A SYSTEM TO PROVIDE GUIDANCE TO STROKE PATIENTS DURING INDEPENDENT PHYSIOTHERAPY

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I. Abstract

Stroke is a serious disease that leaves many sufferers physically disabled. Treatment resources are limited, meaning stroke patients, are in many cases, discharged prior to reaching their full potential of physical recovery. The hypothesis of this research is that a system that enables regular guided and monitored therapeutic exercises in the home can provide a means for stroke patients to achieve a higher level of physical rehabilitation. This research is based on the design, build and testing of an experimental prototype system to allow this, with the aim of investigating the feasibility and potential value for such systems. Any system to assist rehabilitation in the home must clearly be low cost, safe and easy to use. The prototype system therefore aimed to achieve these features as well as focusing on the upper limb. Literature is reviewed in the fields of stroke, human anatomy and mechanisms, motor performance, feedback during motor learning, and existing systems and technology. Interviews are also conducted with stroke physiotherapists to gain input and feedback on concepts that were generated. Although systems exist with similar aims to those mentioned in the hypothesis, there are some areas where investigation is lacking. The prototype system measures movement using a novel combination of gyro sensors and flex sensors. The prototype system is designed with a focus on the method of interaction with patients and the provision of guidance and feedback that simulates that provided by a physiotherapist. The prototype system also provides a unique combination of quantitative information to patients of their personal improvements and graphical feedback of their movements and target movements. Finally, a novel categorisation of movement synergism (a form of movement coordination) is established and a novel method for detecting movement synergism is developed and tested. Performance of the prototype hardware is tested, and it is concluded that identified requirements have been met, although variability of recorded data is high. Tests also indicate that the prototype system is capable of detecting movement synergism. Finally, a controlled test involving healthy participants is performed to investigate the efficacy of the prototype as a whole. It was found that use of the prototype system resulted in a statistically significant improvement in conformance to target movements ($p < 0.05$). Findings are discussed in detail and the hypothesis is concluded as being supported overall. Recommendations for future research are made.

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IV. Glossary of frequently used terms

ADL.............. Activity of Daily Living

ADLs............. Activities of Daily Living

BI................. Barthel Index

DAQ............. Data acquisition module

DOF............. Degree Of Freedom

DOFs........... Degrees Of Freedom

KP............... Knowledge of Performance

KR............... Knowledge of Results

CHAPTER 1. INTRODUCTION

1.1. Background

Around 16 million people per year suffer a stroke worldwide (Lindley 2008). Stroke causes a greater range of disabilities than any other medical condition and has a greater disability impact than other chronic diseases (Adamson, Beswick & Adrahim 2004). There are around 62 million stroke survivors worldwide of whom around 31 million are physically disabled (Lindley 2008). Stroke patients require intensive treatment from the outset, and often physiotherapy thereafter (National Collaborating Centre for Chronic Conditions 2008). Stroke physiotherapy is performed with the assistance of physiotherapists in specialist stroke units or by Early Supported Discharge (ESD) teams in day-care centres or in patients' homes. The cost of stroke care in the UK is around £2.5 billion; 80% of the costs attributable to inpatient hospital care (£1.1 billion) and residential care (£900 million) (Allender et al. 2010). Although this cost is high, resources are lacking in terms of specialised stroke units and trained clinicians (Royal College of Physicians 2010). This leads to patients spending less time in specialist stroke units (Royal College of Physicians 2009). It was also found that only 46% of stroke units met the criteria considered necessary for effective treatment (Rudd et al. 2005). Stroke is therefore a highly resource intensive condition, in terms of both facilities and clinicians, and resources are lacking. This leads to stroke patients in many cases failing to achieve their full potential of physical rehabilitation. In recognition of this situation, researchers have investigated systems that provide a means to rehabilitate further from within the home after discharge (Willmann et al. 2007; Kohler, Schmitz-Rode & Disselhorst-Klug 2010; Durfee et al. 2009; Sanchez et al. 2006). Such systems work by reading a patient's movements during physiotherapy and providing feedback to assist the process of motor learning. In support of such systems is the fact that physical recovery can continue into the chronic stages of stroke (Suputtitada, Suwanwela & Tumvitee 2004), and feedback has been shown to aid motor learning in stroke patients (Subramanian et al. 2010; Cirstea, Ptito & Levin 2006). Also, rehabilitation within the home has been shown to be effective (Young, Forster 1992) and use of devices such as games consoles to practise physical activities from within the home can be motivating (Saposnik et al. 2010). Computer systems are now in most homes which means that remote communication of results with clinicians is easier to

realise. Also, the number of consoles and mobile phones with sensors to read movements has increased. The underlying technology of these devices is becoming more common and the prices of micro sensors have reduced. This means that systems for home rehabilitation can be made for lower costs (Morrow et al. 2006). Although some initial positive results have been obtained from these systems which provide a means to rehabilitate further from within the home (Kohler, Schmitz-Rode & Disselhorst-Klug 2010; Winstein, Merians & Sullivan 1998) there are some areas where investigation is lacking. For example, there has been little investigation into the mechanisms by which patients interact with the system during a session. Also, feedback of patient improvements combined with graphical feedback of their movements and target movements has not been investigated. Moreover, the effects of guidance of movements at one joint on improvements in performance at other joints has not been investigated. Also, although reduced movement coordination is recognised as a physical deficit which requires rehabilitation, little has been done regarding defining and measuring it.

1.2. Problem statement

This research was carried out in relation to the following generalised problem:

Stroke is a serious disease that leaves many people physically disabled. Treatment resources are limited, meaning stroke patients are, in many cases, discharged prior to reaching their full potential of physical recovery.

This research is based on the proposition that additional long-term regular exercise will assist physical recovery of stroke patients with physical deficits. Existing treatment regimes prioritise improvement of mobility which is necessary for patient independence. This work therefore focuses on rehabilitation of the upper limb.

1.3. Hypothesis

A system that enables regular guided and monitored therapeutic exercises in the home can provide a means for stroke patients to achieve a higher level of physical rehabilitation.

1.4. Research questions

1. How do stroke physiotherapists usually assist rehabilitation with respect to the patient's symptoms?
2. What systems exist that provide a means for stroke patients to further rehabilitate?
3. What are the requirements for a system to provide a means for stroke patients to further rehabilitate?
4. What are the limitations of any existing systems?
5. Can a system be designed that overcomes these limitations?
6. What is the efficacy of the designed system in providing a means to further rehabilitate?

1.5. Plan of work

Figure 1.5 shows the main activities to perform which were established with respect to the hypothesis and research questions at the initial stage of this research. The activities are shown in their order of performance, with conclusions and references between one another indicated with arrows. The plan is simplified for clarity, and outlines the scope of this research and the layout of this thesis.
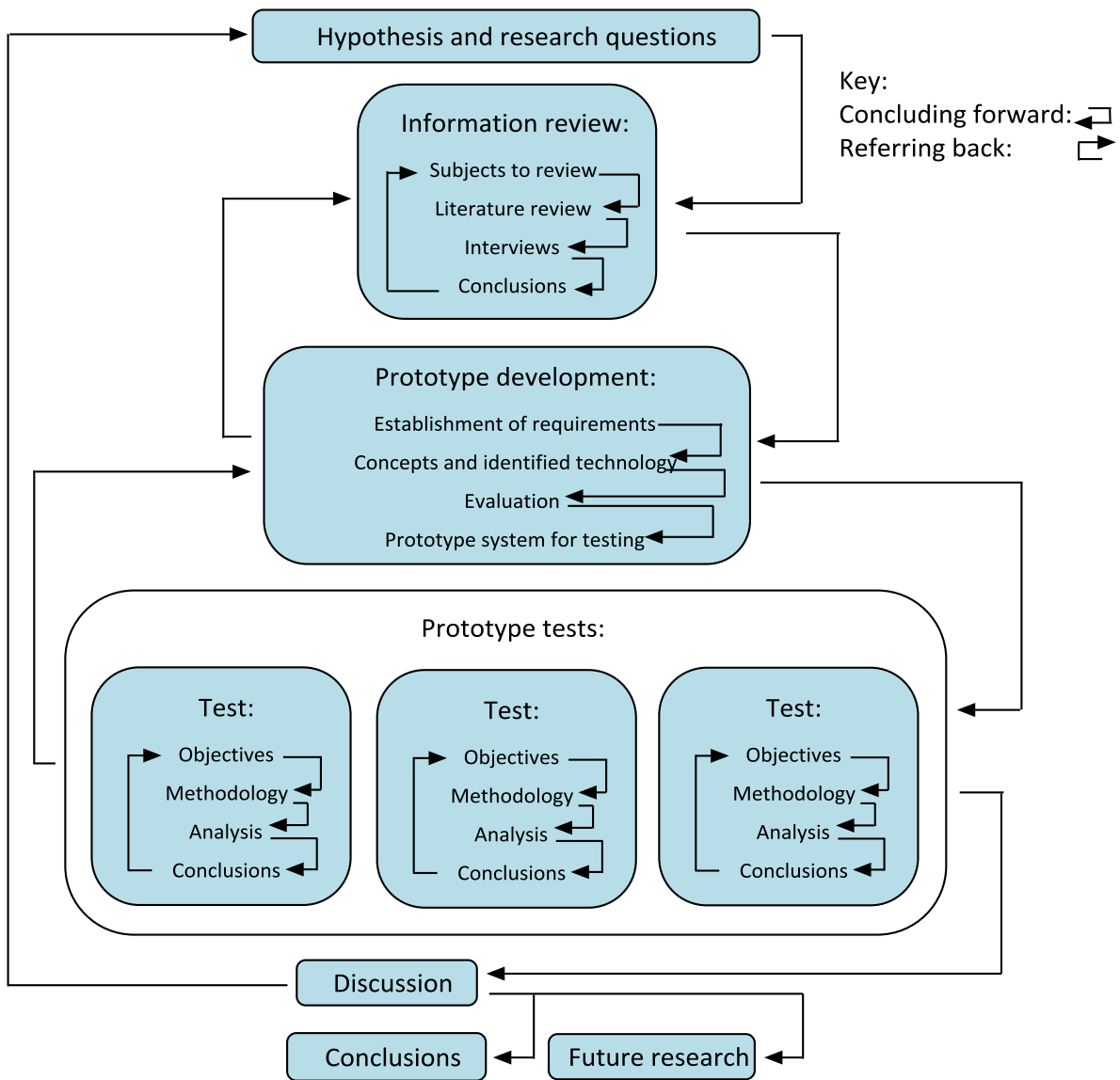
Figure 1.5. Plan of work

Any device or system that can assist rehabilitation in the home must clearly be low cost, safe and easy to use. This research is based on the design, build and testing of an experimental prototype system that could enable regular and appropriate therapeutic exercises with the aim of investigating the feasibility and potential value of such systems.

1.6. Summary of research novelty

The following points summarise the novelty of this research, which was established during the course of this research, but is described in this chapter to aid the introduction. A more detailed description of the novelty of this research is given in section 7.4.

1. A prototype system for testing was designed and built which measured movement using a novel combination of gyro sensors and flex sensors. The prototype system was useable within the home being low cost, compact, easy to set up and safe.

2. A novel mechanism was developed that allowed movements to be performed in a similar way as they would be during a regular physiotherapy session, whilst receiving automated feedback. Patients can pause for as long as they wish between movements to give time to contemplate and remember feedback.

3. The feedback mechanism was a unique combination of two main separate elements. This consisted of quantitative information to patients of their personal improvements during physiotherapy for motivation, combined with graphical feedback of their movements and target movements. The efficacy of this feedback was investigated.

4. The effects of guidance of movements at one joint on improvements in performance at other joints was investigated, which has not been done previously.

5. A novel categorisation of movement synergism was established and a novel method for detecting movement synergism (a form of movement coordination) was developed and tested.

CHAPTER 2. INFORMATION REVIEW

2.1. Introduction to chapter

This chapter describes the investigation that was carried out to gain information to allow the research to be performed. A literature review was performed and interviews were conducted with stroke physiotherapists. The hypothesis, research questions and plan of work led to identification of the following subjects to be reviewed in this chapter:

- How a stroke occurs
- The impact of stroke
- The mechanisms of the healthcare system
- The overall aim of physiotherapy
- The elements that comprise a typical physiotherapy program
- The physiotherapist's intervention with the learning process
- The types of movements performed during physiotherapy
- The anatomy of the upper limb
- Movement characteristics of the upper limb
- Control of movements
- Motor skills
- The mechanisms of motor learning
- Feedback for motor learning
- Mechanisms for providing feedback for motor learning
- The effects of providing feedback during motor learning
- Methods of measuring movement and performance
- Existing physiotherapy interventions
- Existing systems to provide a means to further rehabilitate and their limitations
- The usefulness of a system to provide further guided physiotherapy to stroke patients
- Existing sensors, data acquisition systems and software

These subjects led to literature being reviewed in the fields of stroke, human anatomy and mechanisms, motor performance, feedback during motor learning, and existing systems and technology. The findings from this then led to the generation of questions to be raised in interviews with stroke physiotherapists which are described towards the end of this chapter. Finally, conclusions from the information review are drawn. Although some of the subjects to investigate were of a background nature, the conclusions focused more on specific findings. This allowed necessary background information to be reviewed whilst allowing conclusions to be drawn that were most useful. The findings from this chapter, along with the hypothesis and research questions formed the basis for further discussion and development of system objectives and a design specification for a prototype system for testing in Chapter 3. The literature review is shown below:

2.2. Stroke

2.2.1. Definitions of stroke

Stroke has multiple definitions, three of which are:

- An emergency and a brain attack, cutting off vital blood flow and oxygen to the brain (National Stroke Association 2012)
- A disease of the brain (not the heart) caused by a blockage or rupture of the essential blood supply (Lindley 2008)
- A brain injury caused by sudden interruption of blood flow (The Stroke Association 2008)

A medical definition that includes more detail is given below:

"Stroke is a clinical syndrome characterised by rapidly developing clinical symptoms and/or signs of focal, and at times global (applied to patients in deep coma and those with subarachnoid haemorrhage), loss of cerebral function, with symptoms lasting more than 24 hours or leading to death, with no apparent cause other than that of vascular origin" (Hatano 1976).

2.2.2. Mechanisms of stroke

Blood vessels that carry oxygenated blood away from the heart are known as arteries (Gordon 1999). The brain requires a constant blood supply from the arteries in order to receive oxygen and nutrients. Disruption of this blood supply can result in cerebral oxygen starvation which in turn results in the death of brain cells. This is known as a cerebral infarction (The Stroke Association 2008). The two main mechanisms of stroke are ischemic stroke, where a blockage develops within an artery, or haemorrhagic stroke, where an artery ruptures (National Stroke Association 2007). These basic mechanisms by which stroke occurs can be further categorised in order of their occurrence in the UK:

- 80% Ischemic; of which 50% are large vessel disease (atheroma), 25% are small vessel disease, 20% are cardioembolic/thrombotic disease and 5% are iatrogenic disease and other causes
- 20% Haemorrhagic; of which 75% are primary intracerebral haemorrhage and 25% subarachnoid haemorrhage

 (Lindley 2008)

Ischemic stroke

Large vessel disease stroke is caused by narrowing and occlusion (blockage) of blood vessels damaged by atheroma, which is the build up of abnormal arterial wall material (Lindley 2008). Such build up can be caused by for example high cholesterol, hypertension, smoking and obesity (Gordon 1999).

Small vessel disease stroke occurs when an occlusion caused by deposits of atheroma forms where larger vessels branch into smaller ones. It can also be caused by thickening of the vessel wall by conditions such as arteriolosclerosis, lipohyalinosis or fibrinoid necrosis (Lindley 2008).

A cardioembolic stroke is caused by an embolism that can be caused by fragments of a blood clot, a fragment of a tumour or a mass of air bubbles (Gordon 1999). The embolism originates and grows in the large blood vessel and then becomes dislodged upon reaching a

critical size. The embolism is then carried forward through the larger vessels by the blood stream and eventually causes an occlusion upon reaching the small blood vessels (National Stroke Association 2007).

In the case of a thrombotic stroke, unlike an embolic stroke, a thrombus (blood clot) forms inside an artery which supplies blood to the brain and does not travel. Upon reaching a critical size, the clot can become an occlusion sufficient to prevent localised cerebral blood flow (National Stroke Association 2007).

Iatrogenic disease and other causes of stroke

Less common causes of stroke are Iatrogenic diseases which are conditions accidentally induced by a physician, for example by a drug overdose (Gordon 1999). Other less common causes of stroke include any other condition, injury or disease that blocks or damages the arteries leading to the brain (Lindley 2008).

Transient Ischemic Attack (TIA)

A TIA is an abrupt, focal loss of neurological function caused by temporary ischemia (Baliga, Eagle 2008). It can be considered a temporary ischemic stroke, and is therefore sometimes referred to as a mini stroke (National Stroke Association 2012). The resulting temporary lack of blood flow to an area of the brain can result in temporary numbness, trouble speaking and loss of balance (National Stroke Association 2007). Although TIAs generally cause no permanent damage, they are a serious warning sign that a full stroke could occur in the future, and should not be ignored (National Stroke Association 2007). As of recent, TIAs are not considered to fit the definition of a stroke as symptoms are not chronic. However, the term 'brain attack' has been developed which refers to both TIAs and stroke (Lindley 2008). A medical definition of a TIA is stated below:

> *"A transient ischaemic attack (TIA) is a clinical syndrome characterised by an acute loss of focal cerebral or monocular function with symptoms lasting less than 24 hours and which is thought to be due to inadequate cerebral or ocular blood supply as a result of artery thrombosis or embolism associated with arterial, cardiac or haematological disease"* (Hankey, Warlow 1994).

Haemorrhagic stroke

An intracerebral haemorrhagic stroke is caused by a haemorrhage, which is the escape of blood within the body from any of the blood vessels, normally in response to trauma, or as a result of a clotting disorder such as haemophilia (Gordon 1999). When a haemorrhage occurs within the brain, intracerebral bleeding can occur which causes a cerebral infarction. The three major mechanisms that cause intracerebral haemorrhagic stroke are hypertension, weakened or damaged blood vessels or blood viscosity being too low due to lack of clotting factors (Lindley 2008). Hypertension is the most common cause of intracerebral haemorrhagic stroke (National Stroke Association 2007).

A subarachnoid haemorrhagic stroke is caused by a haemorrhage into the subarachnoid space between the skull and the brain, usually caused by a rupture of an aneurysm on the Circle of Willis. An aneurysm is a localised swelling or dilation of an artery due to weakening of its wall (Gordon 1999). Such bleeding puts excess pressure on the brain which damages or can kill brain cells.

Modifiable risk factors in stroke

The likelihood of having a stroke is mainly determined by one's lifestyle. The following are modifiable risk factors in stroke:

- Smoking
- Diet
- Physical activity levels
- Alcohol
- Hypertension
- Cholesterol
- Obesity
- Diabetes

(Scarborough et al. 2009)

2.2.3. Morbidity and mortality of stroke

It is estimated that around 150,000 people per year suffer a stroke in the UK, of which 90,000 are a first time stroke and 60,000 are a recurrent stroke (Carroll, Majeed 2001) (Lindley 2008). It is also estimated that 16 million people per year worldwide suffer a stroke (Lindley 2008). There are around 62 million stroke survivors worldwide of whom around 31 million are physically disabled (Lindley 2008). Stroke causes a greater range of disabilities than any other condition and has a greater disability impact than other chronic diseases (Adamson, Beswick & Adrahim 2004).

