities were completed, rather than reflecting gradual patient progress in each attempt of ADL. Ultimately, there appears to be insufficient evidence to conclude that robot-assisted therapy provides improvement to ADL, in both unilateral and bilateral therapy (5).

Robotics and portable devices:

Robotic devices are generally restricted to the clinical environment. Portable devices can be more effectively used in rehabilitation programmes (31). After six months of treatment, however, conventional devices used at home were more effective than robot-assisted therapy (6, 17). For a true comparison, robot-assisted therapy requires integration into the home environment.

Robotics and independent recovery:

Robotics can offer patients independent rehabilitation, i.e. rehabilitation without the continuous assistance of clinicians (17, 27), and can thus allow the patient to progress at a rate at which they are comfortable (17). However, safety concerns arise regarding the independent use of electronics with an unsuspecting patient (27), and staff may inevitably be required within a safe distance to ensure the safety of the patient. As such, it may be more appropriate to disregard the idea of true independent rehabilitation when utilising robotics.

Intensity of rehabilitation:

High intensity rehabilitation is well recognised as a key factor in recovery (11, 18, 26, 27). It is claimed that robot technology may provide intense, repetitive rehabilitation over long periods of time (17, 25) while minimising fatigue (21); this may be advantageous over clinician-guided or alternative therapies (25, 31). However, when the intense and repetitive nature of robot-assisted therapy is replicated in alternative rehabilitation regimes, robot-assisted therapy holds no particular advantage over alternative therapies (17). This suggests that some successes in robot-assisted therapy were in fact due to the intensity of rehabilitation rather than the use of robot-assisted therapy itself.

Virtual reality:

Virtual reality therapy involves the combination of robot-assisted therapy and interactive games or simulations (11, 12), and can be a particularly stimulating therapy tool (11, 12). One study has described patients' experience of virtual reality therapy as "*less boring, less confusing, and easier to track progress*" (27). It can provide the patient with visual feedback to review their efforts and progress (25, 27), is relatively easy to implement in the clinical environment (11), and provide the clinician with measurement data for further evaluation of patient performance (12).

However, therapists have reported that the additional components of virtual reality such as glasses and heads up displays pose as an additional distraction to patients already experiencing visual or cognitive difficulties (11, 13). Furthermore, therapists are required to calibrate the virtual reality software prior to its use (27), adding to the complexities of the use of virtual reality.

It may be argued that virtual-reality ultimately aims to replicate a realistic environment, and that if patients can be subjected to their natural, realistic environment with a comfortable, functional device compatible within a patient's typical environment, the advantages of virtual-reality may be matched by an appropriate, alternative device.

Liao et al. state that:

> "*practicing motor skills in a natural context would remove the barrier between robotic training and real life and therefore facilitate impaired arm use in situations of real life.*" (21)

This may support the idea that practicing in a realistic, natural context would promote physical rehabilitation over virtual reality, and help prepare patients for activities of daily living.

Viability for robotic investment:

Robotic devices can be costly (27), and considering their potential benefits, some researchers assert that more consideration should be given to low-cost robot-assisted therapy (6). However, with a shortage of evidence supporting the use of robotics in upper limb rehabilitation, it may be more prudent to investigate the specific reasons for benefits of robot-assisted therapy, and the reasons for improvement in upper limb rehabilitation across all therapeutic interventions rather than investing solely on emerging robot-assisted therapy. Should it be concluded in retrospect that the benefits of robot-assisted therapy were in fact replicable in alternative forms of rehabilitation, investment specifically into the development of robot-assisted equipment is not an efficient and financially viable strategy for the improvement of upper limb healthcare.

Earliest robot:

The earliest robot, studied in 1991, involved a "*simple therapy robot*" capable of recording and repeating movements (11). The presence of many drawbacks in study design, such as the absence of a measurement system for the assessment of movement hindered the overall success of this early study (11).

SEAT device:

The Simulation Environment for Arm Therapy (SEAT) device (11) was subsequently developed, and provided rehabilitation based on bilateral mirror motion. The SEAT utilised a steering wheel with hand sensors to assess applied bilateral arm forces. Arguably, one drawback of the SEAT system is its assumption that patients are capable of understanding and responding to triggers within the driving simulation environment; it is assumed that participants understand the concepts of 'driving', and are thus capable of responding to driving stimulatory triggers appropriately. Various authors suggest that the SEAT system encouraged interest in the subjects, notably due to functional involvement of the affected arm (11).

MIME device:

The Mirror-image motion enabler (MIME) (figure 2.1 below) reconsidered mirrored rehabilitation (11). The non-affected arm guides the affected arm in a mirror-like fashion (11, 17), and provides bilateral training (5).

Original authors claim that the MIME provides training for the upper limb, however only shoulder motion is described; finger motion is apparently uninvolved in motion (6). No negative effects were reported (11), and other researchers question its benefits, suggesting a lack of incentives to validate use of the device (17).

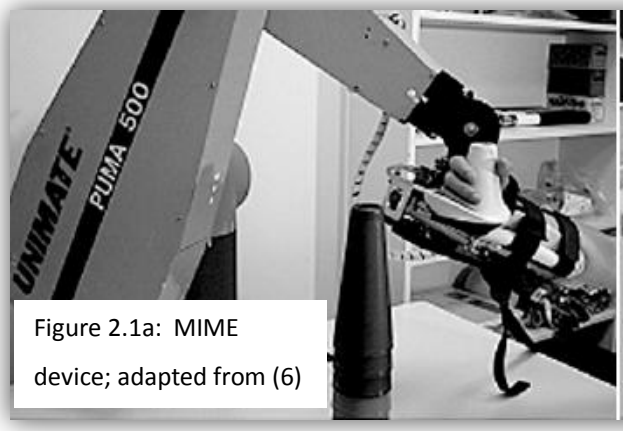


Figure 2.1a: MIME device; adapted from (6)

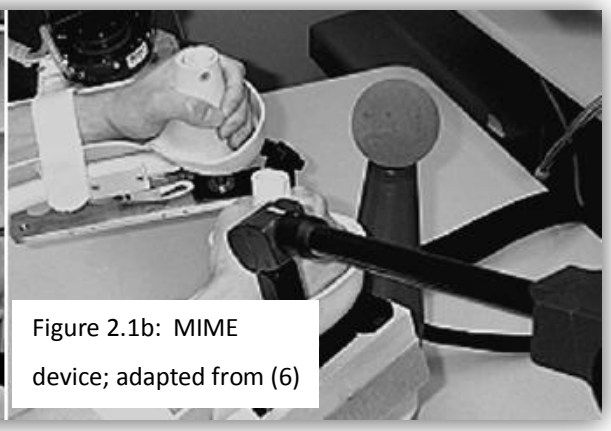


Figure 2.1b: MIME device; adapted from (6)

MIT-MANUS device:

The MIT-MANUS device (figure 2.2 below) was specifically designed for neurologic rehabilitation (4), and to be interactive, user-friendly, and for use in the clinical environment (11). The MIT-MANUS device may not be cost-effective (6), and movements are limited to the horizontal plane (17). Initial studies presented significant recovery (6, 11), however only ten of twenty subjects trialled the device. Subsequent investigations using 76 subjects demonstrated improved rehabilitation, and demonstrated the persistence of improved outcomes after three years (11). Limitations exist in the range of rehabilitation therapies encouraged; in the potential for data collection for device evaluation; and in the absence of bilateral rehabilitation, as provided by the SEAT and MIME devices (11).

The InMotion robot is a modified version suitable for the commercial market (17).

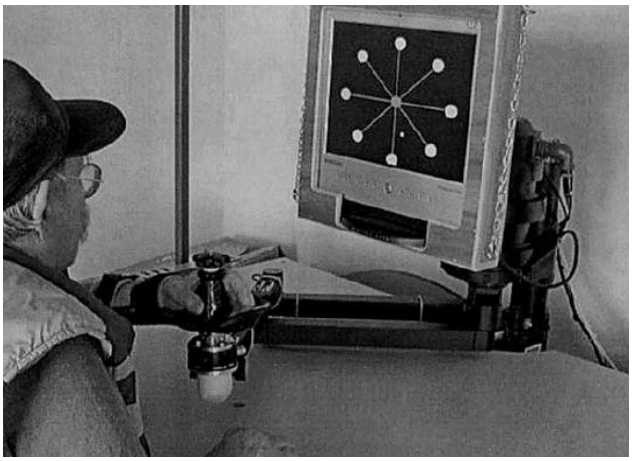


Figure 2.2: MIT-MANUS device, adapted from (4)

Bi-Manu-Track device:

Unlike the MIME and MIT-MANUS devices, the Bi-Manu-Track device provides distal arm rehabilitation (21). Both parallel and mirrored movements provide bilateral flexion and extension of the wrist, and forearm pronation and supination (17, 21). The device provided three operational modes, yet an additional mode was recently developed involving mirrored motion dictated solely by the affected arm (21).

ADLER device:

The Activities of Daily Living and Exercise Robot (ADLER), depicted in figure 2.3, provides unilateral training utilising virtual reality, focussing on functional activities (5). Preset trajectories based on activities of daily living guide the affected arm.

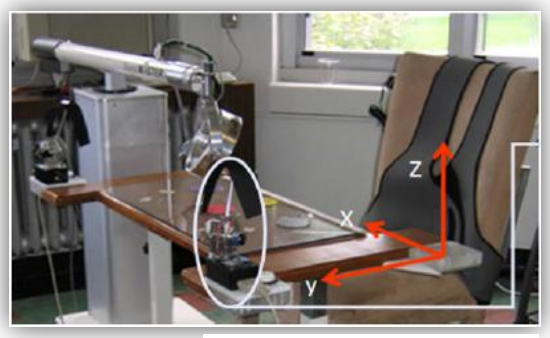


Figure 2.3: The ADLER device. Adapted from (5)

The T-WREX:

The Therapy Wilmington Robotic Exoskeleton (T-WREX) is based on a passive orthosis and supports the arm against gravity. However the T-WREX also records arm position, and by the use of sensors, measures forces in the hand in response to triggers on an on-screen game simulation (27). It aims to address previously recognised setbacks in robotic rehabilitation, conventional therapy, and passive orthoses (27). It is claimed that a larger range of motion for active tasks can be obtained when compared to normal, unassisted motion (27). The T-WREX provided improvement to patients moderately or severely affected by stroke (12).

Similarly to any simple passive device lacking electronic components, the T-WREX may be safer to use than robotics (27). Furthermore, passive devices require effort for the initiation of movement, and are thus associated with reduced risk of relaxation and reduction in effort (27).

Mechanical devices - Upper limb orthotics:

Common orthotic devices suitable for rehabilitation of the upper limb include the mobile arm support, and the balanced forearm orthosis, however options for adjustability are restricted (27). Furthermore, it is difficult to obtain feedback relating to rehabilitative progress of the patient (27).

Mechanical devices such as arm orthoses are associated with reduced costs, fewer safety concerns, and can facilitate independent rehabilitation (27). It is asserted that conventional rehabilitation may have benefits over robot-assisted therapy for functional activities at home (26). Devices used in the home environment were more effective than robotic devices after six months of treatment (6, 17), supporting the use of portable devices for use at home as an alternative to robotic devices.

Housman et al. highlight that with provision of orthoses, it is more difficult to assess the contribution of the patient with regard to the application of forces to the limb (27). If the device applies a constant, static force to support the arm, the effort required for self supporting the arm is reduced.

As previously asserted, passive devices such as orthoses require effort for the initiation of movement, and are thus associated with reduced risk of relaxation and reduction in effort (27).

Cost effective solutions for upper limb rehabilitation:

Robotics for rehabilitation of the upper limb can be expensive (27). It is suggested that cost-effective alternatives to robot-assisted rehabilitation should aim to deliver equivalent benefits, while striving to incorporate the advantage of reduced costs (17).