Table 2.2.3. Estimate of annual stroke incidence in England and Wales (Carroll, Majeed 2001)

Age group (years)	First stroke	Recurrent stroke	Total
0-44	1718	759	2477
45-64	16724	7057	23781
65-74	20944	14174	35118
75+	48354	31727	80081
Total	87739	53717	141456

As the world's population is ageing, the burden of stroke is expected to increase greatly during the next 20 years, especially in developing countries (Donnan et al. 2004). Also, stroke is the third most common cause of death worldwide after ischemic heart disease and all types of cancer combined (Warlow et al. 2003). It is estimated that stroke causes 4.5 million deaths per year worldwide (Felgin et al. 2003) and 60,000 deaths per year in the UK (Allender et al. 2010). In 2004, stroke caused 8% of deaths in men and 12% of deaths in women in the UK, and for those aged below 75, stroke caused 5% of deaths in men and 6% of deaths in women in the UK (Allender et al. 2010). Approximately a third of stroke patients are likely to die within the first ten days, a third are likely to make a recovery within one month and a third are likely to be left with disabilities and needing rehabilitation (The Stroke Association 2006). More than 900,000 people who have suffered a stroke live in England, around half of which are dependent on others for everyday activities (Bourn 2005). One year after a stroke, approximately 80% of people are at home, and 12% live in a residential or nursing home (Tyson 1995).

2.2.4. Stroke healthcare

Stroke guidelines

In the UK, the treatment and management of stroke is performed under official guidelines (Department of Health 2007). The main bodies that develop guidelines are shown below:

- The Department of Health
- The National Institute for Health and Clinical Excellence (NICE)
- The Royal College of Physicians (RCP)
- AGILE

The purpose of the Department of Health is, to *"improve England's health and well-being and in doing so achieve better health, better care, and better value for all"* (The Department of Health 2012). The Department of Health develop and publish the *National Stroke Strategy*; a guide *"intended to provide a quality framework to secure improvements to stroke services, to provide guidance and support to commissioners and strategic health authorities and social care and to inform expectations of patients and their families by providing a guide to high quality health/social care services"* (Department of Health 2007). The guide includes sections on raising awareness and informing the public, the treatment of stroke including the markers of quality service, life after stroke and networks for stroke care. Other bodies also develop and publish stroke guidelines including the National Institute for Health and Clinical Excellence (NICE) that produce *Stroke: diagnosis and initial management of acute stroke and TIA* (National Collaborating Centre for Chronic Conditions 2008). The guide includes sections on recognising the symptoms and diagnosing stroke, pharmacological treatments for stroke patients, nutrition and hydration, and surgery for stroke patients. Also the RCP produce the *National Clinical Guideline for Stroke* (Clinical Effectiveness and Evaluation Unit 2008), which includes detailed sections on service provision and organisation, clinical care and profession specific topics such as physiotherapy and occupational therapy. Guidelines for physiotherapy also exist, for example AGILE produce the *Core Standards of Physiotherapy Practice* (Goodwin, Ramaswamv & Tomas 2008).

The onset of stroke

Fast responses to stroke reduce the risk of disability or death (Department of Health 2007). The signs of a stroke occurring should be learnt by members of the public, and acted upon in the event of a stroke, where the *"FAST test"* can be used to remember the warning signs (National Stroke Association 2012).

Table 2.2.4. The FAST test and how it can be used to identify the occurrence of stroke (National Stroke Association 2012)

F = Face	Ask the person to smile. Does one side of the face droop?
A = Arms	Ask the person to raise both arms. Does one arm drift downward?
S = Speech	Ask the person to repeat a simple sentence. Does the speech sound slurred or strange?
T = Time	If you observe any of these signs (independently or together), immediately alert the emergency services

Upon entering care facilities, low blood sugar level (hypoglycaemia) should be eliminated by clinicians as the cause of the neurological symptoms and a validated tool such as ROSIER (Recognition Of Stroke In the Emergency Room) should be used to rapidly assess the condition of patients (National Collaborating Centre for Chronic Conditions 2008).

Treating stroke

After an initial assessment of the patient's condition has been made, clinicians then assess whether or not it is necessary to perform a brain scan immediately or within 24 hours. Patients are then admitted to an acute stroke unit for specialist monitoring and treatment. Upon admission, patients are screened for malnutrition using a validated tool such as MUST (Malnutrition Universal Screening Tool), and for swallowing before being given oral foods, fluids or medication (Clinical Effectiveness and Evaluation Unit 2008). If problems with nutrition and swallowing are found, a feeding strategy will be established. Patients will then be helped to sit up and to be mobilised where possible (National Collaborating Centre for Chronic Conditions 2008). The type of stroke will then be identified as either ischemic, where 300mg aspirin can be given, or as haemorrhagic. The hydration, temperature and blood pressure of patients should be monitored and oxygen levels should be maintained (Clinical Effectiveness and Evaluation Unit 2008). In the case of ischemic stroke, patients will undergo a decompressive craniectomy where necessary, which is removal of a section of

the skull to allow the brain room to swell. In the case of haemorrhagic stroke, patients will then be assessed to determine if surgical treatment is necessary, either immediately or whenever necessary (Clinical Effectiveness and Evaluation Unit 2008). All stroke patients will then receive cholesterol lowering, blood pressure control and antiplatelet treatment as required along with dietary and lifestyle advice prior to discharge (National Collaborating Centre for Chronic Conditions 2008). If the patient is considered unsuitable for home transfer after completion of their acute diagnosis and treatment, they should be treated in a specialist stroke rehabilitation unit (Royal College of Physicians 2008c). Patients will then undergo physiotherapy where necessary. This is investigated in more detail in section 2.7. The physiotherapy program should meet the following criteria:

- Have specific goals that are meaningful, relevant, challenging and achievable
- Include both short-term (days/weeks) and long-term (weeks/months) targets
- Include both individual clinicians and also the whole team
- Be documented, with specified, time-bound measurable outcomes
- Have achievement evaluated using goal attainment
- Include family members where appropriate
- Include periodic evaluation to guide and inform therapy and treatment

(Royal College of Physicians 2008c)

The physiotherapy program will be established with the patient's input, where their age, emotional state and cognitive ability are noted, and where information that the patients have given to the physiotherapist is treated in confidence (Goodwin, Ramaswamv & Tomas 2008). Also, a published, standardised, valid, reliable and responsive outcome measure is used to evaluate the change in the patient's health status. Once underway, the treatment plan is constantly evaluated to ensure that it is effective and relevant to the patient's changing circumstances and health status (Goodwin, Ramaswamv & Tomas 2008). The Core Standards of Physiotherapy Practice state that physiotherapists must communicate effectively with patients and/or their carers as well as with other health professionals providing relevant services to the patient. Also, every patient who receives physiotherapy must have a record (Goodwin, Ramaswamv & Tomas 2008).

Discharging patients

On completion of the treatment plan, arrangements are made for the transfer of care or discharge (Goodwin, Ramaswamv & Tomas 2008). For discharge, a *"locally negotiated protocol"* (Clinical Effectiveness and Evaluation Unit 2008) should be used to ensure patients and family are involved, general practitioners are informed, equipment and services necessary for safety are in place, and that patients and family are given appropriate information and contact details for available help and services (Clinical Effectiveness and Evaluation Unit 2008). Transfer to home is often stressful to patients, where many feel afraid, unsupported and as if services have 'given up hope'. It is also thought that communication between services is often poor with inadequate information being delivered too late (Clinical Effectiveness and Evaluation Unit 2008). It is important that relevant information is transferred, particularly concerning medication (Royal College of Physicians 2008a). Also, patients should only be discharged from hospital before the end of acute rehabilitation if a specialist stroke rehabilitation team are available and if the patient can transfer safely from a bed to a chair (Clinical Effectiveness and Evaluation Unit 2008). This is known as Early Supported Discharge (ESD), which can be defined as:

"A comprehensive stroke specialist and multidisciplinary team (which includes social care) in the community, but with a similar level of intensity to stroke unit care" (Department of Health 2007).

A patient can undergo ESD if their disability is moderate (Department of Health 2007) and if there is a specialist stroke rehabilitation team able to continue rehabilitation in the community (Royal College of Physicians 2008c). Also, carers of patients unable to transfer independently should receive training in moving and handling and the use of any equipment provided until they are demonstrably able to transfer and position the patient safely in the home environment (Royal College of Physicians 2008c). All patients should continue to have access to specialist stroke services after leaving hospital (Clinical Effectiveness and Evaluation Unit 2008). Patients being discharged who remain dependent in personal activities (for example dressing or toileting) should be offered a transition package of:

- Pre-discharge home visits (for example at weekends)

- Individual training and education for their carers/family

- Telephone counselling support for three months.

(Clinical Effectiveness and Evaluation Unit 2008)

Discharged stroke patients may also be eligible for:

- Employment and Support Allowance

- Disability Living Allowance

- Attendance Allowance

- Carer's Allowance

- Income Support

- Working Tax Credit

- Pension Credit

- Housing Benefit or help with rent

- Council Tax benefit

(The Stroke Association 2012)

Independent audit analysis and results

Since the guidelines are not always followed, performance is periodically audited to monitor conformance. In the UK, the RCP carries out an audit on the stroke healthcare service, known as the National Sentinel Stroke Audit (Royal College of Physicians 2010). The aim of the audit is to help improve the quality of care by involving trusts across the country in large-scale to enable them to compare their results to the national data (Royal College of Physicians 2009). The audit, which is made publicly available online, reveals information regarding the activities and performance of the health care service regarding stroke. Below are some findings from the 2010 audit which were considered relevant to this research:

"Less than half of services specifically run a service that provides educational or vocational training for patients of working age although this should be regarded as a core element of all stroke services. This seems at variance with government policy (both

present and previous) which stated the desire to encourage people off disability and sickness benefits and a focus on improvement in rehabilitation."

"It is clear that there are delays with ESD teams taking patients on and importantly variable delays with ESD in continuing therapy – depending on the discipline. Only a minority of team members have a waiting list of less than 48 hours. Integral to the definition of an ESD team is the ability to provide appropriate therapy within 48 hours of transfer of care from hospital and the majority of services are currently falling short of this standard."

"Non-specialist ESD teams (generic intermediate care teams) are used by one third of centres. Delays for transfer of care are greater than for stroke specific ESD as are delays in receiving ongoing therapy treatment. There is more nursing involvement in generic ESD and it is more often nurse than therapy led. As well as not being timely, such non-specialist ESD for stroke patients is not a substitute for stroke specific ESD and is associated with worse outcomes when compared to conventional care of in-patient stroke unit treatment."

"Just over half of stroke services have specialist community rehabilitation service for their patients. Where services do exist they are typically part of a wider community neurological rehabilitation service. Like ESD, such services have little specialist medical input (21%) and only half of them have specialist nursing. Delays are greater in receiving community neurorehabilitation compared with ESD with delays of more than 14 days being commonplace" (Royal College of Physicians 2010).

This suggests that human resources are limited, where the number of specialist clinicians is insufficient to fully accommodate all stroke patients. The RCP also state:

"One of the most frequent complaints of patients and carers in surveys of unmet need is the lack of information provision. It is important that out-patients are not forgotten when organising information services for patients. It appears that in many services they are neglected. 40% of stroke patients are not given a personalised rehabilitation

discharge plan and 29% still have no named point of contact on discharge" (Royal College of Physicians 2010).

Without adequate information and support, the stroke patient's level of recovery will likely be compromised. Below are some key findings from the 2009 audit.

"The mean length of stay of stroke patients in hospital care has fallen considerably over the last three cycles of audit from 34 days in 2001, to 25.4 days in 2006 and now 23.7 days in 2008. For an estimated 120,000 stroke patients in the UK annually this would translate into a reduction of about 3400 bed days for their care since 2001, or 550 bed days since 2006."

"It is concerning that 2% (82/4432) of patients discharged within 2 weeks were newly institutionalised. In many parts of the country access to intensive rehabilitation in care homes is limited or nonexistent and therefore it seems likely from these data that there are a significant number of patients who are being deprived of effective rehabilitation after their stroke in the rush to get them into a nursing home. Even if it seems inevitable that a patient will require residential care in the future they still deserve a period of treatment to enable them to perform to their maximum potential."

"74% of patients now spend some of their time and 68% spend more than half their time on a stroke unit which is a very considerable improvement from 2006. However we should not be satisfied until the figure reaches about 95%. These figures place us very favourably compared to other European countries. There are still 2,967 people in this audit who were not offered what is known to be the most effective treatment for stroke. Some of these may have been left with unnecessary disability or may have needlessly died as a result of failure to organise care satisfactorily" (Royal College of Physicians 2009).

The audit also reveals that 17% of patients are admitted to an acute stroke unit within 4 hours of admission and that 74% of patients are treated in a stroke unit at some stage of their hospital stay. Also 68% of patients receive more than 50% of their in-patient care on a

stroke unit and 58% of patients spend more than 90% of their hospitals stay on a stroke unit. 29% of patients are admitted to a stroke unit on the day of their stroke and 6% of patients are entered into stroke research trials (Royal College of Physicians 2009). This shows that as well as human resources, the number of facility resources is lacking.

A study analysed results from the 2001-2 National Sentinel Stroke Audit to see if the key characteristics deemed necessary for effective stroke care from research literature were present (Rudd et al. 2005). These were defined as coordinated multidisciplinary rehabilitation incorporating the following:

- Meetings at least once per week
- Staff with a specialist interest in stroke or rehabilitation
- Routine involvement of carers in the rehabilitation process
- Regular programs of education and training
- Provision of information to patients and carers

(Rudd et al. 2005)

It was found that the quality of care on some units defining themselves as specialist stroke units failed to meet basic standards, with only 46% offering all five of the key characteristics shown above, and 28% offering three or less. It was also found that 73% of hospitals audited have a stroke unit but only 36% of stroke admissions spend any time on one (Rudd et al. 2005). This suggests that internal communication and organisation may be lacking. It has been found that the cost of stroke healthcare in the UK in 2006/07 was just over £2.5 billion with 80% of the costs attributable to inpatient hospital care (£1.1 billion) and residential care (£900 million) (Allender et al 2010). Also, a study found that for every stroke that occurs, the cost to the NHS in the UK is around £15,000 over five years. This rises to £29,000 when including informal care (Youman et al. 2003). This shows that stroke has a high financial burden on the UK economy.

2.3. Human anatomy and mechanisms

2.3.1. Anatomy of the upper limb

This section identifies the anatomy of the upper limb, which consists of the arm and hand. The joint types, Degrees Of Freedom (DOFs) and what can result from those DOFs are identified. Anthropometric data of the upper limb is also reviewed. For clarity, the upper limb is broken down into the following sections:

- Shoulder
- Elbow
- Wrist
- Thumb
- Fingers

The identified anatomy of the sections above is shown below in tables 2.3.1a to 2.3.1e. This information was also further described graphically in Figure 3.2.3.

Table 2.3.1a. Anatomy of the shoulder (Behnke 2006)

Joints	Joint connections (bones)	Joint type	Number of DOFs	Movement (of upper arm)
Glenohumeral	Scapular to humerus	Synovial, ball and socket	3	Extension, flexion, abduction, adduction, lateral rotation, medial rotation
Acromioclavicular	Clavicle to scapular	Synovial, gliding	1	Abduction, adduction,
Sternoclavicular	Clavicle to manubrium sterni	Synovial, saddle	3	Extension, flexion, abduction, adduction, lateral rotation, medial rotation
Total DOFs of the shoulder: 7				

Table 2.3.1b. Anatomy of the elbow (Behnke 2006)

Joints	Joint connections (bones)	Joint type	Number of DOFs	Movement (of forearm)
Humeroulnar	Humerus to ulnar	Synovial, hinge	1	Extension, flexion
Humeroradial	Humerus to radius	Synovial, hinge	1	Extension, flexion
Proximal radioulnar	Radius to ulnar	Synovial, pivot	1	Pronation, supination
Total DOFs of the elbow: 3				

Table 2.3.1c. Anatomy of the wrist (Behnke 2006)

Joints	Joint connections (bones)	Joint type	Number of DOFs	Movement (of hand)
Radiocarpal	Radius to carpus	Synovial, ball and socket	2	Extension, flexion, ulnar deviation, radial deviation
Carpals	Carpus to metacarpals	Cartilaginous, sliding	2	Extension, flexion, ulnar deviation, radial deviation
Total DOFs of the wrist: 4				

Table 2.3.1d. Anatomy of the thumb (Behnke 2006)

Joints	Joint connections (bones)	Joint type	Number of DOFs	Movement (of thumb)
Carpometacarpal	Carpus to first metacarpal	Cartilaginous, Saddle	2	Extension, flexion, abduction, adduction
Metacarpophalangeal	First metacarpal to proximal phalanx	Cartilaginous, hinge	1	Extension, flexion
Interphalangial	Proximal phalanx to distal phalanx	Cartilaginous, hinge	1	Extension, flexion
Total DOFs of the thumb: 4				

Table 2.3.1e. Anatomy of the finger (Behnke 2006)

Joints	Joint connections (bones)	Joint type	Number of DOFs	Movement (of fingers)
Carpometacarpal	Carpus to metacarpal	Cartilaginous, hinge	1	Extension, flexion
Metacarpophalange	Metacarpal to proximal phalanx	Cartilaginous, hinge	2	Extension, flexion, abduction, adduction
Proximal interphalange	Proximal phalanx to middle phalanx	Cartilaginous, hinge	1	Extension, flexion
Distal interphalange	Middle phalanx to distal phalanx	Cartilaginous, hinge	1	Extension, flexion
Total DOFs of the four fingers: 20				

The total number of DOFs of the upper limb is therefore 38, which makes it a mechanically complicated appendage.