Because of the cost of equipment, assistance is often unavailable to stroke patients (6). It may be argued that cost effective equipment suitable for independent rehabilitation may reduce challenges with costs associated with therapist assistance.

Functional range of motion at the shoulder:

Depending on the stage of recovery, stroke survivors may present with residual muscle contractures or joint deformities; such complications influence the range of

motion of joints. Consideration must thus be given to a joint's range of motion for both normal and stroke subjects when considering device development. One study has evaluated ranges of motion of the anatomical joints of the upper limb during reach to grasp movements for normal and stroke subjects (3).

The horizontal shoulder rotation for healthy and stroke subjects can be observed in figure 2.4 (below). For healthy subjects, the maximum range of horizontal shoulder rotation was approximately 80°, with seventy five percent of subjects able to obtain 70° or less. Stroke subjects fared similarly, falling just short of angles obtained by normal subjects. The graphs suggest little difference in performance of horizontal shoulder rotation between normal and stroke subjects.

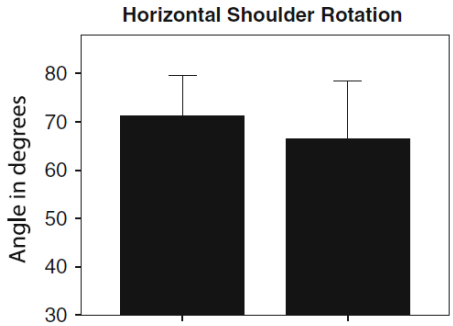


Figure 2.4: Horizontal shoulder rotation (3)

Upward shoulder rotation can be observed in figure 2.5 (below). From the chart, the maximum range of motion normal subjects can obtain is approximately 75°, compared to stroke subjects of 70°; however there appears to be less variance in the data for stroke patients as seventy five percent of subjects can only obtain approximately 60°. Thus, there appears to be a small reduction in stroke subjects' capabilities to perform upward shoulder rotation when compared to normal.

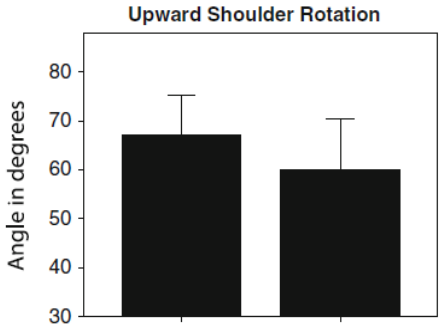


Figure 2.5: Upward shoulder rotation (3)

Internal rotation of the shoulder (figure 2.6 below) involves rotation of the arm about the longitudinal axis; positive values represent internal rotation (3). From the chart, internal rotation of the shoulder between subject groups are functionally analogous between normal and stroke subjects, and 75% of subjects require 40° internal rotation or less. Despite the value of internal shoulder rotation being relatively low, compensation strategies should not be an option when overcoming device design challenges.

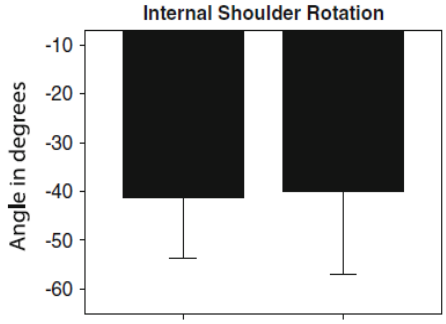


Figure 2.6: Internal shoulder rotation (3)

Values of elbow flexion (figure 2.7 below) when compared between healthy and stroke patients is a significant consideration – all healthy subjects' elbow angles are less than approximately 25°, and almost stretching into extension, compared to only 75° of stroke subjects' angle being less than approximately 40°. We can conclude that stroke subjects tend to demonstrate large values of elbow flexion in reach to grasp movements. Stroke subjects may have demonstrated an attempt to compensate joint angles with the purpose of reducing the moment arm around the elbow in the reach to grasp movement, thus decreasing dependency on musculature. This is in agreement with the common presentation of muscle weakness in the stroke population (5, 11, 20-22).

Figure 2.7 – Elbow flexion (3)

2.7 – Summary of most relevant literature findings

To summarise, literature expresses a need for developments in the field of upper limb rehabilitation of stroke. It is evident that stroke brings significant difficulty in completing activities of daily living, which is one of the main concerns of patients during rehabilitation. Recent trends in rehabilitation practice demonstrate a greater level of independent therapy, and thus a greater need for the delivery of rehabilitation with less clinician involvement.

Successful recovery for the majority of patients involves intense, repetitive rehabilitation delivered over extended periods of time. Robot-assisted therapy has shown significant potential for improving rehabilitation, yet some authors believe it is in the manner of how robot-assisted therapy is delivered, rather than the literal use of robotics, that brings positive outcomes to recovery. Robotics can also be expensive and impractical in portability, which may have significant implications on healthcare investment.

It may be possible to implement the benefits of emerging rehabilitative technologies such as robotic-assisted therapy to less expensive, more readily available alternative therapies, while facilitating intense, repetitive, independent rehabilitation through the use of a mechanical device.

Chapter 3 – Methodology

3.1 – Introduction

This chapter presents the method undertaken to achieve the project aim: to design and evaluate a mechanical training device for upper limb rehabilitation of stroke survivors.

The methodology chapter is broken into the following subsections:

3.2 - Methodological approach

3.3 - Phase 1 – development of the device

3.4 – Phase 2 – device production

3.5 - Phase 3 – Testing the device

3.6 – Ethical considerations

3.2 - Methodological approach

The project followed three phases:

4) Development of device specification,
5) Production of the device, and
6) Device testing on a single healthy subject

The study can be classified as a pre-test/post-test design, because it initially measured change in kinematic motion before and after intervention using the device (32). Device testing added originality in evaluating the potential for device enhancement by the addition of elastics. Elastics provided an active mode of function which provides patients with assisted movement to compensate for muscle weakness or control, to further assist rehabilitation.

Phase 1: Development of device criteria

Design considerations

Based on key challenges discussed in the literature review, the following attributes for the device were considered desirable:

Physical properties

- It should be lightweight. Stroke patients may present with hemiplegic muscle weakness (5, 11, 20-22), and will thus experience additional difficulty with a heavy device. A lightweight device aids in comfort when donned (due to reduced suspension forces), aids device portability, and eases donning, doffing and device fitting.
- It should be portable. The device's size should permit portability, and therefore facilitate use in both clinical and home environments, and be portable between environments.
- It should be strong and durable. Assurance of robustness and durability must be delivered for efficient healthcare investment. The device must also be expected to endure stroke-specific challenges such as in counteracting sizable, uncoordinated forces that stroke patients frequently exert (33).

Comfort

- It should be comfortable to wear for extended use.

Fitting and adjustment

- It should facilitate a comfortable and simple fitting procedure.
- It should facilitate easy donning and doffing.
- It should be adjustable to meet patient-specific dimensions, and it should be possible to make adjustments easily within the clinical environment.

Easy to see and comprehensive

- Functional components should be easy to see, and key device components should be free from visual obstruction. Stroke patients may present with difficulties with vision, and the device should take into account generic difficulties associated with stroke.
- It should be based on a simple, comprehensive design to assist in both device adjustment, ease of donning and doffing, and facilitate patient comprehension. Patients' comprehension is particularly important should the device be used at home – in case of emergency, patients and relevant emergency professionals should demonstrate the ability to quickly and easily remove the device.

Specific functions

- It should support sufficient load to suspend the weight of the arm.
- It should allow locking in specified positions, and permit ease of movement. The device is required to feature a locking mechanism to facilitate resistance against gravity, yet permit free and assisted motion
- Mechanical joints should facilitate a functional range of motion
- Functional movements should be achievable when wearing the device
- It should accommodate detachable components. Components such as a palm rest should be detachable to facilitate individual progress of patients, as not all patients require all attached components.

Manufacturing considerations

- It should facilitate affordable and feasible fabrication

Modes of operation

The device should feature the following three interchangeable modes of operation:

1. Elastic mode: The addition of elastic bands to induce elastic performance. The patient thus moves with assistance by the elastics. The elastic bands chosen, in addition to the particular nodes chosen for elastic attachment determines the extent of assistance provided.

2. Free mode: Elastics do not take effect, and all joints on the device can rotate freely. Lateral flexion, abduction, adduction, internal and external rotation were possible.

3. Locked mode: Where the elbow and shoulder joints are locked in various positions. The shoulder joint will be locked in positions of lateral flexion, however with the existing design abduction, adduction, internal and external rotation could not be locked. The elbow joint can be locked in various positions and can be set by the use of a regular 'flat' screwdriver.

Phase 2: Device production

Original design - Incare^{tm} orthosis design

The device design is based on an orthosis granted for the purpose of this project. The device is manufactured by "InCare^{tm}". Images of the device, taken by the author, are presented in figures 3.1-3.3 below.

Figure 3.1 – Original Incare device. Source: Author's own photographs, taken July 2013.

Figure 3.2- Shoulder joint with locking mechanism

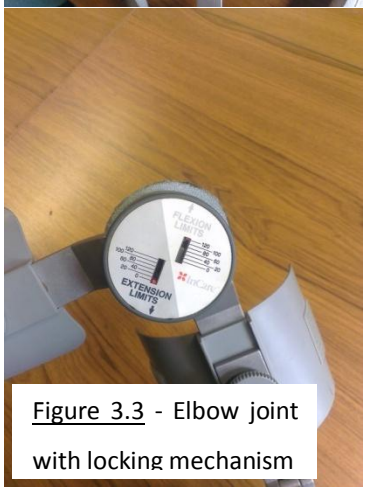


Figure 3.3 - Elbow joint with locking mechanism

The device provided a variety of functions. It featured shoulder and elbow joints, each with adjustable locking mechanisms. Velcro® straps were attached to the buckles for suspension across the torso. By design, motion at the shoulder was limited to a set range of motion.

Passively, the shoulder joint permitted:

1. Neutral internal/external rotation, up to 90° external rotation with range limiting bolt; extended range of up to 180° is possible upon removal of the bolt; no internal rotation was permitted.
2. Abduction up to 90°; no addition was permitted.
3. No flexion or extension of the shoulder was permitted as no joint for such motion was incorporated into the original system

Motion at the elbow provided an adequate range, permitting:

1. Elbow flexion, up to about 120°, and 0° elbow extension

A cylindrical socket existed for insertion of a device for the hand such as a palm rest, however no appropriate componentry was available, and was thus given consideration in the required modifications.

The device was adjustable for specific subject lengths of the humerus and forearm.

Device modifications:

The device required extensive modification so that it matched intended device criteria as close as possible. A full specification sheet is presented in appendix I.

1. Addition of palm rest and related components.

   a) Addition of a metallic palm extension bar, attached to the forearm socket as located on orthotic device; coloured dark grey in figure 3.4. Must be semi-fixed (detachable) to existing socket.

   b) Palm rest bar; 'T-shaped' bar. Metal bar securely fixed to end of bar in part 1. a), coloured orange in figure 2. Supports the palm rest in 1. c).

   c) Addition of soft Velcro on palm rest. Palm rest supported in position by a metal bar as in part 1. b).

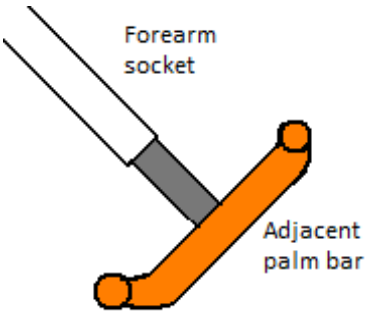


Figure 3.4 – Palm rest
(Author's own design)

2. Addition of elastic band attachment nodes across elbow joint.

   a. Elastic bands attached to the forearm and upper arm sections as appropriate. Elastic band attachment nodes as depicted in figure 3.5; provision of 'T-shaped' pins for easy elastic band attachment and removal.

   b. Elastic bands pass anteriorly and posteriorly to the elbow joint, and tension is at equilibrium when elbow is slightly extended at about 110° extension.