Anthropometric data

The external dimensions of the segments of the upper limb were identified from literature. The 95th percentile male dimensions (largest) and the 5th percentile female dimensions (smallest) were identified to identify a single size range for males and females. The prototype system was to be designed for both males and females. The anthropometric data was sourced from *"Anthropometrics: An Introduction"*, published by BSI Standards in 1990. The locations of measurement for anthropometric data are shown in Figure 2.3.1. and the corresponding data in Table 2.3.1f.
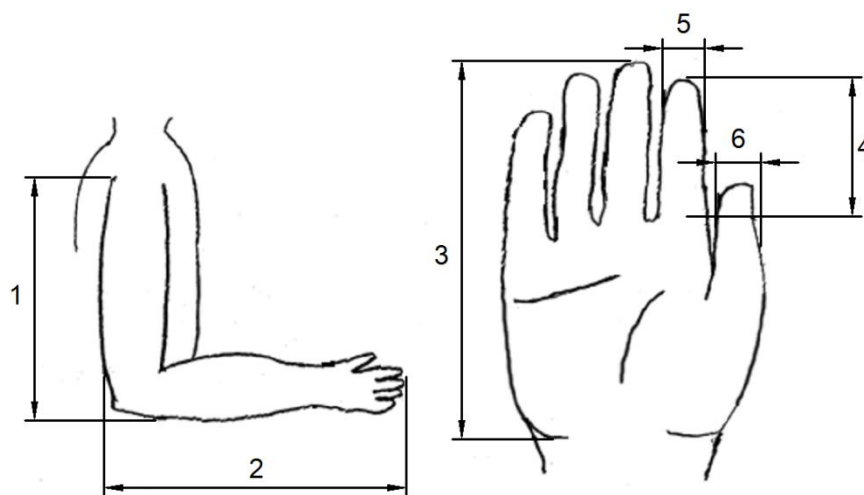
Figure 2.3.1. Locations of measurement for anthropometric data

Table 2.3.1f. Anthropometric data (Pheasant 1990)

Location of measurement on body (see Figure 2.3.1)	1	2	3	4	5	6
5th percentile dimension (mm, females)	300	400	159	60	15	16
95th percentile dimension (mm, males)	400	510	205	80	24	26

2.3.2. Movement characteristics

Upper limb movements

A study (Soechting, Lacquaniti 1981) that investigated the invariant characteristics of a pointing movement in humans discovered that the trajectory in space is largely independent

of movement speed. It was also concluded that the movement can be considered to consist of two phases; an acceleration phase and a deceleration phase, with the movement during the acceleration phase being organised to maintain the ratio of elbow angular velocity to shoulder angular velocity (extension and flexion) with respect to target location in the deceleration phase. Also, the greater the speed of the movement, the less accurate the activity may be performed (Sparkes 2009). Another study (Wu et al. 2000) investigating the contextual effects of reaching, with 14 stroke patients and 25 healthy participants, compared the performance of reaching for physical objects with when imaginary objects were reached for. It was found that the presence of a real object resulted in shorter movement time, less total displacement, higher peak velocity, and greater percentage of reach where peak velocity occurs.

Movements of the upper limb function with the assistance of other components of the human body. This includes the trunk, cervical, thoracic and lumbar spine and pelvis (Sparkes 2009). Function of the upper limb often involves activation of all of these components, which are referred to as the kinetic chain (Hirashima et al. 2008). As well as requiring a stable base on which to function, the upper limb is used extensively to enhance balance and stability of the body (Sparkes 2009). Also, the upper limb is used for Activities of Daily Living (ADLs) such as reaching and grasping an object and moving it, where the arm functions as one unit. Such movements can be broken down into sub movements such as delivery (reach), prehension (grasp) and retrieval, which could be for example bringing the hand to the mouth when drinking from a cup (Sparkes 2009). The term "manipulation component" can also be used to describe movements such as turning a key. Visual feedback during movement is also important. For example the visual feedback on the positioning of the hand is necessary for accuracy of the grasping action, however, even if the movement is carried out without visual feedback, it can often be achieved but may take more time or be less accurate (Sparkes 2009). Vision plays an important role in planning and executing movements (Apker, Karimi & Buneo 2011), for example to allow the size and position of an object to be anticipated, thus providing a smooth and efficient action (Sparkes 2009). The role of vision during movements is investigated further in section 2.4.2. DOFs have ranges of movement, that is, a minimum to a maximum angular displacement. This is known as a Full Range Of Movement (FROM) (Everett 2009). This FROM consists of an inner range, normally

during flexion, and an outer range, normally during extension. Normal activities are carried out in a mid range, which is approximately central between the minimum and maximum angular displacements (Everett 2009).

A study investigating the coordination between rotation of the lower arm (pronation/supination) and rotation of the upper arm (lateral/medial rotation) found that asymmetry was reduced for movements of similar direction (Alazmani et al. 2008). That is, greater movement synergism was present during medial rotation and pronation than during medial rotation and supination. Movement synergism, was considered in terms of the times of peak velocities and accelerations and decelerations of DOFs, and graphical analysis was performed. Movement synergism in a simple form could be considered as the extent of simultaneous movement of two or more DOFs.

A traditional notion is that corrective sub-movements are performed to improve accuracy of target achievement, however, some researchers hypothesise that simple movements contain subtasks including *"accurate target achievement"* and *"movement termination"* (Wisleder, Dounskaia 2007). These subtasks themselves are thought to cause sub-movements. A study aimed to identify the presence of a *"movement termination"* subtask had participants perform both a discrete movement and a continuous movement. It was thought that the movement characteristics showed that the movement termination subtask was only present during the discrete movement (Wisleder, Dounskaia 2007).

Spontaneous physical recovery after stroke

A level of spontaneous neurological recovery after ischemic stroke is common (Rothrock, Clark & Lyden 1995). The term *"Spectacular shrinking deficit"* (SSD) was developed to describe rapid recovery from a major hemispheric syndrome by migration of an embolus (Minemastsu, Yamaguchi & Omae 1992). A study observing 118 stroke patients found 14 to have SSD (12%). Examination within 24 hours showed that embolus migration had occurred in all patients with SSD, but only in 13% of patients without SSD. This suggests that SSD tends to occur in patients with an embolus that migrates (Minemastsu, Yamaguchi & Omae 1992). Another study (Rothrock, Clark & Lyden 1995) observing 68 stroke patients found 16 to have SSD (24%). The study also found that patients who had suffered small vessel disease

stroke were more likely to have SSD, but concluded that the majority of patients with acutely disabling stroke will remain significantly impaired after the stroke onset. When assessing the efficacy of a treatment regime, knowing the level of spontaneous recovery that is likely to occur is important in allowing the causes of improvement to be known (Biller et al. 1990).

2.3.3. Neural control of movement

The main neural components responsible for motor function are as follows:

- Cerebral cortex
- Basal ganglia
- Cerebellum
- Brain stem
- Spinal cord

(Haas 2009)

In terms of the functions of the above neural components, neural control of human movement can be simplified to three major centres; the control centre, the comparator centre and the execution centre (Haas 2009), as shown in Figure 2.3.3a.
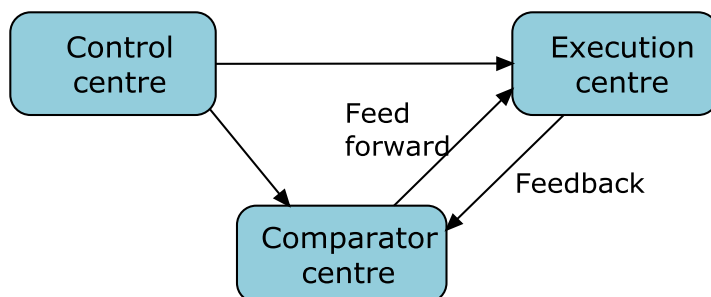
Figure 2.3.3a. The major centres of neural control of movements, simplified from *"Feed-forward and feedback systems of a 'simple' voluntary movement"* (Haas 2009), with feed forward and feedback locations added and worded descriptions removed

The control centre is responsible for both planning and execution of controlled movements. This is where memories of skilled movements are located. These memories can be accessed to enhance the planning of movements and to improve the performance of a physical activity. When a movement plan has been compiled, it will be transmitted via signals in a feed-forward manner to the execution centre (Haas 2009). The execution centre is responsible for activating muscles that allow movements to be made. Once muscles are activated, feedback is provided to the comparator centre. The comparator centre allows the movement to be refined both voluntarily and under reflex. Over a longer time period, the feedback will also build new memories of skilled movements, which is a component of motor learning (Haas 2009). Before the major neural components are discussed further, transmission of information and the role of sensory feedback systems are explored.

Information transmission and sensory feedback systems

In order for the brain to control movement, information must be transmitted. This is achieved through the motor neurones which transmit signals electronically and chemically (Latash 2008). The electrical condition of the motor neurones whilst their respective muscles are in a resting state is the 'resting potential', whilst the condition during muscle activation is the 'action potential'. Information transmission from one cell to another occurs at the synapses (Haas 2009). In order for rapid control of movement, information transmission itself is rapid. This is why electrical transmission is effective. It is the alpha motor neurones that transmit information for muscle contraction. The alpha motor neurone along with the muscles it controls is known as a motor unit (Latash 2008).

The Central Nervous System (CNS) needs to receive continuous feedback regarding movement to allow planning and control. This is achieved by means of receptors. The main receptors are the muscle spindles, which detect the length of a muscle and its rate of change of length, and the Golgi tendons, which detect the tension of a muscle and its rate of change of tension (Brooks 1986). These receptors transmit information to the spinal cord, the cerebral cortex and the cerebellum, which is known as proprioceptive feedback. The muscle spindles transmit information about the dynamic state of muscles via the primary endings, and about the static state via the secondary endings (Haas 2009). The primary

endings transmit signals in the form of pulses which increase in frequency in correlation to rate of change of length. Both the primary and secondary endings continuously transmit signals in proportion to static muscle length. This information is transmitted as feedback by the gamma motor neurones (Latash 2008). The Golgi tendons transmit information about the dynamic and static tension of muscles and are stimulated by increases in muscle tension (Haas 2009). Both the Golgi tendons and the muscle spindles are closely linked to spinal reflexes. When the Golgi tendon detects an increase in muscle tension that is too great, automatic inhibition of muscle contraction prevents additional tension. Also the Golgi tendon reacts to return tension to an appropriate level if it is detected as too low. These reactions can be considered as tension reflexes and stretch reflexes which have opposite effects on a muscle (Haas 2009). As well as assisting in voluntary control, the receptors allow reflex based control which in turn allows smooth actions and good muscle tone. The feedback to the comparator centre forms closed-loop control, as a closed-loop is formed between the control centre, comparator centre and the execution centre. Feedback which forms the closed-loop comes from proprioception, which is sensory information that comes from internal sources such as the muscles and joints, and exteroception, which is sensory information that comes from external sources such as vision and smell (Schmidt, Wrisberg 2008).

The locations of the main neural components involved in controlling movements are shown in Figure 2.3.3b.
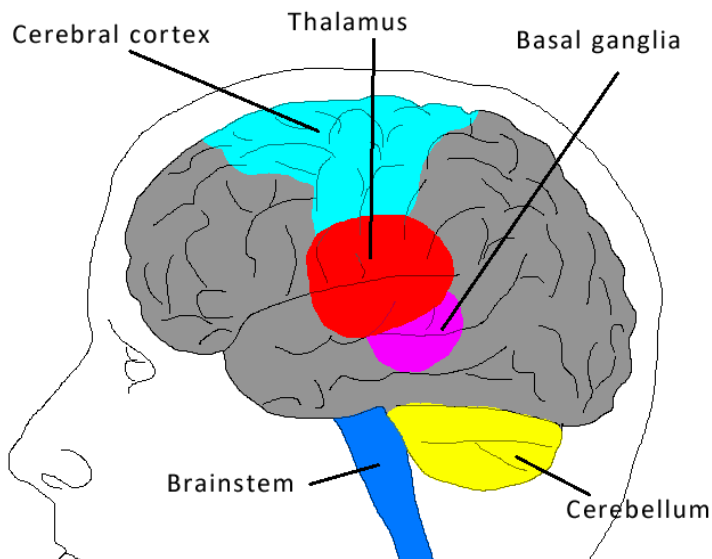
Figure 2.3.3b. The locations (Nolte 1993) of the main neural components involved in controlling movements

Cerebral cortex

The cerebral cortex can be considered the central component in controlling voluntary movement. It uses information from the basal ganglia, cerebellum and other areas, as well as feedback from senses, to allow movement to be executed and controlled (Nolte 1993). The cerebral cortex provides the intellectual and cognitive functions of humans and allows storage of memories and skills and has the ability to recall (Latash 2008). It is the cerebral cortex that perceives, understands and integrates interactivity and feedback with the environment. Regarding movement, the main function of the cerebral cortex is the planning and execution of complex motor activities, for example fine hand movements. Within the cerebral cortex, the motor cortex, primary motor area and motor association area exist. The motor cortex occupies the posterior half of the frontal lobes. It is a broad area of the cerebral cortex that integrates sensory information from the association area to control posture and movements (Thompson 1993). The primary motor area sends signals directly to the spinal cord. The motor association area sends signals to the primary motor cortex to activate multiple groups of muscles. The signals generated here cause more complex muscle actions, usually involving groups of muscles, which perform specific tasks rather than activating individual muscles (Haas 2009). The motor association area is connected to the cerebellum and basal ganglia via the thalamus, which is connected to the motor cortex. Each time a signal is transmitted to the spinal cord, the same information is transmitted to the

basal ganglia, the brainstem and the cerebellum. It is these nerve signals from the motor cortex that cause muscles to contract (Latash 2008).

Cerebellum

The cerebellum is responsible for comparing output movements with planned movements and making corrections if necessary. It therefore aids the process of refining movements and can be considered the comparator centre in terms of neural function (Brooks 1986). The cerebellum plays an important role in controlling rapid muscle movement such as typing and talking. It has many inputs and outputs which carry both motor and sensory information. Interconnections are made between the cerebellum, basal ganglia, thalamus and the cerebral cortex (Nolte 1993). The cerebellum therefore plays a role in motor learning.

Basal ganglia

The basal ganglia consist of five major nuclei which exist in the form of side loops that protrude and return to the cerebral cortex. These are known as the putamen, caudate nucleus, globus pallidus, subthalamic nucleus and the substantia nigra (Thompson 1993). The major function of the basal ganglia is to provide internal cues for smooth performance of movements. It therefore aids the process of refining movements. It is also believed that the basal ganglia aid the process of selecting appropriate movements and suppressing unwanted ones (Latash 2008).

Brainstem

The brainstem is located between the cerebral cortex and the spinal cord. It is linked to the cerebellum, basal ganglia and cortical regions (Nolte 1993). The brainstem, when necessary, initiates contractions of the postural trunk muscles, neck muscles and the proximal parts of the limb musculature. Its role in initiating contraction of these muscles is to generate gross stereotyped movements of the body and to maintain equilibrium against gravity (Haas 2009).

Spinal cord

The spinal cord is responsible for initiating reflex actions and other automatic functions. It is also involved in postural adjustments. Sensory signals enter the spinal cord through nerve roots and then travel to either neighbouring grey matter within the spinal cord in the case of reflexes, or higher centres in the CNS such as the brainstem where they provide conscious experiences (Nolte 1993). The spinal cord itself has processing functions which is an essential function of motor control. This is made possible by Renshaw cells which transmit signals to nearby motor neurones on a subconscious level. This allows for fast reflex responses such as withdrawal from a hot object. Also, together with the brain stem, the spinal cord controls walking (Haas 2009).

Control process of voluntary movement

The processes of generating voluntary movement described above and the signal interconnectivity is summarised in Figure 2.3.3c.
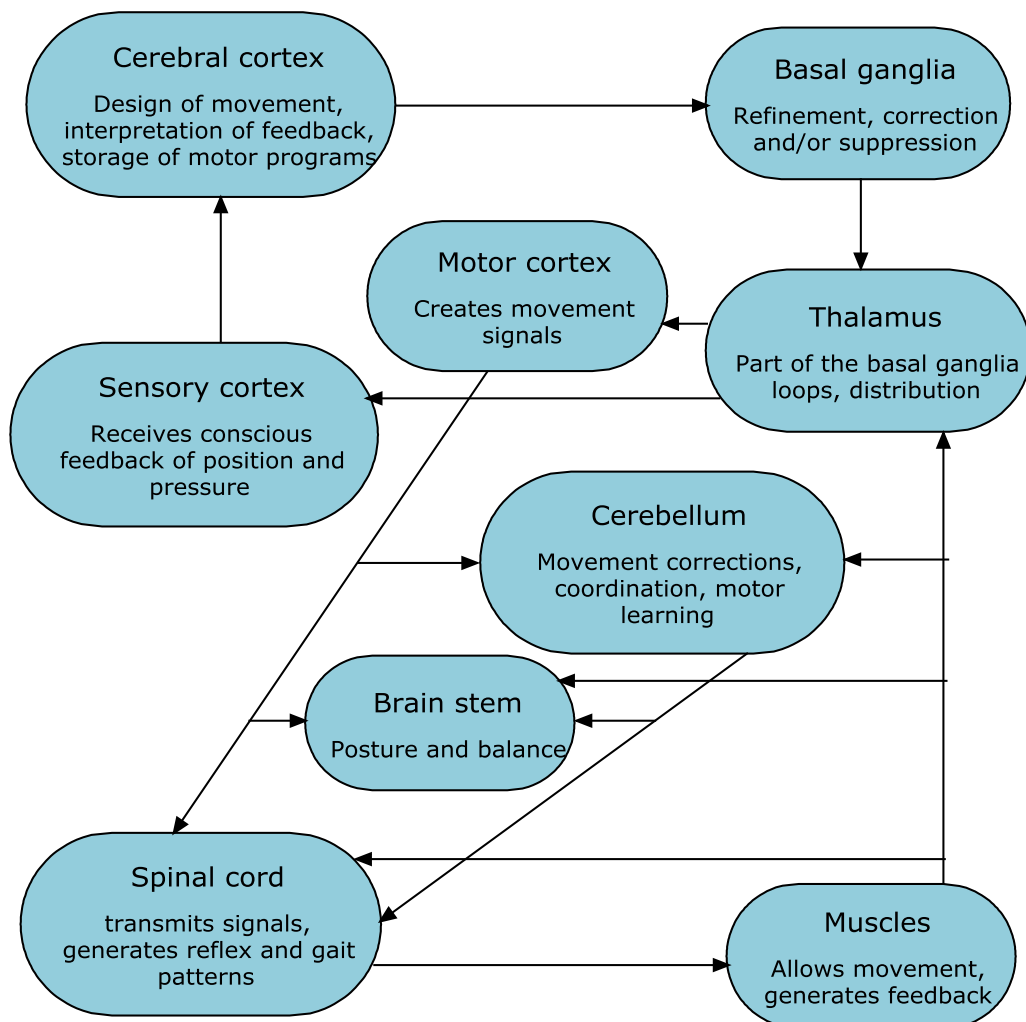
Figure 2.3.3c. The major neural components involved in controlling movement, adapted from *"The control process of voluntary movement"* (Haas 2009), with fewer words and terminology to match reviewed literature

2.4. Motor skill and motor learning

2.4.1. Motor skill

The term *motor skill* can be defined as a task that has a specific goal to achieve. A movement can be defined as behaviour characteristics of a specific limb or combination of limbs (Magill 1998). Movements are therefore required to allow skills to be executed.

When considering motor skills in terms of tasks, the task perspective is adopted. Motor skills can be discrete, serial or continuous. A discrete skill is a skill or task that has one distinct movement having an identifiable beginning and end point (Magill 1998). A serial skill is one that *"combines a sequence of discrete movements in a specific order"* (Wrisberg 2007). A

continuous skill is a skill organised in such a way that the action unfolds without a recognisable beginning and end in an on-going and often repetitive fashion (Schmidt, Wrisberg 2008). Skills can also be considered in terms of the relative importance of the motor and cognitive elements. For movements where a single goal is being aimed for, for example throwing a javelin as far as possible, the motor element is most important, that is, strength, speed and direction. For movements where strategy is required, for example moving chess pieces, the cognitive element is most important whereas the speed and strength are less important (Wrisberg 2007). As motor learning takes place, the importance can shift from the cognitive element to the motor element. The level of environmental predictability that one must perform in will also affect the required skills. An environment that is dynamically predictable would require closed skills to perform in, for example raising a glass. An environment that is dynamically unpredictable would require open skills to perform in, for example catching balls thrown from different directions (Schmidt, Wrisberg 2008). The term *fine motor skill* is used to define skills requiring precision control of small muscles such as skills requiring hand-eye coordination. The term *gross motor skill* is used to define skills requiring less precise movements of larger muscles such as walking (Magill 1998).

Skills can also be considered in terms of the quality of the movement itself, which is known as the performance perspective. Quality can be considered as synonymous with the certainty of a goal being achieved. Motor skills are therefore generally present when the goal can be achieved reliably. A high quality movement could also be considered to be one with minimum expenditure of energy and minimum movement time (Schmidt, Wrisberg 2008).

2.4.2. Motor learning

Motor performance

Motor learning involves improving long term ability to perform high quality movements, where high quality is synonymous with high performance. The stages of motor learning can therefore be classified as the changes in levels of observable performance (Schmidt, Wrisberg 2008). For example, the stages could be a cognitive stage where trial and error

takes place, which then changes to an associative stage where a skill is homed in on. Finally an autonomous stage could be reached where little cognitive input is required. This type of movement is sometimes referred to as automated movement. The general stages of learning with the observable characteristics are shown below:

Early learning (cognitive stage):

- Stiff looking
- Inaccurate
- Inconsistent
- Slow, halting
- Timid
- Indecisive
- Rigid
- Inefficient
- Many errors

Progression (associative stage):

- More relaxed
- More accurate
- More consistent
- More fluid
- More confident
- More decisive
- More adaptable
- More efficient
- Fewer errors

Later learning (autonomous stage):

- Automatic
- Accurate
- Consistent
- Fluid
- Confident

- Certain

- Adaptable

- Efficient

- Performer recognises errors

 (Schmidt, Wrisberg 2008)

Although motor performance is observable, it is susceptible to variation due to temporary factors such as motivation, arousal, fatigue and physical condition (Wrisberg 2007). This should be borne in mind when assessing one's long term ability.

Implicit and explicit learning

Implicit learning is inadvertent, unconscious and characterised by behavioural improvements (Halsband, Lange 2006). It therefore demands less attention (Cleeremans, Destrebecqz & Boyer 1998) and is fundamental to the process of learning ADLs (Howard et al. 2004). A definition of implicit learning is *"movements that occur in a person's capability for correct responding as a result of repeated performance attempts and without the person's awareness of what caused the improvements (or that the improvements even occurred)"* (Schmidt, Wrisberg 2008). Implicit learning appears to take place during most motor learning processes, for example someone who has learnt to throw darts may not be aware of what exactly caused the improvements dynamically or neurologically. Explicit learning is learning through a cognitive process involving the short term memory and can be tested by component recall and recognition (Steenbergen et al. 2010).

Situation

The situation will have an effect on motor learning, and can be considered in terms of who is performing the task, the task itself and the environment in which the task is to be performed (Schmidt, Wrisberg 2008). 'Who is performing the task?' aims to determine the characteristics that can vary from one person to another including their maturation, previous movement experience, sociocultural background, emotional makeup and in some cases their disabling condition. 'What is the task?' aims to determine the dynamic demands of the task and the decisions that performers must make during practice. 'What

environment will the task be performed within?' aims to determine where the person will practise and then perform the task, whether other people will be present or watching, and whether the person will be able to take their time (Schmidt, Wrisberg 2008). Also, environments can change both predictably and unpredictably in some cases (Davidson, Wolpert 2003).

Memory

The memory is usually viewed as the persistence of acquired knowledge or capability for action and can be considered to consist of three systems which are all involved in the processing of information that results in movement production. These systems are the Short Term Sensory Store (STSS) (Schmidt, Wrisberg 2008), the Short Term Memory (STM) and the Long Term Memory (LTM) (Wrisberg 2007). These memory systems are shown in Figure 2.4.2a.
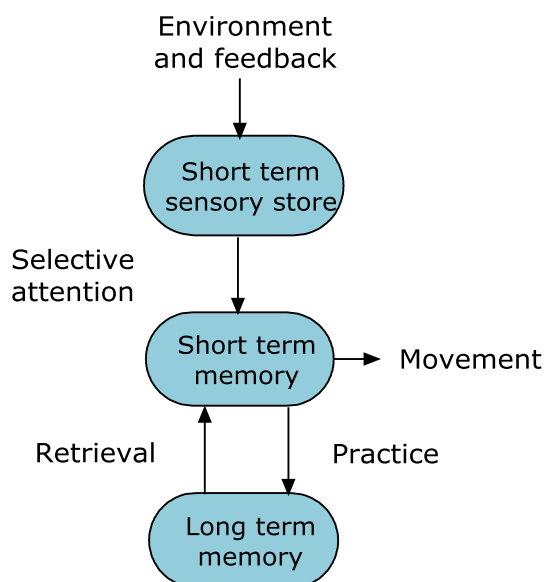
Figure 2.4.2a. The three memory systems, adapted from *"The three discrete components of the human memory"* (Schmidt, Wrisberg 2008), with feedback shown

The STSS holds sensory information such as visual and auditory data. It is believed to be almost unlimited in capacity but very brief in duration. It is also believed that the STSS stores information before the performer is conscious of it, therefore requiring little cognitive attention. A selective attention mechanism selects some of the information from the STSS

for further processing based on its relevance or applicability to the present task (Schmidt, Wrisberg 2008). This information is then held in the STM. The STM allows people to retrieve, rehearse, process and transfer information and therefore it can be considered a holding space (Wrisberg 2007) or working memory (Redick et al. 2011). It is believed to be limited in capacity and brief in duration (Wrisberg 2007). The LTM is considered the storage space for the experiences and skills that people accumulate over their lives. The process of remembering involves retrieving information from the long term memory. Information is stored in the LTM as a result of controlled and effortful processing. It is thought that the process of learning a new motor skill can involve retrieving an existing skill from the LTM and modifying it. Motor skills are developed through practice. The LTM is thought to be virtually unlimited in capacity and duration (Wrisberg 2007). The process of learning results in rearranging and development of new pathways and data in the brain. This process is known as neural plasticity or brain plasticity (Hosp, Luft 2011).

Information processing

In order for a physical action to be carried out, for example picking up a cup, in response to a requirement, for example experiencing thirst, information must be processed. The information processing can be considered to occur in three distinct stages; stimulus identification, response selection and response programming (Schmidt, Wrisberg 2008), which is shown in Figure 2.4.2b.

Input → Stimulus identification → Response selection → Response programming → Output

Figure 2.4.2b. The stages of information processing, adapted from *"An expanded information processing model"* (Schmidt, Wrisberg 2008), with worded descriptions removed

The stage of stimulus identification can be considered as the input during the process of movement. At this stage, the stimulus is detected and identified through the senses and could consist of vision, audition and touch or kinesthesis (Kelso 1982). It is thought that information can be processed in parallel, allowing two or more streams of information to be processed simultaneously. When stimulus identification has been carried out, a

representation of the important environmental information is established (Hohlefeld, Nikulin & Curio 2011), which then passes onto the next stage for further processing. During the stage of response selection, it is decided which, if any, response should be made. During this stage, a translation is made between the sensory information identified and an appropriate response from several available options (Kelso 1982). This process is known as schema theory, where a set of rules are used to serve as a basis for initiating a skill (Schmidt 1975). The response selection stage is affected by whether or not someone has practised a movement and is skilled. During the stage of response programming, the motor system is organised in order to allow the desired movement to be performed (Maslovat et al. 2011). The motor program is retrieved for action, the musculature is prepared for the upcoming commands to contract, the sensory system is orientated appropriately (for example paying attention to vision if required) and the postural system is readied for action (Schmidt, Wrisberg 2008). After this stage, the movement can start.

Motor programs

The concept of closed-loop control, introduced in section 2.3.3, is associated with controlled processed movements where the cognitive element is important. However, in the case of automatic processed movements where the motor element is important, an open-loop control system exists (Wrisberg 2007). Open-loop control tends to occur during short, simple motor tasks, for example dropping an object, where the movement is planned and once underway, little cognitive input takes place and little modification is made throughout (Morris et al. 1994). Even during dropping an object, there are a large number of DOFs which move, including all those within the fingers and thumb. There would therefore be too much information to process cognitively if dropping the object was to be carried out entirely under a controlled process, including the temporal and kinetic control of all DOFs. With practice, even complicated movements, for example a tennis serve, can be controlled using automatic processed control. In this case, a motor program is referred to, which is an abstract memory structure that is prepared in advance of the movement to be produced (Kelso 1982). Once learned, the program is stored in the LTM to be retrieved in future when needed for use in the STM to prepare during the response programming stage of the processing of information in motor control (Schmidt, Wrisberg 2008). Motor programs are

thought to be stored in hierarchical tree-like structures, which are similar for the same motor skills in different individuals (Schack, Mechsner 2006).

The information thought to be contained within a motor program is shown below:

- The particular muscles used to produce the action
- The relative timing and sequencing of these contractions
- The order in which these muscles would be activated
- The relative forces of the various muscle contractions
- The duration of the respective contractions

(Kelso 1982)

Motor programs can be adapted to cater for individual situations (Wrisberg 2007). For example hitting a tennis ball may be controlled using a motor program, but each return shot will be slightly different. In this case, a generalised motor program exists. The generalised motor program defines a pattern of movement rather than a specific movement which allows performers to adapt the program to produce variations of the pattern that meet various environmental demands (Poggio, Bizzi 2004). The modifiable parameters of the generalised motor program are the fundamental timing structure of the movement, the movement amplitude, the movement direction, and the limbs and muscles used. These parameters appear to be independently modifiable, for example increasing the movement amplitude but maintaining the fundamental timing structure when hitting a tennis ball harder than normal. This is known as generalisation (Schmidt, Wrisberg 2008), and is also part of schema theory (Magill 1998). Apart from motor-program-based theory, another theory of motor control is dynamic systems theory. This takes a multidisciplinary perspective involving physics, biology, chemistry and mathematics. Motor control is viewed from the perspective of nonlinear dynamics (Magill 1998). It is believed that changes in motor ability occur in distinct stages rather than through linear progression, analogous to water changing from laminar to turbulent flow in a pipe as flow-rate increases (Magill 1998). However, the dynamic systems cannot account for some of the control systems such as open-loop control, which have been shown to exist (Schmidt, Wrisberg 2008).

Motor performance model

To summarise the mechanisms and to graphically describe the processes of motor performance, a model of motor performance shown in Figure 2.4.2c was constructed.
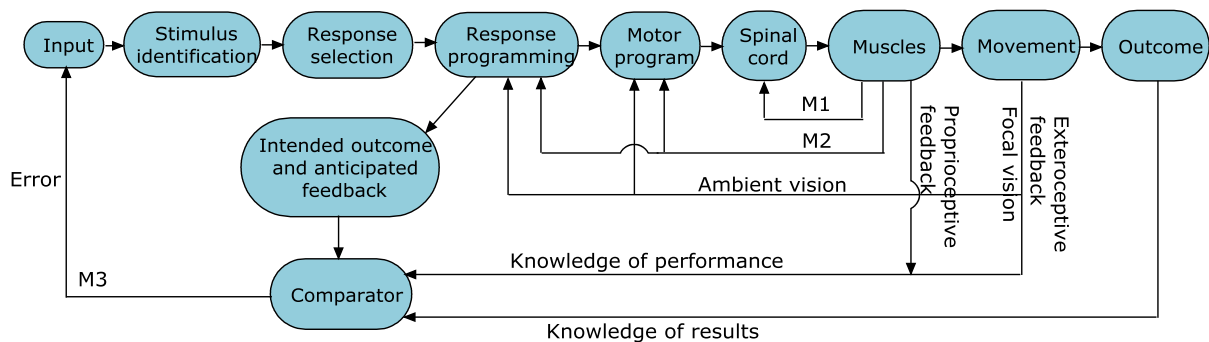
Figure 2.4.2c. Model of motor performance, adapted from *"The conceptual model of motor performance"* (Schmidt, Wrisberg 2008), with M2 and ambient vision also feeding back to response programming, and the locations of intrinsic and extrinsic feedback removed

Reflexes

In Figure 2.4.2c, M1, M2 and M3 depict the pathways of reflex actions. The M1 reflex response is triggered when the muscles are unexpectedly stretched, which stretches the muscle spindles. It is sometimes referred to as the monosynaptic stretch reflex because only one synapse is involved. This means the latency, is very short, around 30 to 50ms, in other words the reaction time is fast (Schmidt, Wrisberg 2008). The M1 reflex response is involved in postural control. The M2 reflex response is triggered when, for example, an unexpected load is added to the muscles. It is sometimes referred to as the functional stretch reflex (Brooks 1986). The M2 response is unique in that the amplitude can be cognitively controlled despite it being too fast to be categorised as a voluntary action. The M3 reflex response is also triggered when an unexpected load is added to the muscles. This type of reaction tends to be learned and requires voluntary reactions that occur in a sequential fashion requiring the learners' attention (Schmidt, Wrisberg 2008).

Vision

Of all sensory information, vision tends to be the most important (Magill 1998). Also shown in Figure 2.4.2c, both focal and ambient vision systems play roles in feedback. Focal vision is specialised for object identification whereas ambient vision is specialised for movement

control (Magill 1998). Focal vision is used to allow objects to be identified consciously and allows details such as size and shape to be detected. Ambient vision allows the positions and velocities of objects to be identified and is used in balance. Ambient vision is wider in field of view and does not require as much light to be effective in comparison to focal vision (Wrisberg 2007). Vision is considered exteroceptive feedback in movement control, as information detected is external to the body.

2.5. Feedback during motor learning

The term 'feedback' can refer to sensory information resulting directly from movements, or feedback provided externally in an artificial form, for example a physiotherapist describing appropriate ways to improve the dynamic performance of a movement at the end of a physiotherapy session. The sensory information available that can be provided in relation to movements is shown in Figure 2.5.
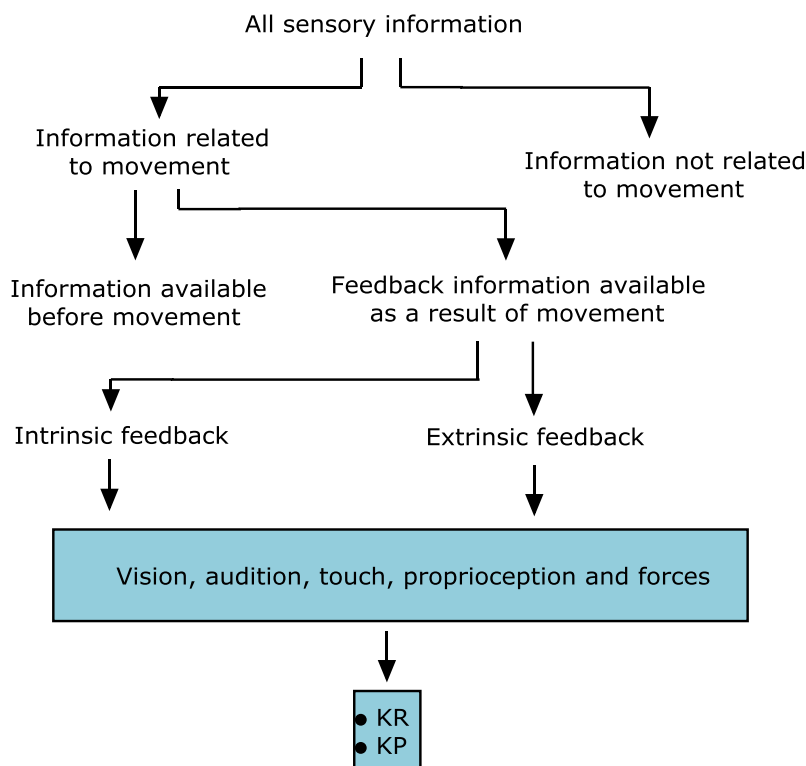
Figure 2.5. Sensory information during movements, adapted from "*A classification system for sensory information*" (Schmidt, Wrisberg 2008), adapted to show both intrinsic and extrinsic feedback through multiple senses and as Knowledge of Results (KR) and Knowledge of Performance (KP)

2.5.1. Intrinsic and extrinsic feedback

Intrinsic feedback is sensory information that is naturally available when learners produce movements. Intrinsic feedback can be in the form of proprioception, which, as described, is sensory information that comes from internal sources, such as the muscles and joints. Intrinsic feedback can also be in the form of exteroception, which is sensory information that comes from external sources such as vision and audition (Magill 1998). Healthy learners are able to receive intrinsic feedback directly without special assistance from other sources. For example when one fills a cup with water, intrinsic feedback takes multiple forms. The weight of the cup increases, the sound of the water changes and one can see as the surface of the water approaches the brim. Extrinsic feedback, or augmented feedback, in contrast is sensory information provided by an outside source in addition to the naturally occurring intrinsic feedback (Wrisberg 2007). These outside sources could include for example the display on a stopwatch screen, a video replay of a movement, or, to use the previous example, a physiotherapist describing appropriate ways to improve the dynamic performance of a movement at the end of a physiotherapy session. Extrinsic feedback can therefore be further categorised into Knowledge of Results (KR), for example provided by the stopwatch screen, or Knowledge of Performance (KP), for example provided by the physiotherapist (Magill 1998).

Knowledge of results (KR)

KR, or outcome feedback, is feedback that indicates the degree to which learners have achieved the desired outcome (Wrisberg 2007). KR can be useful when performing tasks of which one's own intrinsic feedback is difficult or impossible to use or use effectively, for example when manipulating an object that is difficult to view such as hitting a golf ball to a distant target. In this case, KR could be in the form of someone close to the target point of the ball shouting back the distance of the golf ball from the hole. KR can in some cases however be redundant, for example informing someone they have failed a physical task, when it is already obvious from their own intrinsic feedback, for example vision (Schmidt, Wrisberg 2008). KR in this case would be irritating. Research has shown that KR can allow rapid improvement in motor skill and that improvements can be retained in the case when KR is then withdrawn (Bilodeau, Bilodeau & Schumsky 1959).

Knowledge of performance (KP)

KP, or performance feedback, is augmented feedback that provides information about the characteristics of the movement that led to the performance outcome (Magill 1998). It is sometimes referred to as kinematic feedback, which is feedback about the displacement, velocity, acceleration and forces of the movement or the object being moved. KP is particularly important because learners are often unable to assess their own movements whilst they are performing them (Wrisberg 2007). Feedback is therefore one of the most important principles of learning (Schmidt, Wrisberg 2008). It is KP that is used predominantly in rehabilitation settings (Subramanian et al. 2010). Extrinsic feedback in the case of motor learning is generally provided ultimately to increase motor skill, or to increase the speed at which motor skill is acquired, or both. This can be achieved through the provision of information and the resulting motivation and reinforcement (Schmidt, Wrisberg 2008). However, negative effects can also occur, for example dependency can develop (Wrisberg 2007). The various effects of extrinsic feedback, and how they can be utilised or avoided were therefore investigated.