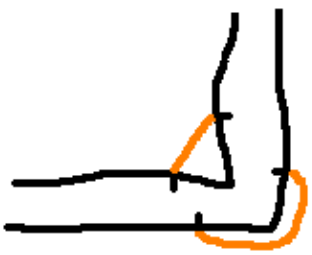


Figure 3.5 – Elbow elastics
(Author's own design)

3. Addition of elastic bands, and elastics attachment nodes across shoulder joint.

    a. Similar to 2. Elastic bands may pass anteriorly, laterally, medially, and posteriorly to shoulder joint. The device can be set up to assist in movement by appropriate positioning of elastics. In a 0° position, tension is at equilibrium anteroposteriorly, mediolaterally and in rotation. These elastics facilitate 'Elastic' mode of the shoulder.

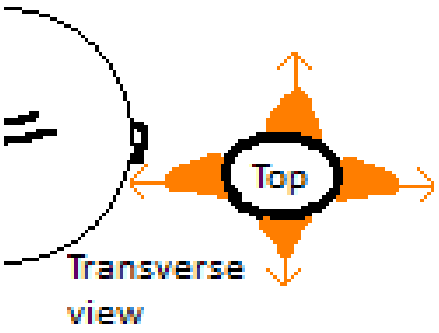


Figure 3.6 – Shoulder elastics (Author's own design)

4. Elastic bands across shoulder for internal/external rotation. Regular elastic bands of sufficient length are attached to the elastic attachment nodes.

5. Removal of external rotation stop bolt

    a. At the shoulder joint, a bolt exists to restrict the range of shoulder rotation from 0° to 90° horizontal external rotation. Removal of the bolt will permit up to 180° external rotation.

6. Addition of soft Velcro to shoulder joint

    a. A layer of soft Velcro added to the proximal section of shoulder joint is added, to prevent impingement on the skin of the axilla as lateral shoulder flexion was initiated.

The CataPULT device:

The resulting manufactured product was named CataPULT to reflect the elastic nature of this Passive Upper Limb Trainer. The device does not reflect the sudden elastic propulsion of a true traditional CataPULT; instead, the elastics behave in a adjustable and controlled manner. Details of the resulting modified device, such as available modes of operation, ranges of motion and tests of functional ability are presented in the Results chapter. The CataPULT device can be seen in figure 3.7.

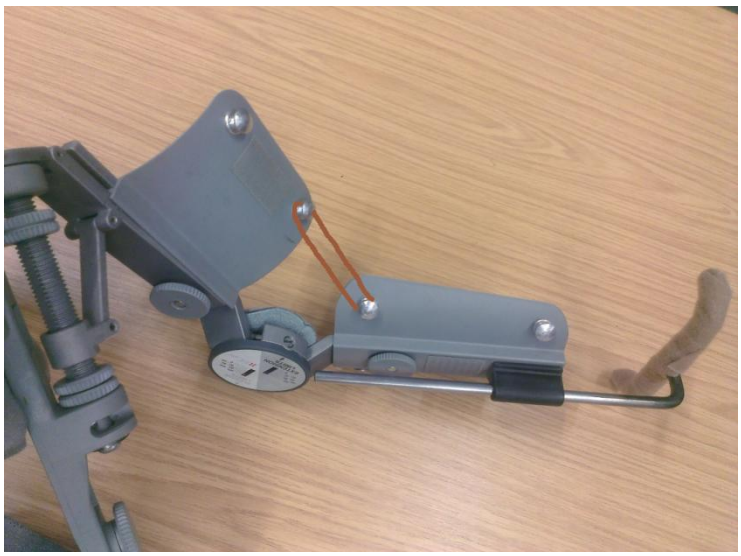


Figure 3.7 - The CataPULT arm section following modification

Six regular elastic bands were attached to the nodes, at a position dependent on the degree of assistance required. The elastic band attachment nodes are represented by the metallic 'T' shaped pins on the cuffs of the device, and the soft Velcro material can be seen across the palm rest bar towards the hand section. The palm rest, complete with the soft Velcro attachment, can be seen distal to the forearm segment.

Phase 3: Testing the device

The CataPULT was tested against the stated criteria (see page 34). Time restrictions prevented the testing of all these properties, therefore the evaluation was limited to the main mechanical properties of the device, i.e. the available range of motion, the capacity to support a load and behaviour during functional movements.

Assessment of isolated range of motion

The CataPULT is required to provide therapy incorporating a functional range of motion. An assessment of the range of movement permitted by the device is critical to a demonstration of its capacity for clinical benefit.

An assessment of joint motion was carried out to quantify the range of motion permitted by the mechanical joints. A goniometer was used to quantify such motion. Both the shoulder and elbow joints were evaluated using this approach; yet evaluation of the wrist section was not included as no mechanical joints for the wrist and hand were featured on the current prototype.

An assessment of the range of motion while wearing the CataPULT was conducted on the following joints:

The shoulder joint:

- Abduction and adduction
- Internal and external rotation

The elbow joint:

- Flexion and extension

Assessment of elastic load capacity

An assessment of the lifting capacity of the elastics has been conducted to evaluate the effectiveness of the elastic system with the current prototype. Quantitative data was collected from a series of mechanical tests which determined the maximum load of each elastic-supported joint. The rationale behind the series of tests was to assess the impact of elastics on load bearing capacity, which complies with experimental design; "*to test the impact of an intervention on an outcome*" (34).

The CataPULT was clamped to a desk vice, and weights of various magnitude were attached at calculated positions along the device arm in order to simulate a normal and exaggerated weight of the anatomical arm.

Weights were positioned at the centre of mass (CoM) of the particular arm segment being tested; table 1, which provides a summary of body segment parameters, was referred to for locations of CoM. It has been assumed that the overall length of the arm extends from the centre of rotation of the shoulder to the distal portion of the palm rest.

SUMMARY OF BODY SEGMENT PARAMETERS

SEGMENT	LENGTH / HEIGHT	% OF BODY MASS	C. of M. as % of length from proximal joint	RAD. OF GYRATION / LENGTH
Entire Arm	0·44	5·97	43·1	0·24
Upper Arm	0·186	3·57	46·1	0·26
Forearm + Hand	0·254	2·4	42	0·25
Forearm	0·146	1·8	42·5	-
Hand	0·108	0·6	43·3	-
Entire Leg	0·53	15·01	41·5	0·24
Thigh	0·245	9·46	42·7	0·23
Shank + Foot	0·285	5·55	46·7	0·29
Shank	0·246	4·2	40·4	-
Foot	0·039 (Vertical)	1·35	-	-

Table 3.1 – Summary of body segment parameters (2)

Each joint undergoing assessment was loaded to the point at which the joint rotated past the horizontal level - in each case past 90°, due to gravitational pull acting on the arm and additional weights. Weight measurements were rounded to the nearest 10g. Six bands were used to assess each joint position, as a maximum of six elastic bands adhered to the elastic attachment nodes.

The adherence of the elastic bands to the CataPULT implemented three methods of elastic band attachment. Six bands were attached to a pair of nodes at either side of the joint, covering a short distance. Alternatively, the six bands could utilise one short and one long distance node, hence stretching over a larger distance across the joint. Combined distances aim to make maximum use of the attachment nodes, and utilise two sets of six-ply elastic bands, stretching over both short and long distances. Values for combined distances at the elbow are not presented as it was simply unfeasible to fit twelve elastic bands to one attachment node. Increasing the number of nodes at the elbow, or replacing the current nodes with a more accommodative node would rectify this issue.

Due to the particular position of elastic attachment nodes on the upper arm in relation to the axilla cuff, lateral shoulder flexion could not be tested without accidental release of the elastics. Solutions to this problem and similar problems with elastic attachment are discussed in the discussion chapter.

Whilst the tests conducted were limited as they only evaluated the isolated strengths of elastics incorporated into the device, the device was not worn by patients during the tests which therefore provides opportunity for further research.

Assessment of functional movement

Due to limitations in motion permitted by the current prototype, particularly in shoulder flexion, the scope for assessment of the device's existing ability regarding activities of daily living was reduced. However, consideration to some functional tasks was still possible, and a series of functional activities were selected for the evaluation of the current prototype during functional tasks.

A single case study was used for the comparison of joint angles with and without the CataPULT. The participant was young and healthy with no known history of difficulties in physical or cognitive ability and is of right hand dominance.

The Vicon motion capture software (Vicon, Oxford, UK) was used to quantify kinematic movement of the elbow and shoulder. The motion capture system first underwent a calibration and set up process as specified by manufacturer guidelines. Figure 3.8 presents an anterior perspective of marker placement used for the upper limb model; additional markers were placed posteriorly at the level of C7 vertebrae and the middle back. An example of the visual marker set up on the participant is demonstrated in figure 3.9 on the next page.

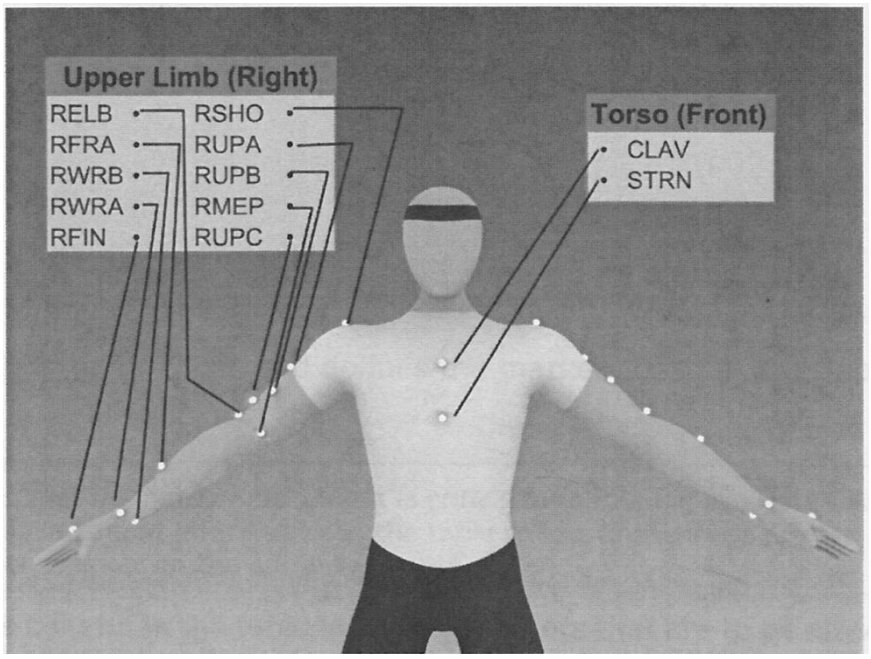


Figure 3.8 - Vicon Marker placement (1)

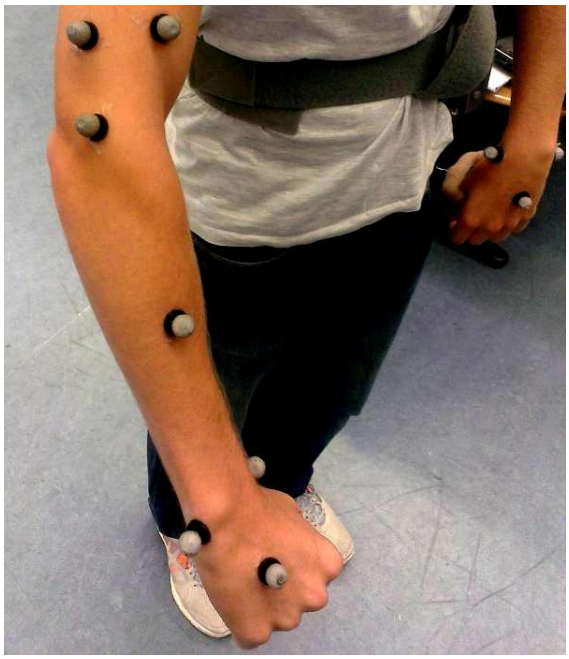


Figure 3.9 - Example of markers used

Data were sampled at 100Hz, and exported to a spreadsheet file for further analysis. The wrist and hand joints were not considered due to the absence of mechanical joints on the prototype appropriate for the rehabilitation of the wrist and hand. Data analysis is discussed later in the methodology section.