2.5.2. Feedback formats

Extrinsic feedback can be provided through different senses, perhaps the most common being audition and vision. Other senses that can provide feedback include touch and proprioception. Of which sense to provide feedback through will depend upon the task being performed, for example visual extrinsic feedback could be a distraction in a task requiring attention to visual intrinsic feedback, whereas it may be the most suitable for simpler movements. Provision of feedback will also be dependent on the nature, amount and precision of the information that is fed back, which is discussed in section 2.5.3. This section investigates some of the most commonly used formats that feedback can be provided in, which include qualitative, quantitative, graphical, verbal and videotape (Magill 1998), as well as using discrete and continuous data.

Qualitative and quantitative feedback

Qualitative feedback refers to the quality of a movement, for example *"good improvement"*, whereas quantitative feedback is when a numeric value is given, for example *"improvement*

by 14.6%" (Magill 1998). Qualitative information may therefore be more effective for communicating emotion, which is useful for motivation. Quantitative information allows for more precision, which becomes more useful as learning progresses (Magill 1998). A study investigated two groups who were asked to perform novel movements with specific target durations. One group was given qualitative feedback, for example *"too fast"* or *"too slow"*, whereas the other group was given quantitative feedback of their deviations from the target time in milliseconds. The performance of the group given quantitative feedback was superior on the final 60 of 120 practice trials (Magill, Wood 1986).

Discrete and continuous feedback

Discrete data is data that is given as a single value which is descriptive of performance over a certain time period. Discrete feedback is therefore suitable for giving average or summary feedback, which is discussed in section 2.5.3. Continuous data is data that can be provided continuously in proportion to a measured medium. Continuous data can also be provided at a single point in time, but must be given with matching time data, for example via a graph. Continuous data may contain more detail, but may be distracting if provided during a movement, or be difficult to interpret if given terminally in graphical form. A study (Schiffman et al. 2006) tested participants who were asked to perform a task involving applying varying force. One group was given discrete feedback only when errors exceeded +/- 4% of their maximum strength. Another group was given continuous visual feedback of their applied force against the target force pattern. It was found that the group receiving discrete feedback had higher standard deviation of residuals between the target movements and their own movements. However, whether feedback should be discrete or continuous will be dependent on the task, and also the timing of the feedback, which is also discussed in section 2.5.3.

Graphical feedback

Graphical feedback in this context is extrinsic feedback provided on a graph. The measured medium, for example position or velocity, is usually displayed on the Y axis of the graph, whilst time is displayed on the X. It is therefore suitable for visually displaying continuous data as described. A study (Newell et al. 1983) examined the learning of participants who

were asked to move a lever to a target position as fast as possible. One group was informed of their movement times verbally, a second group was given their velocity profiles in graphical form, and a third was given no extrinsic feedback. Each group was allowed 25 practice trials, and each was found to have reached a largely stable state after trial 20. However, both verbal and graphical feedback groups were able to improve further upon receiving feedback, where the group who had received graphical feedback improved the most. However, early learners will benefit from graphical feedback only when they are able to interpret it. It is therefore useful to show a template of the target movement, particularly in the early stages of learning (Magill 1998). Also, graphical data requires experience to allow interpretation (Magill 1998), and explanations or training may be necessary.

Verbal feedback

Verbal feedback is extremely versatile and, as described, can be qualitative or quantitative, KP or KR (Magill 1998), and positive or negative (Puddefoot, Hilliard & Burl 1997). Verbal feedback appears to be the most commonly used in physiotherapy and does not require equipment. A distinct benefit to verbal feedback is that emotions can be communicated effectively. This is particularly important for motivation and support, which features widely in stroke guidelines (Clinical Effectiveness and Evaluation Unit 2008). Also, because verbal feedback is communicated through audition, little distraction is caused for movements requiring attention to intrinsic feedback.

Video

Video, or visual replay, is a form of continuous feedback, which can also be paused and moved forward and backward in time. It gives an external perspective of the movement which can be similar to watching someone demonstrate the movement in real-time. Also, videotape feedback can be repeated as many times as necessary. When receiving videotape feedback, learners will initially require the important information to be pointed out. Videotape is most effective when used for long periods of time, perhaps over 5 weeks (Magill 1998). A study (Selder, Del Rolan 1979) examined the learning of gymnastics on a beam, by 13 year old girls, where one group was given verbal feedback and a second group was given videotape feedback. After six weeks, the videotape feedback group was found to

perform better in certain categories, which were precision, execution, amplitude and orientation and direction.

Biofeedback

Biofeedback is information about the physiological processes involved in performing a movement (Magill 1998). The most commonly used form of biofeedback is electromyography (EMG) biofeedback, which is feedback about the electrical responses of muscles during contraction. EMG biofeedback aims to enhance a patient's awareness of their movements, which is often lost in the case of movement disorders (Magill 1998). Biofeedback can be of physiological processes other than electrical responses of muscles. A study (Daniels, Launders 1981) examined the effect of providing heartbeat biofeedback to students studying shooting. This was found to facilitate the acquisition of important performance characteristics which led to improved shooting scores. Another study (Chollet, Micallef & Rabischong 1988) examined the effect of providing feedback to swimmers when they achieved a given propulsion force. The force was measured by sensors in paddles and the biofeedback was in the form of an audible tone played in a speaker in the swimmers' caps. It was found that the biofeedback allowed the swimmers to better maintain their stroke count and swimming velocity. Biofeedback needs to give information that patients can use to alter their movements whilst being presented in a way that avoids dependency (Magill 1998). A review compared the outcomes of providing feedback in the forms discussed above. It was concluded that "*little is known about the relative advantages of the different forms of feedback available or the optimal schedule of which to provide feedback*" (Subramanian et al. 2010).

2.5.3. Effects of feedback and considerations when providing it
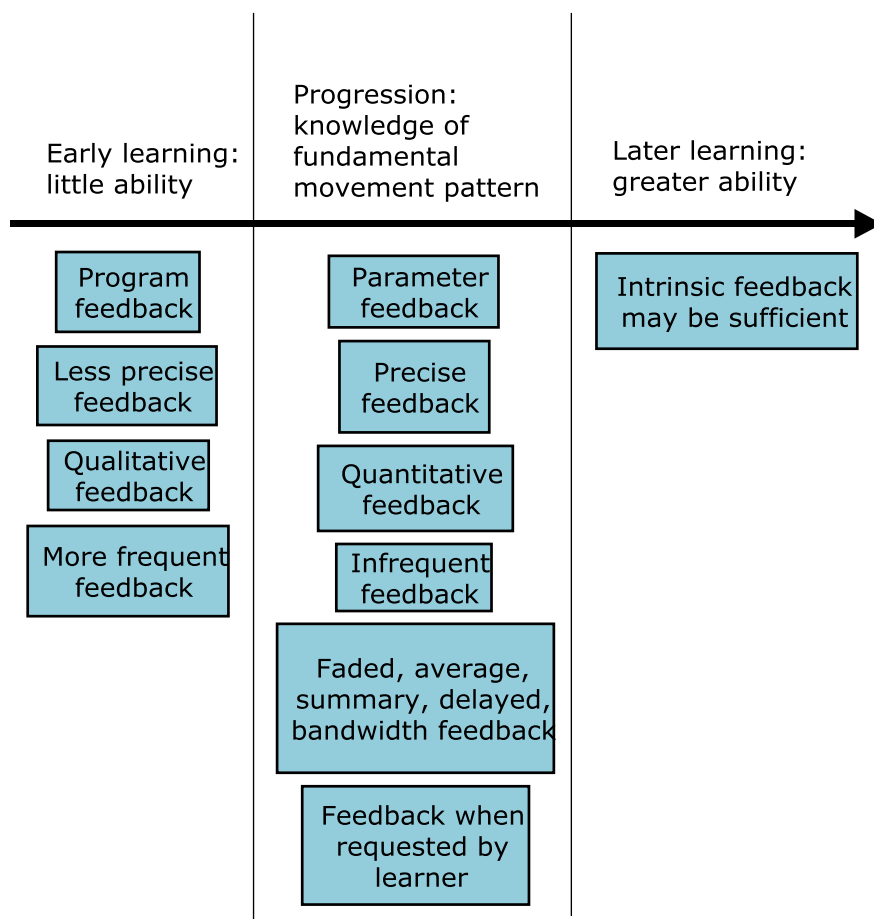
Figure 2.5.3. The stages of learning and the corresponding feedback to provide

Figure 2.5.3 summarises the findings of this section and describes the recommendations that are normally applicable.

Whether or not to give feedback

The first question that a practitioner should ask is whether feedback is needed or not, considering the complexity of the task and the experience of the learner. In general, the more complex the skill to be learned and the less experienced the learner, the more likely it is that extrinsic feedback will be necessary (Schmidt, Wrisberg 2008). It is advisable to refrain from giving feedback unless necessary. In some cases, feedback can be given when it is asked for by learners. Also, it can be useful to point learners towards sources of intrinsic feedback. (Wrisberg 2007). If the provision of feedback is considered necessary, the

content, volume, precision and frequency should then be considered (Schmidt, Wrisberg 2008).

What information to give and informational effects

Practitioners should consider which features of learner's movements should be included in feedback. These should be features that are under the learner's control (Schmidt, Wrisberg 2008). Feedback can be given with program or parameter reference. Program feedback refers to the fundamental elements of the movement such as which DOFs are to be moved and their relative timing. Parameter feedback refers to more detailed elements of the movement such as the magnitude and velocity of the DOF movements. It is often beneficial to begin with program feedback and move to parameter feedback as learning progresses (Wrisberg 2007). As discussed, feedback can also be given as KR or KP and be given in different formats as described in section 2.5.2. KP feedback can be given with an internal focus, referring to movement patterns, or with an external focus, referring to movement effects. An experiment (Wulf et al. 2002) investigating feedback to coach volleyball players compared internal to external feedback. An example of the internal focus feedback was *"Position your bodyweight and the non kicking foot behind the ball"*, whereas the external focus equivalent was *"Be behind the ball, not over it, and lean back"*. It was found that external focused feedback resulted in superior learning than internal focused feedback. Difficulties with the internal focused feedback were thought to be caused by interference with the automatic motor control processes that would otherwise normally regulate the movement. However, this may not always be the case. The kind of feedback that falls into either category is clearly subjective and how to avoid interfering with the automatic control processes seems to be something that should be considered. Extrinsic feedback can be descriptive of a performance or prescriptive, where advice is given on how to improve. Descriptive feedback may be sufficient in the later stages of learning where the learners are more aware of how to improve, but prescriptive feedback can be useful during the early stages of learning (Wrisberg 2007). Research suggests that prescriptive feedback is more useful to learners than descriptive feedback, at least until they are able to interpret the descriptive feedback (Schmidt, Wrisberg 2008).

A study tested a group given feedback erroneously and another group given correct feedback. The group given erroneous feedback followed the feedback even though it was in conflict with their intrinsic feedback (Buekers, Magill & Hall 1992). This shows that extrinsic feedback can be given high priority by learners. Another study (Annett 1959) examined a group with feedback given concurrent to the movement and another group given feedback given terminally (after the movement has terminated). It was found that, although the concurrent feedback group performed relatively well in tests, their performance deteriorated relatively rapidly when feedback was removed. This dependency effect is explored below.

How often to give feedback and dependency effects

In the early 20th century, Thorndike concluded that, because learning involves strengthening the bond between stimulus and response, feedback should be provided as often as possible (Thorndike 1927). It was therefore assumed that as much feedback should be provided as possible, where being as immediate, precise and detailed as possible was preferable. It is still thought that, in general, increasing the frequency of feedback enhances learning (Schmidt, Wrisberg 2008), however, results from later studies have contradicted several aspects of Thorndike's conclusions. Also, some believe that an optimum feedback frequency exists for certain tasks (Schmidt, Lange & Young 1990). Many studies have shown that practising without extrinsic feedback can be more beneficial than practising with it. Without feedback, learners can be forced to do more of their own problem solving and devote more of their attention to the available intrinsic feedback (Wrisberg 2007). If feedback is given too often, then learners try to incorporate feedback each time a movement is attempted. This leaves little time for performances to become stable, which can result in learners being unable to develop a relationship between what to do in terms of the movement and what the results are (Wrisberg 2007). This in turn can result in feedback dependency. This is particularly the case when feedback containing error correction information is given frequently (Magill 1998). It can also be the case when feedback is given about the goal of the movement (Wrisberg 2007). Therefore less feedback in some cases is thought to be preferable (Schmidt, Wrisberg 2008).

The amount of time feedback is given, or feedback frequency, can be given as absolute feedback frequency, which is the number of times feedback is given, or relative feedback frequency, which is the percentage of movement attempts feedback is given for. A study tested two groups given feedback during learning of a movement; one given feedback at 100 % frequency and another given feedback at 60 % frequency. The 100 % frequency group improved relatively well during tests but then performed the same as at the start of the tests when feedback was removed. However, when the feedback was removed from the 60 % frequency group, their performance remained high compared with their initial performance (Winstein, Schmidt 1990). Another study concluded that a relative feedback frequency of 20 % was optimal for the task of baseball batting (Schmidt, Lange & Young 1990). A possible reason why less than 100 % KP feedback can be more effective is that when people do not receive feedback, they engage in various kinds of information processing activities that they do not engage in when they receive feedback (Schmidt, Wrisberg 2008). The optimum relative feedback frequency tends to increase with the complexity of the task and may be as high as 100 % or 50 % at least until learners master the essential movement elements (Schmidt, Wrisberg 2008).

Another study found that those who received feedback at 100 % relative frequency with an external focus were just as proficient as those who received feedback at 33 % relative frequency with an internal focus (Wulf et al. 2002). This suggests that high frequency feedback may not result in dependency as long as the desired outcome is focused upon rather than the movement mechanics involved. As well as the feedback frequency, the timing of the feedback in relation to the movement should be considered. Delayed feedback is feedback given a period of time after the movement, with the aim of allowing sufficient time for learners to evaluate intrinsic feedback (Wrisberg 2007). A study comparing instantaneous feedback to delayed feedback found that on the second day of practice, a group receiving instantaneous feedback exhibited lower performance than a group receiving delayed feedback (Swinnen et al. 1990). This was also the case in retention tests up to 4 months after the initial practice. Also, results from a similar study suggest that learners pay closer attention to feedback and explore available intrinsic feedback more when KR feedback is delayed than when it is given immediately (Anderson et al. 2005). Faded feedback can be used to minimise dependency effects. This consists of a feedback

schedule that is high in frequency during early practice and diminishes during later practice (Schmidt, Wrisberg 2008).

It has been found that asking learners to critique their movements before extrinsic feedback is provided can be beneficial. A study found that swimmers who were questioned by a coach before receiving feedback during practice improved their course times more than swimmers who were not questioned (Chambers, Vickers 2006). Results from a similar study suggested that when 100 % KR is given and learners estimate their own errors, retention is greater than when 100% KR is given without their estimation (Guadagnoli, Kohl 2001). This suggests that extrinsic KR can help learners evaluate the accuracy of their error estimates without creating feedback dependency. The more complicated the skill, the more time will be required for learners to evaluate their movements (Wrisberg 2007). Successful practitioners allow enough time for both feedback processing and error evaluation before providing extrinsic feedback (Schmidt, Wrisberg 2008).

Motivational and reinforcing effects

Feedback can be given to influence a person's attention to their own ability, which can increase motivation (Magill 1998). Some brief descriptions of how feedback can motivate the learner are given below:

- In uninteresting repetitive tasks, feedback can enhance motivation which improves motor performance
- Motivation is strongly linked to goal achievement meaning that when people are making progress towards their goals, their motivation is enhanced
- Keeping learners informed of their progress usually results in greater effort during task practice
- Motivation seems to be maximised by giving feedback relatively frequently, particularly during the early stages of learning
- Learners like to know how they are doing, that is they enjoy what they are doing more upon receiving feedback and are willing to increase effort

(Schmidt, Wrisberg 2008)

Motivation can be particularly useful when one's improvements are minimal and are not clear from extrinsic feedback. Also, feedback is most motivating for learners when it informs them about the progress they are making towards achieving their goals. An example would be a physiotherapist informing a patient of their posture improvements during gait practice, when actual gait speed had not increased. The learners' knowledge that someone is observing and that the observer appreciates the situation that they are in is in itself motivating (Schmidt, Wrisberg 2008). As stated, feedback can be redundant when the same conclusions are reached from one's intrinsic feedback. However if the same information is given in a positive manner, for example someone saying *"well done"* upon a successful outcome, learners will be motivated and will be more likely to perform similarly in the future. This is known as positive reinforcement (Schmidt, Wrisberg 2008) which is similar to a reward. In contrast, negative reinforcement is when an adverse condition is removed following a successful performance, meaning learners will be more likely to perform similarly in the future. Negative reinforcement differs from punishment in that it removes negativity rather than adding it. Research has shown that reinforcement tends to increase motor learning and that punishment tends to have little effect (Tachter et al. 2009). A level of motor learning can occur without feedback, but in many cases, feedback results in better retention of learned skills (Cirstea, Ptito & Levin 2006).

How much information to give and how precise to make feedback

Upon viewing a learner's performance, practitioners may observe a multitude of movement parameters and areas that it would be beneficial to modify. The potential therefore exists to overload learners (Schmidt, Wrisberg 2008). It is thought that learners should be given the most relevant information whilst avoiding overload. It is most beneficial to give basic but specific information at the initial stages of learning, and progress to more detailed feedback once learners have acquired the basic movement pattern (Wrisberg 2007). Another method of reducing the quantity of feedback given is to use summary feedback, which is feedback given in the form of a summary of several of the learner's attempts (Wrisberg 2007). Another method of reducing the quantity of feedback given is to use average feedback, which is feedback that informs of the learner's overall performance and ability after multiple attempts (Wrisberg 2007). Average feedback can be calculated as a mean, and filters out

anomalies leaving learners with reliable information about the aspects they need to change during the next series of performance attempts (Schmidt, Wrisberg 2008).

Feedback precision, is determined by the extent of approximation applied (Schmidt, Wrisberg 2008). Precise feedback may be a physiotherapist saying *"try to lift your hand 5cm higher at the peak of extension"*, whereas a less precise equivalent may be to say *"try to lift your hand higher"* (Wrisberg 2007). It is important to give sufficient feedback to allow effective guidance but not so as to be overly complicated. Research on feedback precision suggests that extrinsic feedback does not need to be extremely precise to be effective (Wrisberg 2007). Feedback can generally be less precise during early learning when learners are establishing the timing patterns of movements. As skills are honed, the benefit to learners of precise feedback will increase (Wrisberg 2007). A method of varying the level of feedback precision is through bandwidth feedback, which is feedback only given if an error or performance exceeds a predefined threshold. A more tolerable threshold should be used with more general feedback at the initial stages of learning. As learning progresses, the bandwidth can be narrowed so that feedback is given to correct even small performance deviations (Wrisberg 2007). Favourable characteristics of bandwidth feedback include minimising dependency effects and providing less feedback as skill develops, which fosters the production of consistent actions (Schmidt, Wrisberg 2008). However, for bandwidth to be effective, learners must be made aware that receiving no feedback means that performance is positive or at least acceptable (Badets, Blandin 2005).