Each functional movement was initially performed by the free, non-braced arm, followed by the arm donning the CataPULT device.

Reach to grab motion: The importance of successful reach to grab movements is commonly expressed throughout literature (3, 5, 6, 11), and was thus included in the assessment of functional activity. This movement required the subject to stand in a comfortable position, 'reach out' and grab a lightweight object from atop a tall stool, and return to a comfortable position.

Teeth brushing motion: A second functional activity chosen for device evaluation was 'teeth brushing'. This activity requires medial movement of the arm, and requires delicate control of the hand and a terminal device, and may be a good

indicator of both intricate control of the device and in its ability to facilitate self-care tasks towards the middle of the body. The subject was required to stand in a comfortable position, and reach towards the centre of the mouth, performing a 'teeth brushing' motion, and subsequently returning to a comfortable position.

Mouse operation motion: Giving consideration to increasing trends of modern day computer use, the concluding evaluation of functional ability comprises of the simulated operation of a computer 'mouse'. The subject was required to move their arm across a tabletop in likeliness to operating a 'mouse'. This activity may provide a good indication of the degree of 'smoothness' of hand dexterity in a position of extended reach, in addition to providing an insight into generic mediolateral functional ability.

Data analysis

Data obtained from the Vicon motion capture system were subject to a number of analysis stages prior to presentation in graph format. Motion capture markers were represented by an upper limb model provided by Vicon, Oxford, UK. Following data collection, data were gap filled (cubic spline, minimum gap of 10 frames) and filtered using the Butterworth filter (a 4^{th} order system with a cut-off frequency of 6Hz. Data were then exported to an excel file for further analysis and for presentation in graph format. Findings on this analysis are presented in the Results chapter.

Ethical considerations

There were no ethical concerns associated with this research project as it did not require involvement of any participants out-with the author, project supervisor and technician. The completion of an ethical form was therefore not necessary

Chapter 4 - Results

4.1 – Introduction

This chapter presents results obtained from the device assessment process, which is based on comparison with the original design specification.

This chapter is broken down into the following subsections:

- Isolated range of motion,
- Functional movement, and
- Elastic load testing

4.2 - Passive range of motion

Limits of passive range of motion (RoM), i.e. without assistance from elastics, were determined as:

Shoulder movement:	
Flexion - extension	(N/A)
Adduction - abduction	0° - 90°
Axial internal - external rotation	(N/A)
Medial - lateral rotation	0° - 180°

No data are available at the shoulder for some motion such as flexion and extension, as no joint was provided to permit such motion. With lateral rotation, movement was stopped at a position of 90° external rotation with the inclusion of a range limiting bolt; an extended range of up to 180° was possible upon removal of the bolt.

Elbow movement:	
Extension - flexion	0° - 120°
Internal - external rotation	(N/A)

Internal and external elbow rotation arises from pronation and supination of the forearm. The motion capture system used specifically recorded internal and external rotation of the elbow, rather than pronation and supination. In congruence with the assessment of shoulder and elbow motion and thus exclusion of the forearm and hand, pronation and supination will be exchanged for internal and external elbow rotation.

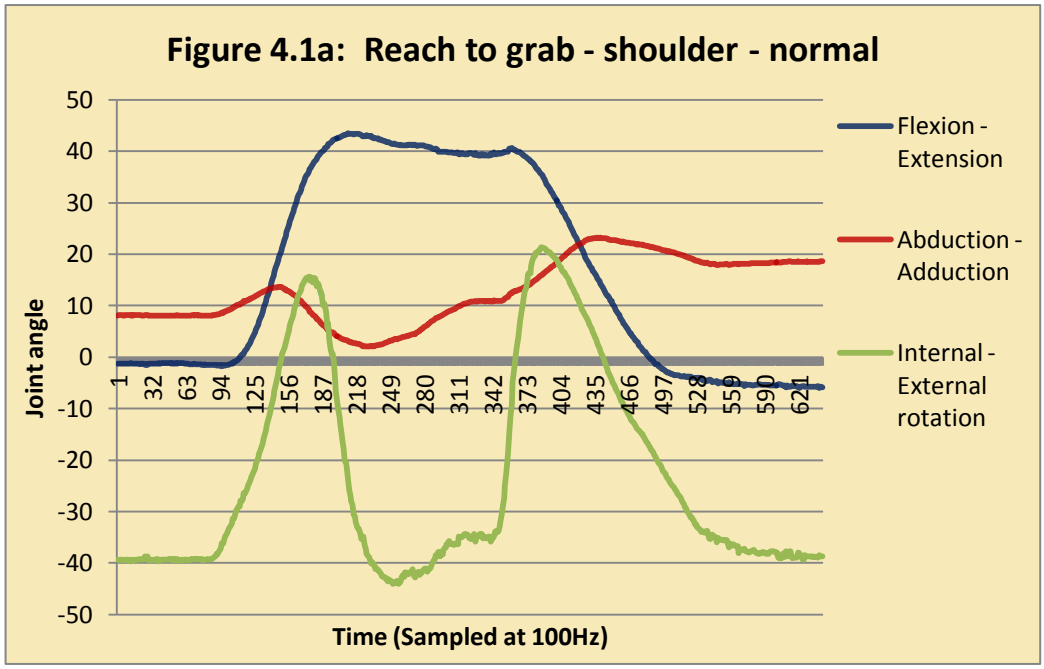
4.3 – Functional movement

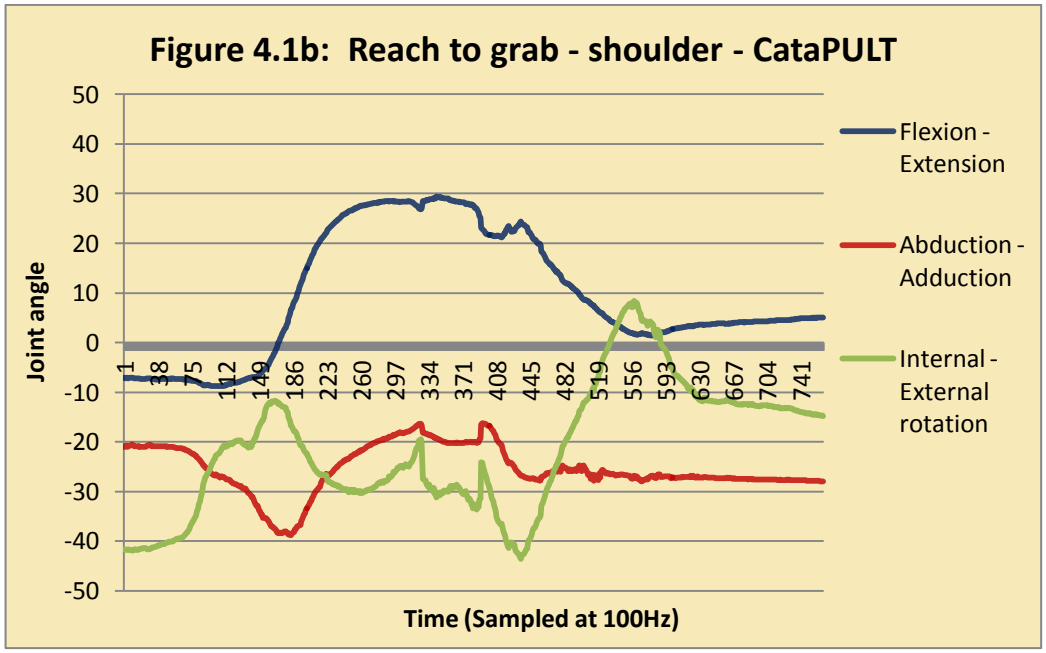
The following figures present joint angles recorded over time during the selected functional activities performed with and without the CataPULT device.

Reach to grasp

Shoulder motion:

The following two figures depict shoulder motion during a reach to grasp movement. Figure 4.1a (overleaf) shows motion without the device, and subsequently in figure 4.1b, with the CataPULT applied.

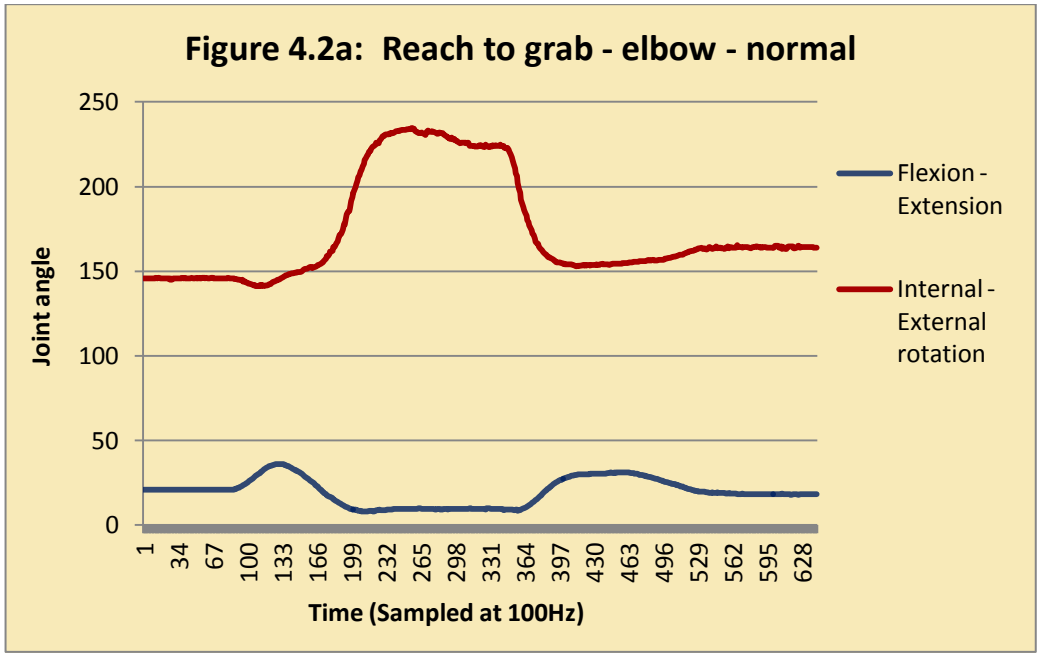


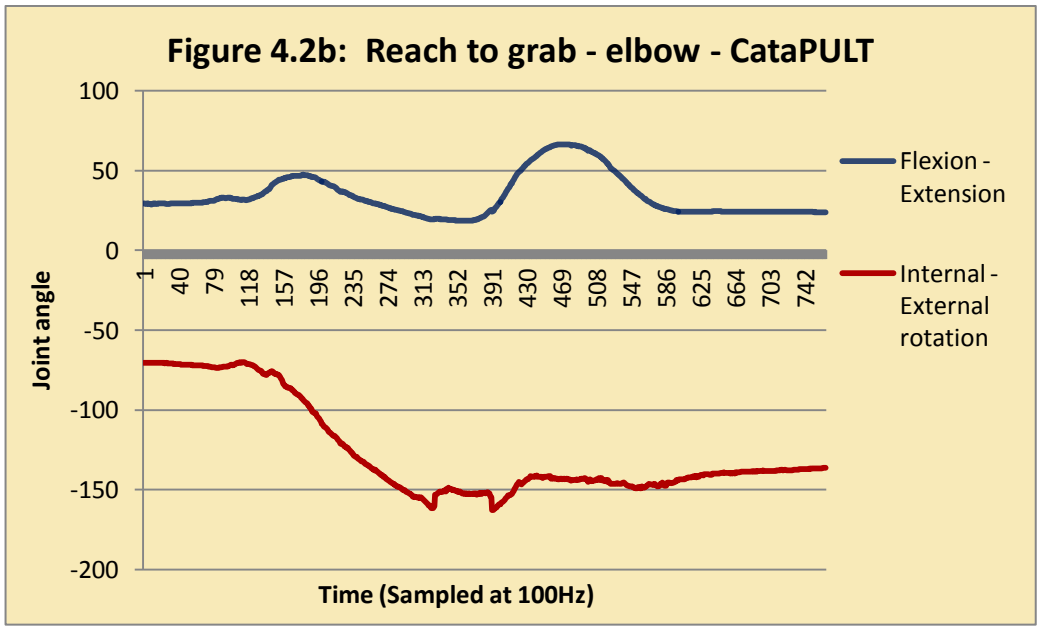


In a reach to grasp movement, the curve shape of joint angles in normal motion appears smooth and regular. In contrast, however, and while generally following similar peak patterns, the shape of the CataPULT curve appears irregular and disjointed. The magnitude of ROM is reduced when compared to normal. Abduction and adduction in CataPULT motion appears shorter in duration and

magnitude, and internal and external rotation using the CataPULT to some degree follows normal motion, but is limited in magnitude and incorporates irregular peaks and troughs.