2.5.4. Feedback during stroke physiotherapy

It has been found that recovery of function of the upper limb can continue into the chronic stage of stroke (Suputtitada, Suwanwela & Tumvitee 2004). This section investigates trials that were performed to evaluate the effects of providing extrinsic feedback during stroke physiotherapy.

A systematic review (Subramanian et al. 2010) evaluated evidence of whether or not provision of extrinsic feedback improves motor learning in the upper limb after stroke. Nine studies, including six randomised controlled trials were evaluated in the review, and it was

concluded that extrinsic feedback is useful for implicit motor learning in stroke survivors. A randomised controlled trial (Winstein, Merians & Sullivan 1998) investigated the effects of extrinsic feedback whilst practising movements with the ipsilesional (less affected) limb. A group of 40 chronic stroke patients and a group of 40 healthy participants were examined. Participants were asked to perform a one second, open-loop controlled elbow extension and flexion and shoulder lateral and medial deviation task. Feedback was given terminally in the form of a *"position-time trace"* of a participant's movement superimposed onto a target movement using a graphical interface displayed on a computer monitor. A figure proportional to the extent of deviation from the target movement was also given. Both groups showed improvements in terms of target conformance, with the stroke patients being less accurate and more variable. It was concluded that stroke patients' control and execution of motor skills was reduced even in the less affected limb, but the capacity to learn was still present. Based on this, it was suggested that the capacity of stroke patients to learn in a similar way to healthy people is generally present. Another randomised controlled trial (Cirstea, Ptito & Levin 2006) investigated the effects of KR and KP verbal feedback to stroke patients practising a reaching task. 75 repetitions of the task were performed per day over a 10 day period by a group given KR and a group given KP. A separate control group practised a non-reaching task. The speed, variability, and precision of the movement were recorded during sessions. It was found that both the KP and KR groups showed superior improvements to the control, where the KP made the largest improvements in speed and variability.

A similar study (Cirstea, Levin 2007) yielded similar results, where stroke patients practised a pointing movement and were given either 20 % KR about their precision, or faded KP (average 26.6 %) about arm joint movements. It was found that only the patients who had received KP showed improvement, which included increased ranges of movement and increased joint coordination. It was also found that KP resulted in less compensation movements of the trunk. Another study (Jang et al. 2005) investigated the effects of feedback in the form of Virtual Reality (VR) to assist practice of ball manipulation exercise movements by stroke patients. The VR feedback was about KR and KR including error rate, speed, direction, joint position, and resistive force feedback. Five stroke patients received training for 60 minutes per day, five days per week for a month. A control group of stroke

patients performed the same exercises without feedback. Neural activity in the multiple areas of the brain was monitored and it was found that feedback had resulted in activity being reduced to mainly the primary sensorimotor cortices. This suggests that the control of movements became more automatic, which is associated with the process of learning. Motor function was found to have improved.

In another randomised controlled trial (Gilmore, Spaulding 2007), two groups of stroke patients were asked to practise putting on socks and shoes. One group of five were given Occupational Therapy (OT) and were shown videotape feedback of their performance, and another group of five were given OT alone. Performance was measured using the socks and shoes subtests of the Klein-Bell Activities of Daily Living Test (KB ADL) and Canadian Occupational Performance Measure (COPM). It was found that both groups had improved, but the group with additional videotape feedback had improved further and felt more satisfied with their performance. In another study (Coote et al. 2006), two groups of ten stroke patients were asked to perform arm reaching exercises. Initially, the range of active shoulder flexion was taken, which is the range achievable under a patient's own motor control. The Fugl-Meyer motor assessment and the Motor Assessment Scale were then used to assess both groups over a period of three weeks. Then one group received robot-mediated therapy for three weeks followed by suspension sling therapy for three weeks, and the other group received the same treatment in reverse order. The robot-mediated therapy consisted of feedback of direction and completion provided on a computer screen, as well as haptic feedback in the form of resistance force proportional to deviation from the target movements. During sling suspension therapy, the arm was de-weighted using a free moving elbow splint attached to an overhead frame, and the trunk was also supported. Although each patient had a varied response to the therapy interventions, the overall rate of recovery was greater in the robot-mediated therapy phase than in the sling suspension phase and initial phase.

2.6. Existing systems and technology

2.6.1. Methods of measuring movement

Movement is measured under different circumstances including medical research and sports applications. The focus here is physiotherapy. In this discipline, the most commonly used methods of measuring human movement are through visual inspection or feeling of patient movements by hand. However, the prototype system was to be capable of gathering quantitative data. The following methods of measuring movement were therefore investigated:

- Goniometers
- Electrogoniometers
- Video
- Motion analysis systems
- Electromyography
- Game console technology

Goniometers
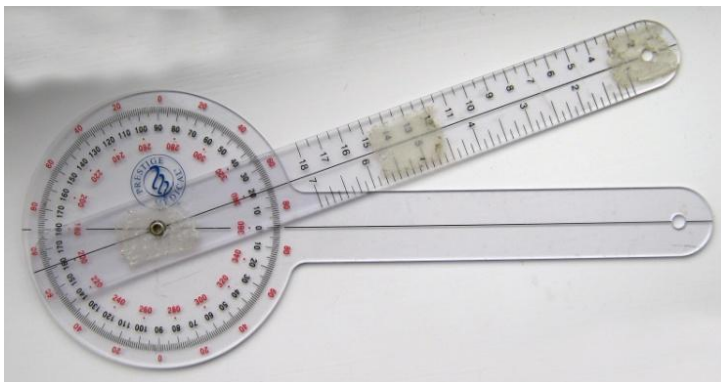
Figure 2.6.1. A 12 inch 360 degree goniometer

A goniometer, or universal goniometer as shown in Figure 2.6.1, is a jointed device usually consisting of two parts. Each part is aligned visually with the segments on either side of the joint to be measured. This allows a static angle to be measured. The goniometer, is the most commonly used form of joint measurement in the clinical setting (Norkin, White 2003). The Goniometer shown in Figure 2.6.1 was purchased by the researcher from MediBargains

(MediBargains 2013) for approximately £11. The angle is read in a similar manner to that of a protractor, meaning it is easy to use and only occupies a relatively small space. However, alignment with limb segments must be achieved manually, which can reduce repeatability. Also, variations amongst body regions measured and measurements by different examiners can reduce repeatability further (Gajdosik, Bohannon 1987).

Electrogoniometers

Most electrogoniometers have two arms, similar to those of the universal goniometer, which are attached, rather than manually aligned, to the limb segments (Norkin, White 2003). A potentiometer is connected to the two arms, which rotates as joints move. The potentiometer is connected to an electrical circuit that produces a voltage in proportion to joint angle to be measured (Norkin, White 2003). As the electrogoniometer is attached to the segments, it may be more suited to measuring movements than the universal goniometer. Electrogoniometers can be high in repeatability but low in accuracy (Christensen 1999). Flexible electrogoniometers also exist which have two plastic end blocks connected by a flexible strain gauge. Flexible electrogoniometers can be used to measure angular displacement in one or two planes (Norkin, White 2003). Electrogoniometers are relatively expensive and take time to attach to the subject and calibrate accurately, which means they are used more often in research than in clinical settings (Norkin, White 2003).

Video

Videotape was discussed as a form of feedback to patients. It can also be used by clinicians and researchers to assess movements. As identified previously, videos can be paused and repeated, which means they are a form of visual enhancement of watching a movement in real-time. Video has been used to analyse stroke patients. A study (Walker et al. 2004) examining stroke patients putting on a shirt identified impairments including reduced visuospatial perception, neglect and apraxia by visual examination of recorded footage. Video can be recorded for low costs, for example by laptop webcam or peripheral webcam. An example of a webcam is the Logitech C170 which is capable of recording in 1024 x 768 pixels resolution and costs £16.50 (eBuyer 2013). In order to gain quantitative data, graphical analysis is necessary, which must be performed using computers in motion analysis systems.

Motion analysis systems

An example of a motion analysis system is VICON, which was used extensively for testing the prototype system described in chapters 4 and 5. VICON is mainly used for analysing physical performance during sport for research purposes and costs approximately £200,000. VICON is further explained in section 4.3.1, the calibration process in section 4.3.6 and the variability in section 4.4.2. Since motion analysis systems are expensive and complicated to operate, they, like electrogoniometers, are used more often in research than in clinical settings (Norkin, White 2003)

Electromyography (EMG)

EMG measures the electrical responses of muscles during contraction. This is achieved using an apparatus known as an electromyograph. An electromyograph consists of a series of sensors placed on the muscles to be measured. The sensors are either in the form of a fine electrode needle, which is inserted into the muscle (Rabie, Jossiphov & Nevo 2007), or an electrode pad, which is placed onto the skin in a non-invasive manner (Cram 2003). The latter is known as surface electromyography (SEMG). The recorded data is in the form of muscle response samples taken over a time period, which is known as an electromyogram. EMG can be used to detect movement disorders in a medical setting, but appears to be more commonly used in research settings. As the sensors are in electrode form, any system capable of recording voltage samples could theoretically be used, for example an oscilloscope. However, specialised electromyograph recording devices exist such as the PowerLab 26T (AD Instruments 2013). The data recorded will relate more to the muscle activity than the movement profile, meaning that conversion or further analysis would be required for some applications. A study (Rabie, Jossiphov & Nevo 2007) compared the detection rate of EMG in detecting muscle disorders with muscle biopsy methods (removing tissue for examination). It was found that the detection rate for myopathic motor unit potentials (disease causing muscle weakness), was low. However, for neurogenic (the nerves) and neuromuscular (nerves and muscles) disorders, the detection rate was high. The accuracy or repeatability of EMG systems for measuring motion does not appear to have been investigated. This is perhaps because performance in these categories would depend on the interpretation methods of the EMG signals.

Game console technology

Game consoles widely available include the Nintendo Wii and Wii Fit system, and the Microsoft Xbox 360 and Kinect system. These systems are designed mainly for playing games for entertainment. Movement is therefore read during interaction, which forms the input to the systems. Of particular interest is the Wii Fit, which aims to allow guided training to be performed within the home, without a personal trainer present. This is analogous to the hypothesis of this research in that monitored exercise in the home can improve one's condition.

Both Nintendo and Microsoft consoles are forms of computers, whose output is displayed on a television. The input, or method of measuring movement, of the Wii is via a hand held controller. The controller is held in the right hand and has a series of buttons and can measure accelerations and tilt angles. The controller has an accompanying *"nunchuk"* which attaches to the controller by a cord, but is held in the other hand and has a joystick and additional buttons (Nintendo 2009). The controller is powered by two AA batteries, which allows for wireless communication with a sensor bar, that is connected to the console (Nintendo 2009). The sensor bar reads infrared signals transmitted by an emitter on the controller, which allows the direction of the controller to be measured (De Amici et al. 2010). This along with an accelerometer allows motion to be measured. The Wii Fit system consists of a balance board and additional software. The balance board is placed on the floor and stood upon in use, and has a pressure sensor located at each corner (Nintendo 2008). This allows shifts in the user's position to cause changes in pressures on the board. The board is powered by four AA batteries, which allows wireless communication with the console (Nintendo 2008). The Xbox 360 is also controlled with a hand held controller, with a series of buttons, two analogue triggers and two joysticks (Microsoft 2010b). The controller is also powered by two AA batteries, which allows wireless communication with the console (Microsoft 2010b). The Microsoft Kinect system detects motion of the human body (Microsoft 2010a). This is achieved by again using an optical sensor bar, which contains a laser grid and sensor array, capable of detecting depth at a resolution of 640 x 480 (Ning, Guo 2013). The sensor bar also has an RGB camera, which along with the depth sensor, allows measurement of motion. Also, skeletal tracking algorithms can be used to detect real-time activity of multiple joints over the entire human body (Shotton et al. 2013). A

study (Molnar, Toth & Detrekoi 2012) of the accuracy of the Kinect found the performance to be sufficient for morphologic measurements (considering structure rather than function), although no specific requirements are given. Also, another study (Kim et al. 2012) found that the Wii controller had good inter-repeatability in measuring head-posture.

At the time of writing, console systems cost around £200 each including either the Wii fit accessory or the Kinect. This is a relatively low cost compared with non-domestic optical measurement systems. The accelerometer used in the Wii controller is investigated in section 2.6.7. Also, use of the Wii as a rehabilitation tool is investigated in section 2.6.6.

2.6.2. Movement performance measures

There are many different performance measures in existence with many different uses, varying from research to rehabilitation and from measuring muscle strength to measuring movement impairment (Murphy, Roberts-Warrior 2003). Some motor function impairment measures commonly used to assess stroke patients are listed below:

Motor function impairment measures
- Muscle strength impairment measures
    - Manual Muscle Testing
    - Motricity Index
    - Hand Held Dynamometry
- Movement impairment measures
    - Motor Assessment Scale
    - Rapid Alternating Movement
    - Nine Peg Hole Test
- Balance impairment measures
    - Sensor Organisation Test
    - Postural Stress Test
    - Functional Reach
    - Postural control in standing
    - Bohannon balance scale

- o Berg balance scale

- o Postural Assessment Scale for Stroke

- o Step Test

(Murphy, Roberts-Warrior 2003)

Methods of testing muscle strength include Manual Muscle Testing (MMT), which is when force is manually applied to a limb by a physiotherapist, and the subsequent resistance force is felt by the physiotherapist, and rated on a scale of 0-5. Also, Hand Held Dynamometry (HHD) is used to test muscle strength, which works using hand held pressure sensors with scales, positioned to measure the force applied by patients. A study (Wadsworth et al. 1987) examining MMT and HDD found the inter-repeatability to be satisfactory for both measures, but found MMT results to vary more at scores greater than 3.

The Motor Assessment Scale (MAS) is used to measure impairment and disability relating to motor performance using a scale of 0-6. The MAS covers eight areas of motor function and one item relating to muscle tone, and includes transitions such as sit to stand, sitting balance, walking and upper limb movements and functions (Murphy, Roberts-Warrior 2003). A study (Lowen, Anderson 1988) found the MAS to have high intra and inter-reliability. The Rapid Alternating Movement (RAM) measure includes exercises such as touching the hand on the opposite shoulder (Dittiger, Bohannon & Andrews 2001) or foot tapping, of which the number of repetitions within a given period is counted. The RAM scale has been found to be repeatable and valid (Dittiger, Bohannon & Andrews 2001). The Nine Hole Peg Test (NHPT) assesses hand impairment, which addresses the difficult task of measuring finger movement control (Murphy, Roberts-Warrior 2003). The test requires patients to place and sometimes remove nine 9 mm wooden dowels in nine holes whilst sitting. The test is timed, or stopped at 50 seconds, and the number of pegs placed is recorded (Sunderland et al. 1992). The NHPT was also found to be repeatable and valid (Heller et al. 1987). The NHPT and RAM therefore generate quantitative results compared with the MAS which generates qualitative results.

The Functional Reach (FR) is a balance impairment measure used to test postural control. From standing straight, patients are asked to reach forward with their arm extended horizontally and their legs remaining stationary. The distance achieved before forwards stepping is required is then measured (Duncan et al. 1990).

Disability measures

Some disability measures commonly used to assess stroke patients are listed below:

- Basic mobility disability measures
    - Trunk Control Test
    - Stroke Rehabilitation Assessment of Movement
    - Rivermead Mobility Index
- Upper extremity disability measures
    - Action Research Arm test
    - Frenchay Arm Test
    - Jebsen Test of Hand Function
    - Wolf Motor Function Test
- Physical activity of daily living disability measure
    - Barthel ADL Index (BI)
- Global disability measures
    - Rankin Scale
    - Functional Independence Measure

(Murphy, Roberts-Warrior 2003)

As shown above, there are multiple measures to assess disability of the upper extremity. The Action Research Arm (ARA) test is an upper extremity disability measure used to measure grasp, grip, pinch and gross movement types (Murphy, Roberts-Warrior 2003). Each of these four movement types has either four or six exercises which are to be attempted in sequence and quantitatively scored. An advantage to the ARA test is that it requires little time to complete (De Weerdt, Harrison 1985).

The Frenchay Arm Test (FAT) examines the proximal upper extremity control and hand dexterity of stroke patients but does not assess the quality of movement or speed of performance. The FAT uses a pass or fail scoring system over five tasks (Murphy, Roberts-Warrior 2003). The scale has been reported as valid (Heller et al. 1987). The Jebsen Test of Hand Function uses performance time as an indicator of functional ability and does not assess the quality of the movement (Murphy, Roberts-Warrior 2003). The test focuses on seven timed hand function tasks which are common to ADLs. These include writing a sentence, picking up objects and simulation of feeding. The Jebsen Test of Hand Function was found to be repeatable (Hackel et al. 1992). The Wolf Motor Function Test (WMFT) was developed to determine the effectiveness of Constraint-Induced Movement Therapy (which is investigated in section 2.6.4), and involves 14 timed activities and two strength tests. Tasks are sequenced from proximal to distal joint movements and from gross to fine motor skills, and all joint movements and functional tasks are then combined (Murphy, Roberts-Warrior 2003). Research has found the test to have high intra and inter-reliability (Morris et al. 2001). Also, minimal training and equipment is required to administer the WMFT, and it can be streamlined to six tasks for certain uses (Bogard et al. 2009).

The Barthel ADL Index (BI) assesses the patient's ability and help required to perform ADLs, and as such gives in indication of their independence (Mahoney, Barthel 1965). BI is explored further in section 2.6.3.

As well as motor function impairment measures and disability measures, there are kinematic parameters which can be measured to assess the way in which a movement is performed (Lehrer et al. 2011). This allows a patient's condition or ability to be better understood. Some kinematic parameters associated with upper arm activity are below:

Body function kinematic parameters:
- Joint function:
    - Range of movement (shoulder, elbow and forearm)
    - Error (shoulder, elbow and forearm)
    - Consistency (shoulder, elbow and forearm)
- Compensation:
    - Shoulder elevation

- o Shoulder protraction
- o Torso flexion
- o Torso rotation about midline
- o Pre-emptive elbow lift
- Joint synergy
  - o Shoulder flexion and elbow extension
  - o Forearm rotation and shoulder flexion
  - o Forearm rotation and elbow extension
  - o Shoulder abduction and shoulder flexion
  - o Shoulder abduction and elbow extension

Activity level kinematic parameters:

- Trajectory profile
  - o Real-time distance to target
  - o Real-time horizontal trajectory error
  - o Real-time vertical trajectory error
  - o Maximum horizontal trajectory error
  - o Horizontal trajectory error consistency
  - o Maximum vertical trajectory error
  - o Vertical trajectory error consistency
- Temporal profile
  - o Real-time velocity
  - o Peak velocity
  - o Peak velocity consistency
  - o Reaching time
  - o Reach time consistency
- Targeting
  - o Initial spatial error approaching target
  - o Final spatial error approaching target
  - o Final spatial consistency

(Lehrer et al. 2011)

Which measure should be used and when will depend upon the particular situation and it seems that a degree of judgement must be made. Different systems or scenarios seem to require different kinematic parameters to be calculated, which is demonstrated by the systems evaluated in section 2.6.6.

2.6.3. Physiotherapy exercises

An investigation into specific stroke physiotherapy exercises was performed which is described below. Exercises recommended for stroke patients include the following:

- Gait training and walking aids
- Stretching (Range of movement) exercises
- Strength exercises
- Aerobic exercises
- Positioning
- Task-specific training
- Mental practice
- Self-efficacy training

(Clinical Effectiveness and Evaluation Unit 2008)

Gait training and walking aids

Regaining independent mobility is a high priority because mobility is necessary for most activities. Patients should be taught and encouraged to practise moving around the bed, transferring from bed to chair, walking indoors and outdoors and using stairs (Clinical Effectiveness and Evaluation Unit 2008). Patients should also be taught to use walking aids where necessary, for example a four-point cane (Laufer 2002). It is recommended that patients be tested to determine their Metabolic Equivalent (MET) value, which can then be used to calculate a walking speed to aim for during practice. In week one, walking should be practised for approximately 2.5 minutes 3-5 times per week, and if progression allows, to 45 minutes 3-5 times per week (Gordon 1993).

Stretching (Range of movement) exercises

Patients with reduced ranges of movement, caused by contracture, should have a program of passive stretching which should be performed on a daily basis, which should be taught to patients and/or carers (Clinical Effectiveness and Evaluation Unit 2008). If stretching alone is insufficient in preventing contractures, castings around the joint should be considered, although inflatable arm splints should not be used routinely (Lannin et al. 2007). As well as

reducing contracture, stretch exercises should be performed prior to aerobic or strength exercises to prevent injury. Stretch exercises can be performed on any DOF and should involve moving the joint to an extremity either actively or passively. The joints should not be moved to the point of pain, sudden movements should be avoided and stretched positions should be held for 2-3 seconds at joints with reduced ranges of movement, and 10 to 20 seconds at joints with regular ranges of movement (Gordon 1993).

Strength exercises

In the past it was feared that strength training, or resisted exercises, would increase involuntary muscle tone, but recent evidence shows that this is not so (Clinical Effectiveness and Evaluation Unit 2008). Resisted exercises can be used to improve strength in targeted muscles and to improve gait speed and endurance (Ada, Dorsch & Canning 2006). Unlike stretching exercises, resisted exercises should only be performed up to 2-3 times per week and not on consecutive days. Some recommended resistive exercises of the upper limb include shoulder extensions, elbow flexions, elbow extensions against an elastic strap from the ground to the hand, and seated rowing exercises using elastic from the feet when sitting and performing backwards shoulder flexions (Gordon 1993). Similar exercises can also be performed using free weights.

Aerobic exercises

As aerobic training, or fitness training, is known to help reduce vascular disease, and stroke is a form of vascular disease, aerobic training is recommended (Clinical Effectiveness and Evaluation Unit 2008). Recommended aerobic exercises include walking, jogging, cycling (stationary or outdoors) and arm-cycle ergometry (Gordon 1993). Aerobic training has been shown to improve speed, tolerance, and independence during walking (Braxxelli et al. 2011). It is recommended that 10 to 20 calories per kilogram of body weight are expended per week on aerobic exercise. It is also recommended that aerobic exercise be performed on 3 to 5 days per week, for 2.5 to 45 minutes. The intensity of aerobic exercise is largely proportional to the heart rate, which for stroke patients is recommended as 160 to 185 % of their resting heart rate (Gordon 1993).

Positioning and task-specific training

Stroke patients should be helped to sit up as much as their condition allows (National Collaborating Centre for Chronic Conditions 2008). Lack of movement ability whilst in bed can result in pressure ulceration, limb swelling and, contracture and pain. Patients therefore need careful periodic repositioning to reduce harm (Clinical Effectiveness and Evaluation Unit 2008). However, intermittent compression should not be used as it has been found to be an ineffective treatment (Roper, Redford & Talus 1999). A main aim of physiotherapy is to increase the ability of the patient to perform tasks, therefore practicing the tasks themselves is often most effective (Clinical Effectiveness and Evaluation Unit 2008). This is particularly the case for standing up and sitting down and gait speed and endurance (French et al. 2009).

Mental practice and self-efficacy training

Mental practice, or imagery, is when patients imagine the visual aspects of movements without physical practice. The efficacy of mental practice in improving motor ability was investigated in section 2.6.4. It is recommended that patients are encouraged to use mental practice of an activity to improve arm function (Clinical Effectiveness and Evaluation Unit 2008). However, little is yet known of an optimum content for imagery during practice (Braun et al. 2013). Self-efficacy, the extent to which a person believes that they can control their activities, is synonymous with self-confidence but is lower in the case of depression and anxiety (Clinical Effectiveness and Evaluation Unit 2008). Therefore patients with low or reduced self-efficacy should be offered motivational interviewing and positive feedback during physiotherapy (Watkins et al. 2007). As well as reducing the degree of disability, stroke physiotherapy can therefore have emotional benefits such as improving self-esteem. Stroke physiotherapy also reduces the chance of stroke recurring (Gordon 1993).

Occupational therapy

The role of an occupational therapist is to assess and train stroke patients in everyday activities, often around the home, to increase their independence. Occupational therapists often work to improve fine motor skills, where physiotherapists would have focused more on gross motor skills (Magill 1998). It is also necessary for occupational therapists to assess the patient's ability to perform functional activities (Lindley 2008). To do this it is

recommended that a standardised assessment be used (Royal College of Physicians 2008b), preferably the BI scale. The BI scale is a method of scoring the patient's ability based on the amount of time and physical assistance required to perform a series of activities (Mahoney, Barthel 1965). Performances in activities are then scored based on the patient being unable with help, able with help or able independently, and a total score is then derived. The BI ADLs are shown below:

- Feeding
- Moving from wheelchair to bed and return (includes sitting up in bed)
- Personal toilet (wash face, comb hair, shave, clean teeth)
- Getting on and off toilet (handling clothes, wipe, flush)
- Bathing self
- Walking on level surface (or if unable to walk, propel wheelchair)
- Ascend and descend stairs
- Dressing (includes tying shoe laces, fastening fasteners)
- Controlling bowels
- Controlling bladder

(Mahoney, Barthel 1965)

2.6.4. Stroke physiotherapy interventions

The following stroke physiotherapy interventions were investigated, with an emphasis on arm rehabilitation:

- Physiotherapy approaches
- Bilateral arm training
- Constraint-induced movement therapy
- Electrostimulation
- Mental practice
- Repetitive task training
- Robotics
- Splinting

Physiotherapy approaches

There are different general approaches that can be taken when performing physiotherapy, including Bobath, which is most commonly used (Langhorne, Coupar & Pollock 2009). The Bobath, or neurodevelopmental treatment (NDT) approach is a broad, hands-on approach, which focuses on normalising muscle tone and movement patterns (Lindley 2008) and aims to promote motor learning. Different approaches have been defined and compared with Bobath. For example, the Motor Relearning Program (MRP) was developed which is based on tasks rather than movement characteristics. A study (Langhammer, Stanghelle 2000) found that the MRP approach allowed greater improvements than Bobath in the early stages of stroke. Another approach is impairment-oriented training, whose aims include improving force generation, control of rapid movements and inter-joint coordination. A study (Platz et al. 2005) found that impairment-orientated training resulted in greater improvements in arm motor performance compared to Bobath in stroke patients (Platz et al. 2005). Also, a systematic review of physiotherapy approaches found that no approach is superior overall (Kollen et al. 2009). Combinations of approaches are therefore often taken depending on the individual physiotherapist and situation (Lindley 2008).

Bilateral arm training

Bilateral Arm Training (BAT), involves patients practising identical activities with both upper limbs (paretic and non-paretic) simultaneously (Morris et al. 2008). The effects of BAT in stroke are assumed to arise from the coupling effect in which the less affected limb provides a template for the paretic (weaker) limb in terms of movement characteristics, facilitating restoration of movement (Morris et al. 2008). It is thought that, symmetrical bilateral movements activate similar neural networks in both hemispheres when homologous muscle groups are simultaneously activated (Lacroix et al. 2004). Activation of the undamaged hemisphere is thought to increase activation of the damaged hemisphere which promotes neural plasticity which improves motor recovery (Cauraugh, Summers 2005). Studies of the efficacy of BAT have mixed results. One study (Morris et al. 2008) compared improvements in functional limb performance of stroke patients who received BAT with those who received unilateral arm training and little difference was found. Another similar study (Summers et al. 2007) concluded that BAT may be effective when used as a short-term supplementary intervention.

Constraint-induced movement therapy

Constraint-Induced Movement Therapy (CIMT) is the restriction of movement of the less affected limb of hemiparetic (weaker on one side of the body) stroke patients in order to encourage use of the paretic limb. Restriction is achieved via a mitt, sling, or glove. Patients typically participate in CIMT for 6 to 7 hours per a day during home activities, the aim of which is to avoid learned non-use of the paretic limb (Bonifer, Anderson 2003). A study (Boake et al. 2007) comparing CIMT therapy with traditional therapy at frequencies of up to 3 hours per day, found that those who had received CIMT showed slightly superior functional performance. Another controlled study (Suputtitada, Suwanwela & Tumvitee 2004) found stroke patients could improve pinch strength to a greater extent having received CIMT. CIMT seems to have merit, and appears to be an area of interest for research.

Electrostimulation

Electrostimulation is the application of external electrical signals to the muscles of a paretic limb to assist the natural signals that control movement. The electrostimulation can be triggered by detection of the occurrence of the natural signals through EMG (Cauraugh et al. 2000). A study (Cauraugh et al. 2000) compared physiotherapy using electrostimulation in this form to similar physiotherapy without. Stroke patients who had received electrostimulation were better able to move blocks and could apply greater forces. A similar controlled study (Gabr, Levine & Page 2005) concluded that electrostimulation had resulted in little increase in functional performance, but allowed for significant increases in wrist extension ability. It was noted that more research was needed to determine the optimal duration, timing and mechanisms of electrostimulation.

Mental practice

Mental practice, or imagery, is when patients imagine the visual aspects of movements without physical practice. A further description as well as investigation of the psychological effects is given in section 2.6.3. A study (Page et al. 2001) compared the functional performance of stroke patients who had received imagery sessions (guided and at home) in addition to regular therapy, with patients who had received regular therapy only. It was found that functional performance was superior in the imagery group, and it was concluded

that imagery is clinically feasible and cost-effective. Two similar studies (Page, Levine & Leonard 2007; Page, Levine & Leonard 2005) also showed positive results in terms of functional recovery. It was noted that little is known of the neural mechanisms responsible for the benefits observed (Page, Levine & Leonard 2005).

Repetitive task training

Repetitive task training involves practice of functional, unilateral and bilateral tasks that are designed to improve gross and fine manual dexterity (Higgins et al. 2006). This is opposed to simpler exercises, such as arm extensions, that do not relate to a specific skill. A study (Higgins et al. 2006) compared stroke patients given repetitive task training to those who participated in walking exercises. No improvements were observed in a task involving moving blocks. Another, more detailed study (Blennerhassett, Dite 2004), compared stroke patients given functional tasks to improve reach and grasp, hand-eye coordination, range of motion and strength, with a group who participated in walking exercises. The patients who had received functional training improved significantly on the Jebsen Test of Hand Function and the Motor Assessment Scale.

Robotics

The term 'robotics' in the context of stroke physiotherapy interventions, seems to have a wide meaning. Some robotic devices move the patient's limbs by applying external forces (Fazekas et al. 2007) allowing movements to be performed passively. This is similar to exercises performed by patients with physiotherapists to increase the ranges of motion. Some robotic devices are capable of applying resistance forces (Hesse et al. 2005) which must be overcome by the patients in order for movements to be achieved. This is similar to weight training based strength exercises which are in some cases performed by stroke patients. Other robotic devices support the patient's limbs against gravity (Seo, Kamper 2008) to allow patients to focus in isolation on aspects of the movement other than support and lift. This is a form of orthosis (artificial support) and is perhaps more of an exoskeleton based splint than a robotic device. Splinting is explored below. A fourth function of robotic devices is to provide haptic feedback. A robotic device (Lam et al. 2008) applies a vibration to the limb during a reaching exercise when difficulty in reaching a target is detected. The objective of this is to encourage patients to reach further. A study (Volpe et al. 2000)

investigated the efficacy of a robotic device which supported the arm, assisted movement where necessary by applying external forces and provided an audible tone when a target was reached on screen. A group of stroke patients performed a reaching exercise with the device, and another group performed similar exercises without. It was found that patients who had used the device showed superior motor performance and functional ability, measured using the Functional Independence Measurement scale. Another study (Kahn et al. 2006) compared stroke patients performing reaching exercises with assistance from a robotic device with those performing the same exercises without assistance. No significant improvements in the assisted group were found in terms of range, velocity and functional ability, however, smoothness improved more in the unassisted group. Robotics in stroke physiotherapy seems to be gaining more interest and acceptance. Guidelines (Clinical Effectiveness and Evaluation Unit 2008) now state that robot-assisted movement therapy can be used, but only in addition to conventional therapy when the goal is to reduce arm impairment. Stroke physiotherapy exercises and their goals are investigated further in section 2.6.3.

Splinting

If a joint is not moved regularly, the surrounding tissue can shorten, which is known as contracture, which can restrict movement. Splinting, a form of orthosis, involves immobilising a joint, for example the wrist, in a functional position (Lannin et al. 2003). This prevents excessive uncontrolled flexion of the wrist which can occur post stroke, and help to prevent contracture. A study (Lannin et al. 2007) investigated the effect of wearing a splint to maintain either 0 to 10 degrees, or >45 degrees wrist extension for 9 to 12 hours per night for four weeks on groups of stroke patients. A control group was also employed. The range of wrist extension with extended fingers was then tested by a blind assessor (an assessor not informed of which patients were from which group). Neither the 0 to 10 degrees group or the >45 degrees group was found to have increased extensibility compared with the control group. It is however argued (Marossezky, Gurka & Baguley 2008) that splinting may still be beneficial if used in conjunction with physiotherapy, and splinting is useful for joint protection, to maintain alignment and for spasticity management. There are mixed opinions on the benefits of splinting and it does not appear to be a widely used practice.

2.6.5. Home stroke physiotherapy

This section describes the investigation of home stroke physiotherapy and its efficacy. A review (Britton, Anderson 2000) was made of the evidence on the effects and costs of home stroke rehabilitation, as opposed to rehabilitation during inpatient care. Seven controlled studies were evaluated but no significant difference between the outcomes of home rehabilitation and hospital-based alternatives was found. It was also found that home rehabilitation was similar in cost to conventional rehabilitation, but less costly than day care. A study (Young, Forster 1992) involving 124 stroke patients comparing the functional improvements of those attending day hospitals to those undergoing home physiotherapy found that both groups showed improvements in functional abilities, where the improvements were significantly greater for patients treated at home. It was also concluded that home physiotherapy seemed to be more effective and resource efficient. Another review (Novak 2011) evaluated home rehabilitation programs to identify characteristics that lead to success. 32 studies were reviewed and it was found that further home intervention was more effective than no further intervention, and that home intervention can be as effective as physiotherapy provided by a physiotherapist. In order to achieve this, patients should be involved in establishing the program structure and goals. Also, the individual, task and environment should be considered and feedback about the progress should be provided (Novak 2011). Another study (Anderson et al. 2000) investigated 86 patients with acute stroke, who were split into a group given conventional hospital care, and another group who were discharged earlier to receive home-based rehabilitation. Rehabilitation costs were found to be 20% less on average for those who had received home-based rehabilitation. However, it was thought that home-based physiotherapy is likely to be most effective with patients of mild disability.

A study (Monger, Carr & Fowler 2002) evaluated a task-specific home-based exercise program to improve sit-to-stand in stroke patients. Six stroke patients were employed, all at least one year post-stroke and discharged from rehabilitation services for at least six months. The exercise protocol consisted of sit-to-stand, step and calf stretch movements, which were performed daily under supervision and independently for three weeks. Verbal feedback, for example about weight distribution and speed, as well as encouragement was

provided. Assessment was made using the standing up element of the Motor Assessment Scale, and by assessing walking speed. Scores on the Motor Assessment Scale were found to be significantly higher upon completion of the program, and walking speed over 10 metres was found to have increased from a mean of 0.86 ms^{-1} to 1.10 ms^{-1}. Grip strength, which was not trained, did not change. Some studies have viewed home rehabilitation as an alternative, whereas it may be more effective if used as a supplementary intervention. Clear advantages to home rehabilitation are that resources such as space in day care units are freed. Also, patients may be more comfortable within their own homes, and have access to family and their possessions.

2.6.6. Existing systems to provide a means to further rehabilitate

In section 2.5.4 some existing systems which aim to provide a means to further rehabilitate within the home were mentioned. In this section, such systems are investigated further, to allow their objectives and mechanisms be understood. The following systems were identified:

- Stroke Rehabilitation Exerciser for personalised exercise at home
- Feedback device for improvement of coordination of reach-to-grasp after stroke
- Feedback Training System for guided home rehabilitation
- Rotating tabletop handle and feedback system
- Exoskeleton system for hand and wrist tele-rehabilitation from home
- Therapy-WREX gravity reducing feedback robot
- Wearable kinaesthetic system for capturing stroke patient upper limb gestures
- Wearable conductive fibre system for long-term measurement of DOF movements
- Adaptive mixed reality feedback system
- Virtual Reality through Nintendo Wii console technology
- Virtual reality through Microsoft Xbox console and P5 Glove technology

For each of these systems, the following aspects were investigated where possible:

- System definition
- Objectives of the system
- How the system works, including what is measured and what is fed back
- The efficacy of the system
- Costs of the system
- Advantages
- Limitations

Stroke Rehabilitation Exerciser for personalised exercise at home

This system (Willmann et al. 2007) by Phillips Research aims to support physiotherapists and patients and allow planning for clinicians and increased training intensity for patients. The physiotherapist uploads exercises to the system and as exercises are performed, deviations from the movement target are identified by the system and the patients and physiotherapists are provided with feedback. Information to patients is given as on-screen text and through speech output. Movement is recorded by three inertia sensors, or accelerometers, attached to the torso, upper arm and lower arm, which transmit data wirelessly to a computer. A *"gesture recognition algorithm"* is used to detect movement attempts and to distinguish one movement from another. A real-time animation of a person and arm is shown on a screen. Parameters such as duration, jerk and speed of motion can be calculated and fed back to the patients and physiotherapists. The system is described as allowing progress to be tracked by the physiotherapist and that target movements can be specified based on this. Little information about the feedback and communication methods is given and the efficacy of the system was not tested. As the system consists largely of accelerometers, transmitters, the computer system and software, the system may be low cost and the space required is similar to that of a desk and computer. The system is capable of reading movements at individual DOFs, but is incapable of measuring hand movement.

Feedback device for improvement of coordination of reach-to-grasp after stroke

This system gives feedback both to the patient and physiotherapists of the time between the start of the hand opening and the start of the transport component during reach and

grasp movements (van Vliet et al. 2012). The system aims to improve coordination of the hand and arm at the beginning of reach and grasp movements by directing the patient's cognitive focus to timing these events simultaneously. This allows a more normative temporal coordination of reach and grasp movements. The system consists of a circuit breaker switch attached to the patient's finger and thumb which is activated upon opening the hand, and another circuit breaker switch which is activated by reaching forward from a starting position. These sensors are connected to a timer and user interface that displays the time lag. The efficacy of the system was investigated by recruiting six stroke patients who each performed 40 repetitions of reaching to grasp a jar. The participants were able to reduce the time lag between the start of the hand opening and the start of the transportation component. Two of these reductions were found to be statistically significant and it was concluded that the system was potentially beneficial in addition to regular physiotherapy. The system focuses on one category of movement performance only. The system could be low cost because simple sensors and a readily available timing device is used. It is also compact and simple.