Elbow motion:



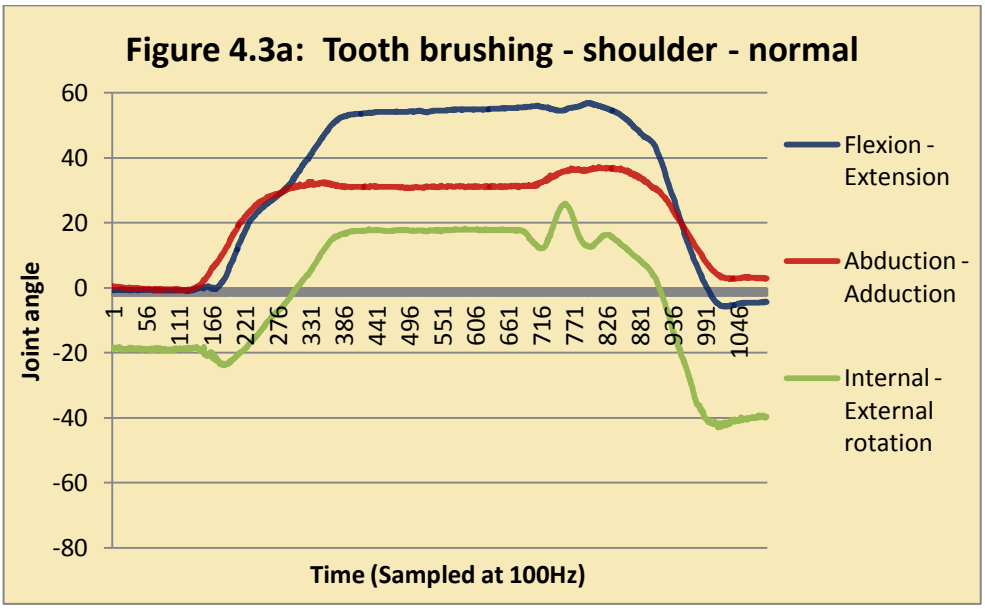


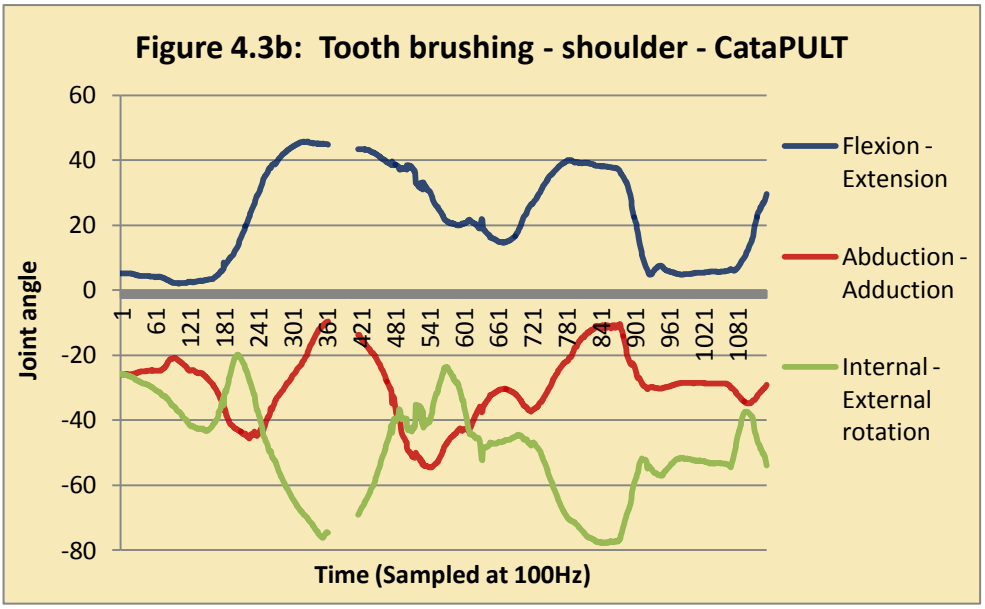
Flexion and extension of the elbow appear similar in shape and magnitude; however increased elbow flexion can be observed while using the CataPULT. Although values of internal and external rotation with the CataPULT appears offset when compared to normal, this is most likely due to marker labelling errors, as similar ranges in motion can be observed.

Brushing teeth

The following two figures depict shoulder motion during 'teeth brushing'.

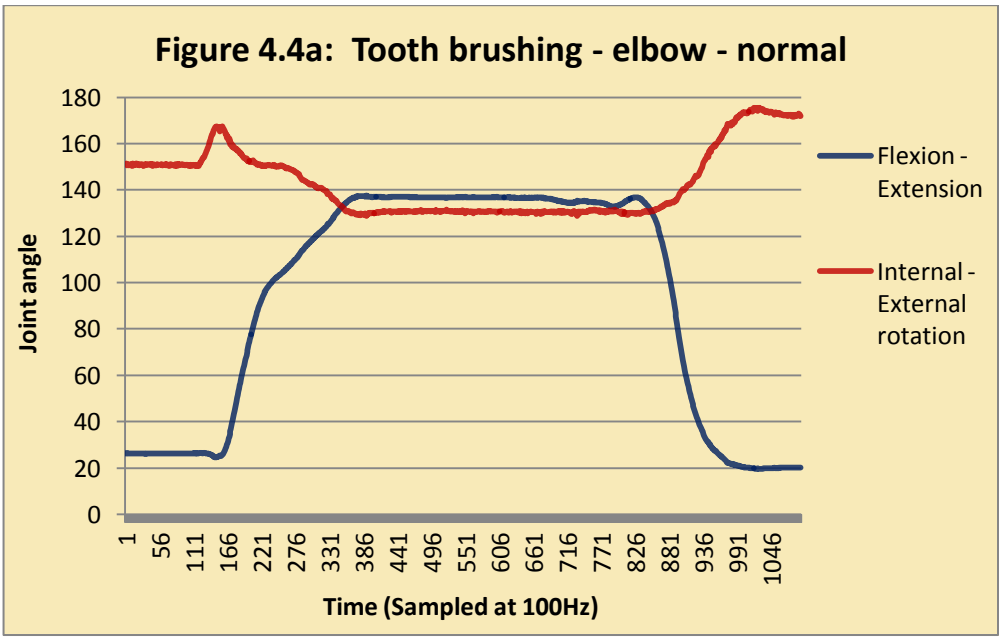
Shoulder motion:

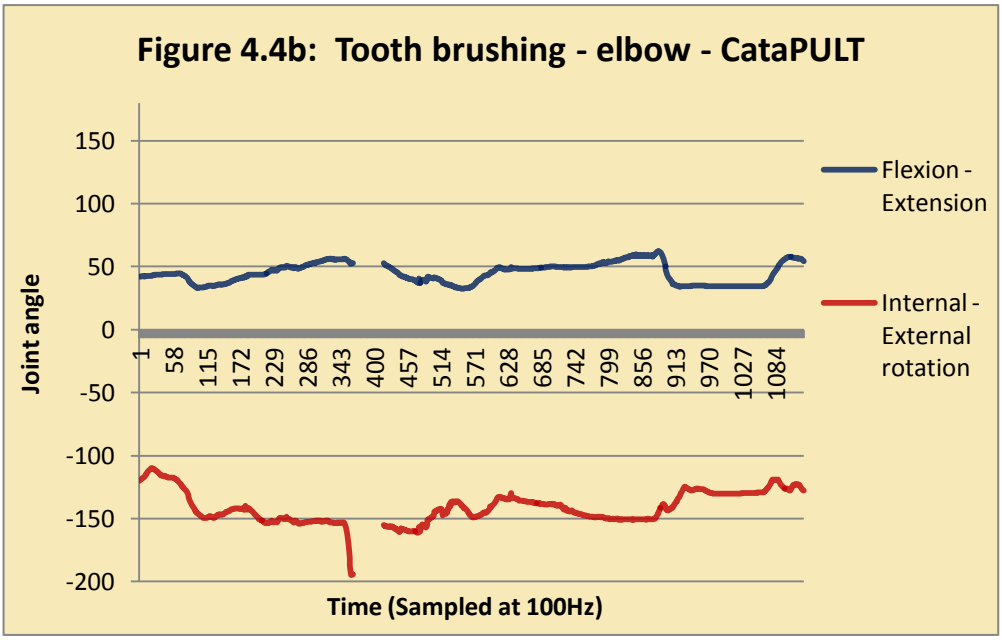




Similarly to previous figures, errors in the marker labelling process are most likely responsible for the offset values presented above. Teeth brushing motion with the CataPULT appears rough and irregular, and features an area of data loss. Losses in data are likely due to the device obstructing the view of motion markers. Apparent reductions in magnitudes of RoM exist when using the device.

Elbow motion:



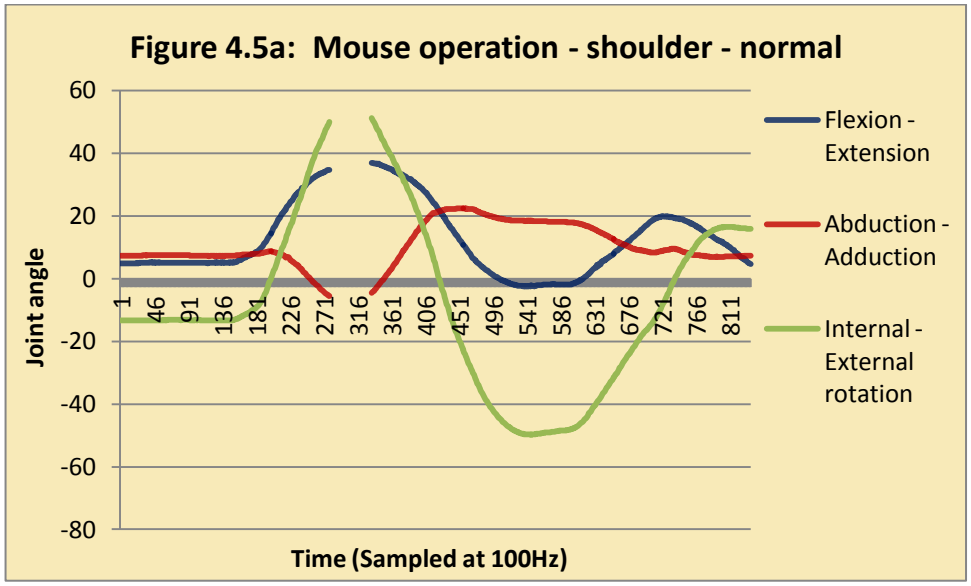


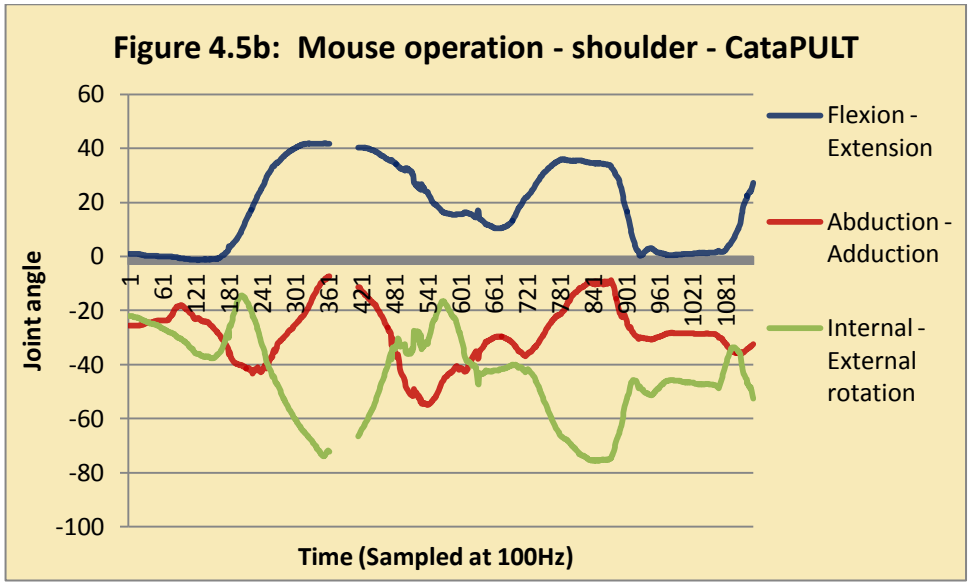
Additional areas of data loss can be observed in this movement. Magnitudes in RoM is significantly reduced when using the CataPULT. Furthermore, a lack of smoothness in the graph of CataPULT motion suggests difficulty was experienced in suspending the arm in space when performing motion towards the core body.

Computer mouse operation

The following two figures illustrate shoulder motion during the simulated operation of a computer mouse.

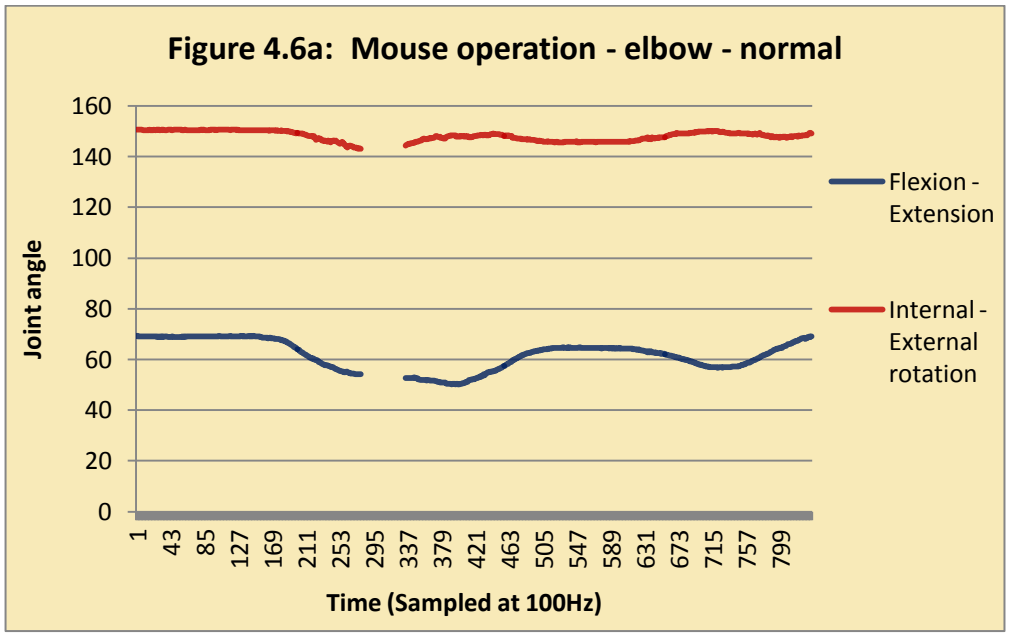
Shoulder motion:

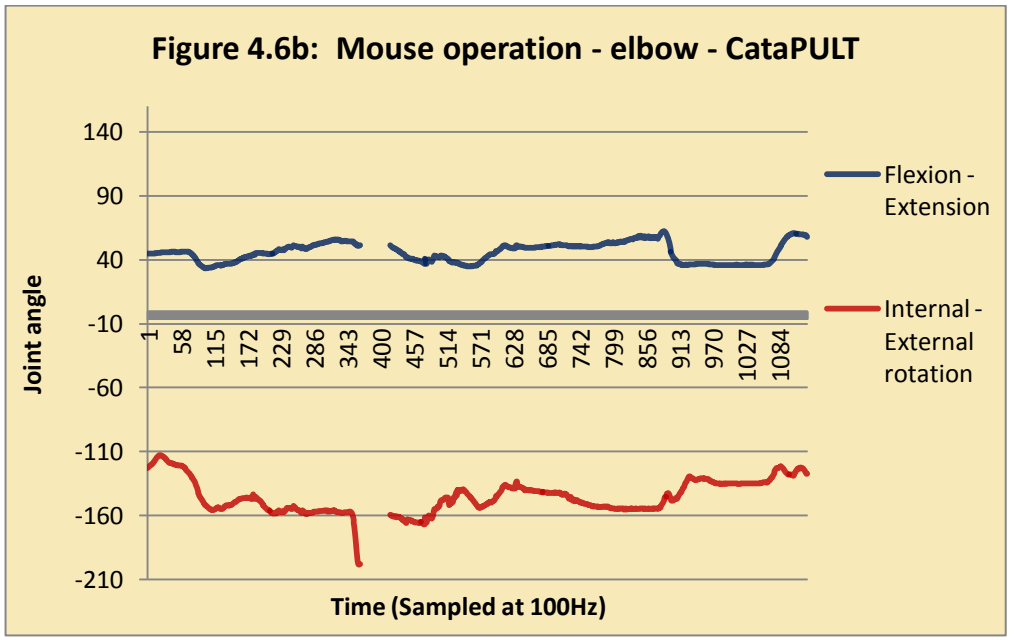




While values of shoulder flexion and extension correlate with values of normal motion, generally, CataPULT motion does not appear smooth; such irregular motion suggests difficulty when performing this particular movement.

Elbow motion:





Significant reductions in elbow motion can be observed when using the CataPULT. Furthermore, angle transitions do not appear as smooth compared to normal motion. Offset values of internal and external rotation again suggest faults in the marker labelling process, however it can be observed that RoM in rotation appear similar.

4.4 – Elastic load testing

An assessment of the CataPULT's elastic lifting capacity was conducted to evaluate its capacity for assisted motion. Elastic bands were attached to a selection of nodes to induce an elastic pull on the joint being tested. The shoulder (table 4.1) and elbow (table 4.2 overleaf) were tested. Combined motion consists of a combination of short and long distance elastics.

Shoulder Internal/External rotation (set in neutral rotation, 90° abduction)	
Total length from shoulder joint centre to palm rest: 475mm.	
Distance from joint centre to COM: 43.1% x 475mm = 204.73mm	
Applied shoulder internal rotation:	
Short distance	300g
Long distance	1,270g
Combined	2,130g
Applied shoulder external rotation:	
Short distance	300g
Long distance	1,350g
Combined	2,180g

Table 4.1: Elastic load testing of the shoulder

Elbow Flexion/Extension	
Total length from elbow joint centre to palm rest: 280mm	
Distance from joint centre to COM: 117.6mm	
Applied elbow flexion:	
Short distance	1,710g
Long distance	2,700g
Applied elbow extension:	
Short distance	1,800g
Long distance	3,800g

Table 4.2: Elastic load testing of the elbow

4.5 – Synopsis of device evaluation

The CataPULT device has demonstrated the capacity for engaging three modes of operation; between 'Elastic', 'Free', and 'Locked' modes. These modes are interchangeable within the clinical environment with appropriate tools.

The RoM and loading capacity of the CataPULT has been evaluated for the purpose of investigating the potential benefits for stroke patients. It has been demonstrated that an optimum passive RoM is provided at the elbow, however the range of shoulder movements are limited. A selection of functional movements have been recorded and reproduced in graph format for the comparison of non-device and device motion; functional RoM was restricted when wearing the device and movement was less smooth when compared to normal motion. The device also demonstrated clear capacity to support upper limbs of varying weight.

The following chapter will present a discussion on the above findings.

Chapter 5 - Discussion

5.1 - Introduction

The aim of the project was to design and evaluate a mechanical training device for the upper limb rehabilitation of stroke survivors. The CataPULT device was fabricated to facilitate this rehabilitation.

This chapter provides a discussion on issues pertaining to the assessment of the device, the findings of which are presented in the results chapter. Limitations and opportunities for further product development and evaluation will also be presented.

The structure of the discussion chapter is as follows:

5.2 – Modes of operation

5.3 – Passive range of motion

5.4 – Functional activities

5.5 – Elastic load testing

5.6 - Device limitations

5.7 – Project limitations

5.8 – Opportunities for further research

5.9 – Conclusion

5.2 - Modes of operation

As previously stated, the CataPULT device utilises three modes of operation – Elastic mode, Free mode and Locked mode.

In Elastic mode, elastic bands are attached to the device to assist movement and support the weight of the upper limb. Similarly, the elastic bands can be appropriately arranged if resistance to movement is desired. However considering the common presentation of muscle weaknesses following stroke, (5, 11, 20-22), assisted movement is the more desired attribute. Free mode did not involve elastic band recruitment, and joints were thus free to rotate. Locked mode facilitated locking of the joints in specified positions.

The patient is not expected to replace elastic components, as the clinician will have set a quantity of tension as indicated by patient assessment.

5.3 - Passive range of motion

The range of motion of existing joints on the CataPULT was evaluated. Elastics were removed for the evaluation to determine the true maximum range of motion.

It has been demonstrated that shoulder flexion plays a key role in activities such as reach to grasp movement, teeth brushing and in operation of a computer mouse. Whilst the anatomical shoulder can perform abduction past 90°, basic functional movements such as reach to grasp motion (3) do not require abduction angles in excess of 90°, and thus the CataPULT device would not restrict basic therapy regimes or activities of daily living involving shoulder abduction.

The CataPULT does not permit internal or external rotation. This movement is essential for basic activities of daily living, and it has been demonstrated that internal and external shoulder rotation play a crucial role in activities such as teeth brushing. As previously conveyed, the device originally limited lateral rotation to 90°, however an extended range of 180° could be achieved upon removal of a range

limiting bolt, which significantly enlarges the 'functional envelope' for activities of daily living.

Elbow flexion was prevented past 120°, due to impingement of the forearm cuff on the upper arm cuff. Should additional flexion be desired, an additional modification involving removal of material from either cuff could be implemented.

5.4 - Functional activities

To substantiate the CataPULT's purpose as a training device for the upper limb, it must accommodate appropriate ranges of motion about the mechanical joints. The range of motion for each joint provided by the CataPULT has been presented. While the range of motion for the elbow was fully functional, range of motion of the shoulder was either fully functional or not permitted as a result of the original shoulder joint design. With the current prototype, this poses as a significant challenge to the feasibility of the CataPULT as a rehabilitative tool.

An evaluation of the CataPULT's performance during functional activities was conducted to establish a comparison in joint angles between activities performed without and with the device. While the data output presents reportedly inhibited movements of the current CataPULT such as shoulder flexion, these movements were likely achieved by consequential compensation using similar movements such as abduction and horizontal rotation. Compensatory movements do not suffice for the replacement of anatomical movements, and should be eradicated with further device development.

Reach to grasp

It is recognised that a reach to grasp movement is an important functional activity (3, 5, 6, 11). Reach to grasp activities were conducted with and without the CataPULT device, and motion at the shoulder and elbow joints was evaluated.

Reach to grasp – shoulder

Flexion/extension:

Movement pattern: Regarding shoulder flexion and extension of CataPULT motion (figure 4.1b), a similar pattern can be observed to that of normal motion (figure 4.1a), suggesting that shoulder flexion is similar to anatomical motion when conducting a reach to grab movement.

Range of Motion (RoM): Motion angles and moments of rest, peak at similar times. However, the magnitude of CataPULT joint angles are reduced by approximately 15° at the peak. This suggests either that the reach to grasp movement was conducted differently between tests, and the CataPULT's movement required less flexion, or that the CataPULT restrained shoulder flexion by approximately 15°. However, assuming that the reach to grasp activities were conducted with consistency, the CataPULT appears to have limited normal shoulder flexion.

Abduction/adduction:

Movement pattern: The pattern of the CataPULT follows a similar pattern to normal, where the larger peak of abduction occurs after a period of small adduction. Yet over the course of the movement, abduction and adduction occurs within a much narrower period of time, and appears almost consciously 'induced' rather than being represented by a smooth, elongated pattern. This may suggest rigidity in the device as the participant appears to consciously 'force' the device into abduction/adduction suggesting that the CatPULT is somewhat 'stiff' and prevents easy abduction/adduction during the reach to grasp movement.

RoM: Abduction/adduction of the CataPULT (figure 4.1b) appears offset by approximately 30°; the reason for which is unclear. Considering the arm's apparent resting position of 20° adduction which would be considerably uncomfortable, in addition to the evaluation that shoulder adduction was not permitted by the joints, the offset result it is most likely due to measurement errors. Whilst the values of CataPULT motion are offset, an approximate value of 25° for the CataPULT's RoM

matches the RoM of approximately 25° for normal motion, supporting the idea that the recorded values of CataPULT motion are offset, and that limits of motion with and without the device are relatively similar.

Internal/external rotation:

Movement pattern: In normal motion, internal/external rotation is represented by a very simple and smooth curve, featuring two peaks of external rotation and a subsequent resting phase. With the CataPULT's motion, a general 'mound' shaped curve exists between the major two peaks of external rotation. This may suggest difficulty in maintaining a position of internal rotation while establishing other joint movements such as shoulder flexion. While the first, and more notably the second peak of external rotation is similar in shape and timing to normal, the movement between peaks appears extremely irregular. This may either represent a difficult transition between internal and external rotation or measurement errors. However the most likely reason for such movement is a combination of stiff movement and measurement errors, as it is unlikely for internal rotation to fluctuate so rapidly without significantly affecting the smoothness of other movements such as flexion and extension. Furthermore, the CataPULT did not specifically permit internal/external shoulder rotation; the participant may be attempting to force motion that would not normally be permitted, hence inducing irregular angle transitions.

The multiple inflections in the patterns may exist for various reasons. The Vicon motion capture system uses multiple cameras arranged circumferentially around the laboratory, and is generally setup to record ambulatory motion for purposes such as gait analysis. Yet in this test, the subject is statically positioned in the centre of the room where there is an increased risk of visual obstruction of the markers. For example, as the subject brings the arm antero-medially across the torso, a 'blind spot' for visual markers may momentarily exist in the cavity between the subject's torso and the forearm. When combining this concept with the act of wearing the

CataPULT device which may itself momentarily impede the view of visual markers, the motion capture system is at a much greater risk of momentarily loss of marker placement. This may give rise to the presence of irregular peaks and troughs in data.

Despite the use of gap filling process in data analysis (cubic spline, minimum 10 frames), gaps are still present on the figures. However, the gap filling process only considers gaps of up to 10 frames in order to preserve the reliability of the data; thereafter, gap filling assumptions are less accurate.

The presence of irregularity in data should not be immediately regarded as measurement errors. Apparent irregular movements may in fact exist due to the presence of irregular movements demonstrated in testing. When wearing the device, irregular motion may result from the participant overcoming forces of inertia on the device, or releasing a buckled hinge joint for example. By repeating movements during testing, such irregularities in data can be reviewed and a more reliable conclusion can be made.

RoM: The maximum value of normal internal rotation of approximately 45° correlate with findings of other investigators for reach to grasp movements (3). Motion of this magnitude is also achieved when using the CataPULT, and similar values of external rotation are demonstrated; yet as aforementioned, the shape of the pattern for CataPULT motion has a significant influence on the dissimilarity between normal and CataPULT motion.

Reach to grasp – elbow

Flexion/extension:

Movement pattern: The patterns of elbow flexion and extension without (figure 4.2a) and with the CataPULT (figure 4.2b) are similar in magnitude and timing. Similarity the magnitude and timing of peak elbow flexion between normal and

CataPULT motion suggests the device does not appear to substantially impede the elbow.

RoM: The elbow flexion angle peaks at approximately 40° in normal motion compared to 65° with the CataPULT, and the second flexion peak occurs at approximately 300 frames after the first peak for both. This has relative correlation with findings in other literature, where normal elbow flexion angles of 25° were obtained in a reach to grasp movement (3).

Internal/external rotation:

Movement pattern: A comparison in the shape of the curves highlights a general lack of congruence between CataPULT and normal motion. However, maximum ranges of motion appear to peak at identical locations relative to flexion and extension motion. Further tests are required to determine the reason for such variation in motion, however it can be understood that the device has a significant effect on the general pattern of internal and external rotation of the elbow in a reach to grab movement.

RoM: With normal rotation, the elbow appears to rest at approximately 150° external rotation, whereas the CataPULT rests at approximately 75° internal rotation, and does not appear to return to rest. Such offset values suggest issues relating to the marker labelling process which may render elbow internal/external rotation unsuitable for reliable comparison. However, it may be possible to compare the range of values. Up to approximately 80° external rotation is demonstrated in normal movement, and approximately 90° is observed in the CataPULT pattern, demonstrating similar values of internal/external rotation. While the reliability of these values is debatable, and that further investigation is required to determine a comparable result, it appears that the CataPULT does not significantly impede on values of internal and external rotation during the reach to grab movement.

Brushing teeth

The brushing of teeth involves medial movement of the arm, requiring delicate control of the hand and a terminal device. This activity may demonstrate smooth joint angle transition, joint stabilisation, and in a realistic environment, the ability to facilitate self-care tasks located towards the middle of the body.

Brushing teeth – Shoulder

Movement pattern: The figure depicting teeth brushing without a device (figure 4.3a) provides an unambiguous representation of normal movement. However, teeth brushing with the CataPULT (figure 4.3b) appears irregular with a period of data loss.

When comparing this to normal, this figure would support the aforementioned suggestion that the application of a mechanical device can impede on the motion capture system's view of markers, which leads to subsequent data loss.

Angles for abduction/adduction and internal/external rotation appear incongruous with that of normal motion, and show little resemblance for comparison. Similarly with previous observations, it is unclear as to why values of abduction/adduction and internal/external rotation appear offset; this is likely due to issues in the process of associating markers with anatomical landmarks. It can be concluded that attempting to perform teeth brushing with the current CataPULT prototype was met with significant difficulty due to restrictions in available range of motion at the shoulder.

RoM: An attempt to attain sufficient flexion for teeth brushing (approximately 55° in normal motion) can be observed in early sample frames, with a subsequent period of rest as the participant could only achieve approximately 45°. A second attempt at achieving adequate shoulder flexion can be observed in the second peak. However, the normal shoulder flexion angle of approximately 55° has not been possible with the CataPULT.

Brushing teeth – Elbow

Movement pattern: In likeness to motion at the shoulder, elbow motion for normal movement (figure 4.4a) is clear and distinguished. CataPULT motion has been capped at its previously recorded maximum angle of 65°, and elbow flexion does not show deviation from this maximum value until the end of the movement. In combination with the 'oscillating' appearance of movement, this motion suggests a constant attempt to attain sufficient flexion for this activity.

RoM: Approximately 140° of elbow flexion was required for the regular brushing of teeth. Elbow motion with the device (figure 4.4b) is significantly reduced – a maximum of approximately 65° was obtained compared to the normal 140°. This agrees with values obtained from the CataPULT's reach to grasp motion; that a maximum of 65° was observed at the peak. However with CataPULT motion, the arm oscillates while attempting to suspend the arm at this angle, suggesting difficulty in maintaining a stable arm suspended medially. This may also be a result of the participant 'forcing' the arm into the desired elbow flexion angle of 140°. Ultimately, this would suggest that the device does not currently facilitate activities of daily living located towards the core, such as brushing teeth or fastening the zips of clothing due to the current inability to achieve desired joint angles, and that improvements would have to be implemented to further consider medially directed ADL.

Computer mouse operation

Considering society's current dependence on computers, an evaluation of the ability to operate a mouse assesses the CataPULT's integration into realistic activities of modern daily living. The subject was required to move their arm in space in a similar fashion to utilising a computer 'mouse'. In addition to assessing the ability to operate a mouse, this activity may provide a good indication of the degree of 'smoothness' of operation of a handheld device in a position of extended reach, and provide insight into the subject's generic mediolateral functional ability.

Computer mouse operation – Shoulder

Movement pattern: Despite the momentary loss of data at the initial data peak, the pattern of normal motion (figure 4.5a) sets a clear definition of shoulder angles when operating a mouse. An unambiguous curve representing shoulder flexion and extension can be observed. Values of abduction/adduction and internal/external rotation for the CataPULT do not appear to follow a regular pattern, and movement appears disjointed. This suggests that movement could be made smoother to facilitate easier operation of a computer mouse.

RoM: Similar peak values of shoulder flexion and extension can be observed when wearing the device (figure 4.5b), however movement does not appear as smooth when compared to normal movement. The range of values for abduction/adduction appear to correlate with that of normal motion, suggesting similarity in the magnitude of motion both required and obtainable for computer mouse operation.

Computer mouse operation – Elbow

Movement pattern: The transition between angles does not appear as smooth with the CataPULT (figure 4.6b) when compared to normal motion(figure 4.6a); this indicates that the device restricts the implementation of smooth motion at the elbow during this movement.

RoM: Values of elbow flexion and extension show reductions in magnitude when using the device. An offset angle of elbow internal/external rotation can be observed, again likely due to marker labelling errors.

Incongruence between passive and functional ROM

Giving consideration to the previous evaluation that normal range of motion was possible on all joints on the CataPULT, it is not immediately clear why ranges of

motion in the evaluation of functional activities are consistently lower when compared to normal.

One possible reason is that compensatory movements were responsible for the attainment of what was previously inhibited motion. To achieve compensatory movement, normal joint motion may have been consequently exaggerated, and in the assessment of functional activity, the CataPULT's joints approached the limits of their range. Whilst anatomical joint motion was recorded as insufficient, mechanical joint motion performing compensatory movements may have been pushed to their limits in order to simulate anatomical motion. An example of this is that shoulder flexion was obtained, despite the fact that shoulder flexion was inhibited by the CataPULT device.

The solution to this problem would ultimately be to incorporate shoulder joints which mimic the line of action of anatomical joints, to facilitate the patient's normal anatomical movement.

However, the more likely reason for incongruence between passive and functional ROM may lie in the fit of the device on the participant. Should the device's joints fail to align with the anatomical joints, the subject may attempt to force movement against inevitable rigidity of the device. This may be substantiated by the regular occurrence of oscillation or 'quivering' movements observed in figures depicting CataPULT motion; muscles acting against the rigidity of the device may induce movement fluctuations and oscillations which are subsequently picked up as 'quivering' markers.

Synopsis on functional activities

The CataPULT's functional range of motion and performance during functional activities was evaluated to assess its potential in upper limb rehabilitation. Further development is required in order to establish smooth joint movement, larger functional ranges of motion and to incorporate additional anatomical joint motion.

Regarding reach to grasp movements, CataPULT shoulder motion showed similarity to normal motion, but joint angle magnitudes were generally limited and movement could have been smoother. Elbow motion was generally unrestricted by the device.

The teeth brushing activity requiring medial arm movement proved more challenging, and highlighted significant restrictions in shoulder joint motion with the CataPULT. Elbow motion was severely restricted when using the CataPULT and limited the ability to perform teeth brushing effectively.

Computer mouse operation involved a smooth gliding motion at reach. While ranges of motion at the shoulder were sufficient for this activity, improvements to the smoothness of motion at the shoulder and elbow are required, in addition to improvements in range of motion at the elbow.

Finally, the fit of the device could be further improved to help eliminate the risk of device displacement. Should the device displace on the body, the alignment of joints may be consequently compromised, resulting in detrimental effect to the smoothness and range of motion.

5.5 - Elastic load testing

The capacity for assisted motion is central to the CataPULT's purpose. As such, the load bearing capacity of the elastics was evaluated by attaching weights of various magnitudes to the elastic bands attached to the joint being tested.

A mere 300g can be supported by short distance elastics assisting internal and external rotation of the shoulder. However, elastics assisting this motion would not be expected to carry the load of the arm, as the weight of the arm acts downwards. Instead, these elastics would carry a smaller load, and the suspension of 300g may be sufficient for this purpose. Significantly higher load values can be obtained by utilising longer distance elastics, and even higher values when combining short and long distances.

It has been demonstrated that the elbow can suspend significantly high loads. Assuming a standard body weight of 68kg and using table 3.1 as presented in the Methodology chapter, the forearm and hand may weigh 1.6kg. The forearm section of the device has a weight that must be added to this value. Even at a short distance, the elastics demonstrated capacity for load suspension, in demonstrating the suspension of loads of 1.7kg in flexion, and 1.8kg in extension. When the elastics are applied over a longer distance, this value increases significantly, to 2.7kg and 3.8kg respectively. With the instalment of additional elastic attachment nodes at the elbow, combined elastic distances can likely suspend significantly higher loads than long distance set ups.

These results demonstrate that the CataPULT device is capable of assisting motion at the elbow, and can assist loads well in excess of standard body masses. Furthermore, it may even be possible to suspend additional objects in the hand, such as a telephone or book, to further aid rehabilitation of activities of daily living.

The additional weights acted parallel to the joint axis. The elastics were therefore tested with the full force of the added weights. In a realistic environment, the elastics would not be expected to carry the full load, as the device structure bears

some load. Thus, the results presented are significantly higher than is required for a functional load.

5.6 - Device limitations:

A number of limitations existed with the CataPULT device as follows:

Whilst the use of simple elastic bands for the Elastic mode is beneficial as they are widely available, and are inexpensive, a number of drawbacks exist in the use of elastic bands. Elastic band manufacturers do not often give indication to specifications, such as elastic band quality, tension, degree of elasticity, or other properties that could be used to evaluate its performance. An alternative is to invest in specialist components where there is a greater reassurance of quality, however this reduces the cost effectiveness and readiness of component replacement.

Another limitation is in the reliability of elastics. It is often difficult to detect when an elastic band approaches the point of rupture and the tendency of elastic rupture increases towards the end of a joint's range of motion, in addition to the effects of fatigue.

As discussed in the Passive range of motion and Functional Activities sections, limitations exist in the range of motion provided at the shoulder, both in passive motion, and in functional activities.

Another limitation lies in the emission of forearm pro/supination and hand movements. The device design does not permit pro/supination of the forearm as the device applies grip to the forearm, and does not extend to the hand. The musculature of the forearm and hand therefore cannot be trained using this model.

5.7 - Project limitations:

A number of project limitations also exist:

The choice of the participant for device testing created several limitations. The subject was young and healthy with no known history of difficulties in physical or cognitive ability. Stroke is associated with elderly patients (11, 12), and a common presentation of stroke is cognitive difficulty (13). The selection of a young, healthy subject without cognitive difficulty helps minimise complications in the testing procedure; however this also has consequences in the relevancy of the device to stroke patients. Further device assessment is required to determine the device's usefulness specifically to stroke patients. Another limitation lies in the selection of only one participant for device testing; testing performed on additional participants helps provide more reliable results.

Whilst the CataPULT device was designed for rehabilitation, and whilst testing has demonstrated significant potential for therapy, it is unknown whether the device can actually provide successful rehabilitation. The device was not tested over an extensive period of time to assess improvement therefore an evaluation of the device's effectiveness over time is essential to determine the device's usefulness in the recovery of stroke patients.

Another limitation lies in the absence of values for elastic load bearing capacity of shoulder abduction and adduction. Due to the positioning of the elastic attachment nodes of the shoulder, elastics could not be securely fastened to the nodes while performing shoulder abduction and adduction, without release of the elastics. Without a valid method of testing such motion with the existing elastic attachment node positions, these values were emitted from results.

Whilst great effort went into the design and plan of device assessment, the tests were not carried out under a rigorously controlled environment, with precisely controlled movements. For example, in the mouse test, a 'left-right-left' motion was not exactly implemented across all tests. Furthermore, there was no specified distance from the body to the mouse, so movement such as elbow flexion was

naturally variable. Instead, the subject simulated mouse movement as soon as recording started, with maximum and minimum ranges of motion in mind, as well as smoothness/easiness of motion. Greater precision would have enhanced the repeatability of the test procedure however this provides potential for further research.

Tests of functionality were not carried out using elastics due to time constraints and practical limitations relating to the secure positioning of elastics in motion. The position of the upper arm elastic attachment nodes in relation to the axilla cuff would not enable the feasible assessment of lateral shoulder flexion without accidental release of the elastics. This provides opportunity for further research into functional assessment of elastics.

Finally, the subject had right hand dominance. During testing, the device was worn on the left hand which was compared to no device on the right. This increased the tendency for bias as the right hand was more capable of functional activity than the left. Future tests should compare the effects using a sample group of subjects incorporating both left and right hand dominance.

5.8 - Opportunities for further research

From the above discussions a number of opportunities for project and device development are suggested:

1. Incorporation of additional shoulder joints to mimic anatomical joint motion, therefore facilitate normal anatomical movement
2. Further manufacture consideration to improve to the smoothness of joints
3. Improvements to device fit, to prevent joint displacement and subsequent anatomical-mechanical joint misalignment
4. The addition of a mouldable palm rest to replace the suggested metal bar would provide additional comfort to the patient. This may comprise of a thermoplastic to conform to the specific patient's hand

5. Further evaluation of functional movement with elastics is required to determine the benefits of elastic assistance in activities of daily living
6. While the contribution of elastics has been established, Electromyography (EMG) testing would provide an insight into the true degree of assistance provided by elastics in functional movements, and allow the statistical comparison of normal and assisted muscle input
7. Additional tests of functional activity, such as answering a phone handset, can be incorporated in evaluation to provide a better insight of the capabilities of the device
8. Testing of the device using stroke subjects to give a true evaluation of the applicability of the CataPULT device with the stroke population

Conclusion

This chapter has presented a discussion of the findings from assessment of the CataPULT device, including limitations of the research and has highlighted opportunities for further research.

The aim of this project was to design and evaluate a mechanical training device for the upper limb rehabilitation of stroke survivors. To achieve this aim a number of objectives were established to ensure a logical and staged approach to the research. Objective one was achieved through a review of current literature was carried out to gain fundamental understanding of existing devices, concepts and ideas pertaining to stroke rehabilitation. From key challenges presented in literature a list of desirable attributes to be included in the new device was established thereby achieving objective two. These considered factors such as physical properties, comfort, fitting and adjustment, visual and user-friendly design, functionality and manufacturing considerations.

The project adopted a three-phased approach to the development and evaluation of the CataPULT; Development of device specification, Production of the device, and

Testing of the device on a single healthy subject. An existing orthotic device was modified according to the desirable properties. The resulting manufactured product was named CataPULT to reflect the elastic nature of this Passive Upper Limb Trainer. This addressed objectives three and four. Objective five was achieved through the testing and evaluation of the CataPULT device.

It can be concluded that the CataPULT demonstrates the potential to support the arm, and also provide assisted movement through a functional range of motion to facilitate upper limb rehabilitation following stroke. The elastics enhance device function by applying forces over the mechanical joints to assist in joint motion, thus reducing the energy required to perform functional activities. Other advantages of the CataPULT in comparison with alternative technologies such as robotic devices are that the device involves a cost effective manufacturing process, components are readily available and inexpensive to replace, and the device is extremely portable at home and in the clinical environment. These features may make it particularly desirable for use in the hospital or clinical setting. With further development of the device, additional benefits may be possible, and to this end, opportunities for further research have been identified.

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Appendix I

DEVICE SPECIFICATION SHEET

1. Addition of palm rest and related components.

   a) Palm extension bar. Metal bar attached to the forearm socket as located on orthotic device; coloured dark grey in figure 2. Sized to fit current forearm socket, and to length ~600mm. Must be semi-fixed (detachable) to existing socket.

   b) Palm rest bar; 'T-shaped' bar. Metal bar securely fixed to end of bar in part 1. a), coloured orange in picture. Supports the palm rest in 1. c). Length ~60mm.

   c) Addition of soft Velcro on palm rest. Palm rest supported in position by a metal bar as in part 1. b).

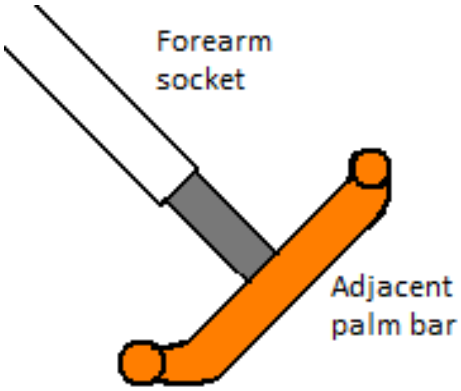

Figure 2 – Palm rest (Author's own design)

2. Addition of elastic band attachment nodes across elbow joint.

   a. Elastic bands attached to the forearm and upper arm sections as appropriate. Elastic band attachment nodes located as in picture; provision of 'T-shaped' pins for easy elastic band attachment and removal.

b. Elastic bands pass anteriorly and posteriorly to the elbow joint, and tension is at equilibrium when elbow is slightly extended at about 110° extension.

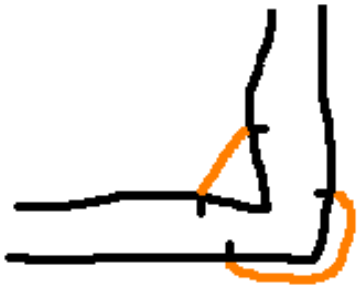

Figure 3 – Elbow elastics (Author's own design)

3. Addition of elastic bands, and elastics attachment nodes across shoulder joint.

   a. Similar to 2. a). Elastic bands may pass anteriorly, laterally, medially, and posteriorly to shoulder joint. The device can be set up to assist in movement by appropriate positioning of elastics. In a 0° position, tension is at equilibrium anteroposteriorly, mediolaterally and in rotation. These elastics facilitate 'Elastic' mode of the shoulder.

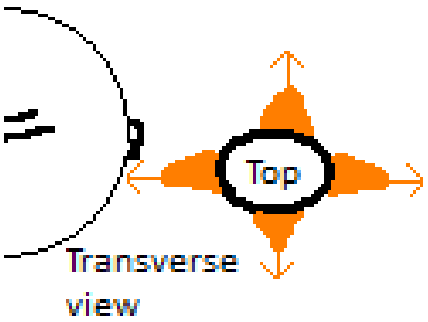

Figure 4 – Shoulder elastics (Author's own design)

4. Elastic bands across shoulder for internal/external rotation. Regular elastic bands of sufficient length are attached to the elastic attachment nodes.

5. Removal of external rotation stop bolt

    a. At the shoulder joint, a bolt exists to restrict the range of shoulder rotation from 0° to 90° horizontal external rotation. Removal of the bolt will permit up to 180° external rotation.

6. Addition of soft Velcro to shoulder joint

A layer of soft Velcro added to the proximal section of shoulder joint, to prevent impingement on the skin of the axilla as lateral shoulder flexion was initiated.