Feedback Training System for guided home rehabilitation

The Feedback Training System (FTS) (Kohler, Schmitz-Rode & Disselhorst-Klug 2010) aims to allow stroke patients to perform stroke rehabilitation exercises under their own control from home. The system consists of a handle attached to the ground via an elastic material. Exercises are then performed whilst the handle is held in the hand, which causes the elastic to stretch. A strain gauge is attached to the elastic to record the applied force. During exercise, a target movement is given in graphical form on a screen of force with time. During a movement, data from the strain gauge is used to draw the patient's movement onto the graph on the screen in real-time. This allows patients to compare their movement with the target movement and to identify any errors, for example moving too slow or not far enough, and correct them. A controlled test was used to assess the efficacy in guiding movements, where one group of healthy participants were asked to perform movements with feedback and another without. Although the same description of the target movements was given to both groups, it was found that feedback resulted in higher conformance to target movements. The system appears to be simple and low cost and requires only the normal space required in which to perform standing exercises. However, because the recorded data

is based on radial distance, it would be impossible for the system to distinguish between certain movements and the system is incapable of reading movements at individual DOFs.

Rotating table-top handle and feedback system

A system was developed (Winstein, Merians & Sullivan 1998) to assess a stroke patient's ability to learn with the less affected limb compared to healthy people. Testing of the system was described in section 2.5.4, and the working mechanisms are further explored here. The system consists of a handle attached to a light-weight lever on a tabletop. The handle is then rotated through shoulder lateral and medial deviation by stroke patients. The system samples angular position of the lever at 200 Hz, but the method of recording is not disclosed. As described, the target movement was short in duration (one second) thus requiring open-loop control. Feedback is given after movements in the form of a *"position-time trace"* of the participant's movement superimposed onto a target movement using a graphical interface displayed on a computer monitor. A figure proportional to the extent of deviation from the target movement was also given. As described, both healthy participants and stroke patients showed improvements after use in terms of target conformance. The system could be low cost as it mainly consists of a handle, lever and possibly a potentiometer. The space required is similar to that of a desk and computer. An advantage of this system is that no mounting to the patient is required. However, the patient's position relative to the lever would have an effect on readings, and the system is incapable of reading movements at individual DOFs.

Exoskeleton system for hand and wrist tele-rehabilitation from home

This system (Durfee et al. 2009) aims to allow home-based clinically directed therapy that involves cognitively challenging movement exercises. The term tele-rehabilitation entails rehabilitation over distance with communication between patients and clinicians. The system consists of a tracking system for the hand and wrist, a data acquisition system, a computer with a custom program, a cell phone, a webcam and a landline. The tracking system consists of a custom electrogoniometer with mechanical members attached to straps which affix to the wrist and hand. The members are connected to potentiometers, which move in correlation to wrist extensions and flexions, and opening and closing of the fingers. During exercise, a target movement is given in graph form of force with time on the

computer screen. During a movement, data from the potentiometers is used to draw patient movement onto the graph on the screen. At the end of a trial, the patients are given a summary of their performance which includes worded feedback of how to improve. During a trial of the system, periodic face-to-face communication was made between a therapist and patients to give feedback and encouragement. The method of sharing performance data recorded by the system was not disclosed. Whilst the system appears to be compact and low cost, it is incapable of catering for arm exercises.

Therapy-WREX gravity reducing feedback robot

The Therapy-WREX (T-WREX) (Sanchez et al. 2006) aims to allow home-based training and provide quantitative feedback. It consists of a series of members attached to the back of a chair or wheelchair, to which the upper arm and forearm are strapped. The T-WREX has 5 DOFs at which movement is read using potentiometers. A hand held grip sensor was also used during tests. T-WREX also counterbalances gravity using elastic bands. The system allows therapeutic games to be played on *"Java Therapy 2.0"* software. Games include moving virtual items and squeezing with the hand to simulate making lemonade, which is shown on a computer monitor. Quantitative feedback is also provided, although little description of this is given. It was found that stroke patients who had used the T-WREX were better able to better perform reaching and drawing movements. It was also found that after eight weeks of training with the system by five stroke patients, improvements were made to unassisted movements tested by the Fugl-Mayer scale. The system is complicated to allow accommodation for patients of different sizes, and costs approximately 4000 USD (Sanchez et al. 2004). Although the system is capable of reading movements at individual DOFs, it is only capable of detecting hand strength and not hand movement.

Wearable kinaesthetic system for capturing stroke patient upper limb gestures

The system (Tognetti et al. 2005) consists of a garment for the torso and arms, which incorporates conductive elastomer strips allowing movement to be detected. The system was designed to be incorporated into remote support systems that enhance stroke physiotherapy performed within the home. The conductive elastomer strips bend when movements are performed, which causes changes in resistance. With an electrical circuit and a voltage applied, the changes in resistance are converted to electrical signals that are

imported into a computer for processing. An algorithm was also developed to detect gestures. The performance of the system was tested against an existing system (an electrogoniometer) and the outputs at the wrist and elbow were found to be similar for both systems. The cost of the materials and their exact composition is not disclosed. The system is light-weight and was comfortable to wear during tests. However, a single garment may not be suitable for people of different sizes. Hand movement is not recorded by the system.

Wearable conductive fibre system for long term measurement of DOF movements

This system (Gibbs, Asada 2005) was designed to allow for long term day-to-day monitoring and act as an input device to other recording systems. The system works in a similar manner to a linear potentiometer. A conductive fibre is integrated into a skin-tight garment to align with the outside of a joint. The conductive fibre is attached to a spring on the garment at one end and secured directly to the garment at the other. This means that as the joint flexes, the garment will stretch on the outside of the joint, but because the conductive fibre is fixed at one end, it will move relative to the garment. A current is applied at the fixed end of the fibre which is picked up at a point towards the spring end. The pickup point is fixed to the garment so will move further along the conductive fibre during joint flexion. This means that current flows through more of the conductive fibre, which causes an increased resistance. Electric circuits allow this change in resistance upon flexure to be converted into an analogue change in voltage which correlates with joint angle. As the output is non linear, if proportionality to angle is required, some signal processing is necessary. The system was found to give similar performance to a flexible electrogoniometer. The system is compact and lightweight but appears to be slightly complicated and delicate.

Adaptive mixed reality feedback system

This system (Lehrer et al. 2011) records movement through motion analysis, where 17 reflective markers are placed in specific positions on the patient's back, arm and hand. 14 cameras are used to detect motion of the markers. Movements are also detected by a touch sensitive table surface and through force sensors in a small cone shaped object. Data from the cameras and sensors is delivered to a computer system connected to a large screen. Reaching and grasping exercises can be performed by either reaching for the cone on the

touch sensitive surface, or by reaching for a virtual object displayed on the screen. The system is capable of generating a wide range of feedback for clinicians about the parameters of the movements. This includes range of motion, error, consistency, distance to target, speed, peak speed, time, movement synergism and jerkiness. Movement synergism was considered in terms of pairs of joints including shoulder extension and elbow extension, forearm rotation and shoulder flexion, and forearm rotation and elbow extension. An exact definition of movement synergism is not given, but the term *"joint correlation"* is used. Feedback for stroke patients includes real-time visual cues about trajectory error and hand rotation and real-time audio indications of the speed of the hand's movement, elbow extension, and torso and shoulder compensation (Duff et al. 2012). The system appears to be more aimed at enhancing regular physiotherapy rather than at providing a means for further independent physiotherapy. The physiotherapist was present during tests, and gave verbal feedback in addition to the feedback provided by the system. The system is adaptable and capable of generating a wide range of feedback. However its complexity and required space make it unsuitable for home use.

Virtual Reality through Nintendo Wii console technology

A study (Saposnik et al. 2010) investigated the efficacy of playing games on the Nintendo Wii game console (described in section 2.6.1) in improving motor function in stroke patients. Nine stroke patients played a tennis simulation and a cooking simulation game in eight 60 minute sessions over a two week period. As a control group, eight stroke patients participated in recreational therapy involving cards, bingo or *"Jenga"* over a similar schedule. It was found that the games group had improved more than the control group by a mean of seven seconds on the Wolf Motor Function Test. The study concluded that the Wii presents a safe, feasible and potentially effective alternative to facilitate stroke physiotherapy. The Wii is similar to theories outlined in the hypothesis of this research in that it aims to allow physical activity to be performed in the home under motivation. The interface and hardware of the Wii system are highly refined. As identified previously, the system costs approximately £200. However, the system is incapable of measuring movements at individual DOFs and the games available do not relate directly to ADLs which must be relearned by stroke patients.

Virtual reality through Microsoft Xbox console and P5 Glove technology

This system (Morrow et al. 2006) consists of a P5 glove, an Xbox, custom software and a PC monitor. The system aims to be low-cost, easy to install and use and to allow rehabilitation of the hand to be realised at home or at outpatient clinics. The P5 glove consists of a plate to strap to the back of the hand, and five protruding flex sensors to attach through rings to the ends of the fingers and thumb. The flex sensors consist of a silver based metal that varies in resistance under flexion. Three degree resolution is achieved from zero to 90 degrees. The glove emits infrared light from an LED which is monitored by an accompanying base station allowing the position of the glove, in terms of the X and Y axis on the monitor, to be tracked. The Xbox has some modification to the operating system to allow purpose made Java based exercise games to be played. One game asks the patient to extend and flex their fingers as fast as possible. A virtual hand on screen shows the patient's movement and a virtual butterfly flies away if a target velocity is achieved. Another game exercises the range of motion of individual fingers by revealing a hidden image on screen progressively in proportion to achieved finger flexion. For motivation, fireworks are shown on screen and applause sounds are emitted from speakers upon achievement of goals. The efficacy in aiding stroke patients is untested. The system is 549 USD according to the authors and is compact and lightweight. However, it is incapable of catering for arm exercises and the glove must stay in front of the tracking station during use.

2.6.7. Sensors, DAQ systems and software

Nintendo Wii motion sensor

The accelerometer used in the Nintendo Wii, ADXL330, can be purchased for approximately £20 (RobotShop 2012). The ADXL330 is an example of a Micro Electro Mechanical System (MEMS). The accelerometer is in the form of a breakout board, which is a series of electrical components on their own board. The sensing element consists of a polysilicon surface suspended by springs over a silicon wafer. Acceleration causes deflection of this surface, which is measured using a differential capacitor (Analog Devices 2006b). The input to the sensor is 2 to 3 V and +/- 3 g. The output is 300 mV per g (Analog Devices 2006b).

Accelerometers

Accelerometers such as the SparkFun ADXL203CE Dual Axis breakout board can be purchased from electronics shops for approximately £19 (STMicroelectronics 2009). The working mechanisms are the same as that of the Wii motion sensor, where an element is suspended by springs and deflection is measured using a differential capacitor (Analog Devices 2006a). The input to the sensor is 5 V and +/- 1.7g. The output is 1 V per g (Analog Devices 2006a).

Gyro sensors

Gyro sensors such as the SparkFun LPR530AL Dual Axis 300 degree per second breakout board can be purchased from robotic shops such as Active Robots for approximately £15 (Active Robots 2012b). According to the data sheet, the gyro sensor is built as a combination of an actuator and an accelerometer integrated into a single micro machined structure. It includes a driving mass kept in continuous oscillating movement and is able to react when an angular rate is applied based on the Coriolis principle (STMicroelectronics 2009). The input to the sensor is 2.7 to 3.6 V and +/- 300 degrees per second. The output is 0.83 or 3.33 (amplified) mV per degree per second.

Flex sensors

Active Robots also sell flex sensors such as the Spectra Symbol 4.5" Flex Sensor, which costs approximately £16 (Active Robots 2012a). The Flex sensor works using a resistive liquid contained in cells along the structure, whose resistance increases from 60K to 110K phms upon flexure (Spectra Symbol 2010). The sensor can be used with a voltage divider circuit which when powered will give a varying output voltage upon flexure (Spectra Symbol 2010).

Infrared sensors

Also from Active Robots, the Inex 38 kHz Infrared Rec Board is available for approximately £5 (Active Robots 2012c). The input is 5 V and an output of either logic "0" if a 38 KHz infrared light is directed at the sensor, or logic "1" if not (Active Robots 2012c). The board must therefore be used in conjunction with an infrared source.

Universal Serial Bus (USB) Data Acquisition Modules (DAQs)

National Instruments produce USB DAQ systems such as the NI USB-6009 Low-Cost Multifunction DAQ, which they sell for £179 (National Instruments 2012d). The DAQ is powered by the USB voltage (5 V) and has eight analogue voltage inputs of which samples can be recorded at 48 KHz (National Instruments 2008). The DAQ then digitises these input signals using a 14 bit scale. These signals can then be brought into a computer using a USB interface, where they can be processed as necessary within programs or software environments (National Instruments 2008).

Peripheral Component Interconnection (PCI) DAQs

As well as connection through USB, DAQ modules can connect through PCI. The PCI-BASEII is an example of such modules, which is available from Audon Electronics for £149 (Audon Electronics 2012). Instead of remaining outside the computer as did the NI-USB-6009, the PCI-BASEII connects to the motherboard within a computer. The DAQ accepts up to two input modules, either analogue voltage or digital signal, which allow for up to 32 channels. The DAQ is powered by the PCI slot and has a sample rate of 500 KHz under a 16 bit scale (BMCM 2012).

Wireless DAQs

National Instruments also produce wireless DAQ systems such as the NI 9201 Measurement System, which they sell for £498 (National Instruments 2012b). The DAQ is mains powered and has eight analogue voltage inputs of which samples can be read at 500 KHz (National Instruments 2012c). The DAQ then digitises these input signals using a 12 bit scale. These signals can then be brought into a computer using a USB interface, but also an Ethernet or 802.11 Wi-Fi connection if required (National Instruments 2012c).

DAQ compatible software

The most widely used and most developed software packages that are widely used for DAQ applications appear to be MATLAB, LabVIEW and Visual Studio. MathWorks, the developers of MATLAB, describe the working environment as a high-level language and interactive environment for numerical computation, visualisation, and programming (MathWorks 2012). MathWorks also describe the main capabilities of MATLAB as numeric computation,

data analysis and visualisation, programming and algorithm development, and application development and deployment (MathWorks 2012). The price and availability of the software are less important aspects in this case. This is because, for the purpose of this research, licences can be obtained through the University. Also, if a marketable version of the prototype system was to be developed, it would likely have a stand-alone software program and not be run from a development software package. National Instruments, the developers of LabVIEW, describe the working environment as system design software that provides engineers and scientists with the tools needed to create measurement and control systems through hardware integration. Also stated is that LabVIEW has a unique graphical programming language with built-in engineering-specific libraries of software functions and hardware interfaces which allow for data analysis, visualisation, and sharing (National Instruments 2012a). Since National Instruments also produce DAQ systems, when used together, data acquisition and analysis is enhanced. For example, templates specific to National Instruments DAQ systems are available, and specific LabVIEW hardware drivers are available such as NI-DAQmx (National Instruments 2012a). The working environment consists of a block diagram, where inputs are specified and the program is written, and a front panel, where graphics and outputs are displayed. Microsoft, the developers of Visual Studio, describe the software as an Integrated Development Environment (IDE), which has architecture and modelling, support for multiple platforms for example Windows and web development, and debugging and diagnostics capabilities (Microsoft 2012). Visual Studio also offers high-level language support, but is more oriented towards development of computer programs than accepting data from external sources and performing analysis when compared to MATLAB and LabVIEW.

2.7. Interviews with stroke physiotherapists

Reviewing of literature in the fields of stroke, human anatomy and mechanisms, motor performance, feedback during motor learning, and existing systems and technology, led to the generation of questions to be raised in interviews with stroke physiotherapists. The questions were set as a semi-structured interview and the principles of interviewing from "*Research Methods in the Social Sciences*" (Frankfort-Nachmias, Nachmias 1996) were followed. Also, the questions were verified by an experienced psychologist prior to

commencing the interviews. Two stroke physiotherapists were interviewed by the researcher, who for ethical reasons are kept anonymous. The interview questions and answers from both physiotherapists have been combined, to avoid splitting the subjects discussed, for clarity. The questions and responses are shown below:

What is the overall focus in stroke physiotherapy programs?

The overall focus is to increase the independence of the patients.

What are the physical deficits stroke patients exhibit?

The main physical deficits are lack of strength, poor coordination, spasticity and reduced range of movement. Also energy required to perform a movement which will be a function of these.

Which of these physical deficits do you aim to improve during physiotherapy?

All of them.

How do you measure and define these physical deficits and what else do you monitor to assess performance during physiotherapy?

The extent of the deficits in the categories above is generally judged visually, or in the case of weakness and spasticity, by feeling the patient's movements with the hands. GPs define strength using the Medical Research Council (MRC) Scale for muscle strength, or the Oxford Scale. Range of movement can be measured using a goniometer.

What feedback would you give to stroke patients during a physiotherapy session?

- Instruction of exercises
- Information of performance
- Information of how to improve
- Praise where due for motivation

Instruction can be made clearer by demonstrating a movement to be performed by the physiotherapist performing the movement themselves. Also, the physiotherapist can assist

patients during movements by applying external forces to demonstrate a target movement. Praising patients when they perform well, and informing them of any improvement is important for motivation.

What is said to patients? For example an internal focus saying *"try and avoid moving your body as you reach with your arm"*, or *"try and move in one smooth movement"*? Or using an external focus saying for example *"try and place the cup there"*, or *"try and walk faster"*?

Feedback must be simple enough to be understandable by patients. The cognitive understanding of movements is external, for example considering the position of the hand during reaching for a cup as opposed to considering the activity of the individual muscles. Feedback should therefore be in this external format also.

Would a system that provides further exercise guidance be useful?

Yes, it would be useful to motivate patients to train on their own.

Would it be useful to be able to remotely monitor patient performance, for example exercises performed, performance and improvements?

Yes, it would be useful to tell if patients are actually performing the exercises they have been asked to perform. It would also be useful to gain more detailed information about movements. It would also be useful to be able to detect small movements and small improvements in patients with severe impairments.

Is it most important to train the patients any particular skills, for example to walk?

Stroke patients are taught to sit up, to walk and then to use their upper limb. These activities are generally taught in that order.

What exercises are performed during physiotherapy?

Poor coordination is often caused by conditions in the cerebellum. Poor coordination can be improved by practising and performing multiple repetitions to relearn the movement. Spasticity can be overcome by performing stretches sometimes with weights on the limb.

Recovery can occur in progression along the arm from the shoulder to the hand. Patients with haemorrhagic hemiplegia (paralysis on one side of the body; more severe than hemiparesis) often see a level of spontaneous recovery.

How long does a stroke physiotherapy session typically last?

Around 5 to 45 minutes, depending on the condition and ability of the patient.

How many repetitions will typically be performed during a session?

Approximately three sets of 10 repetitions, or three sets of 15.

How many times per week are sessions typically performed?

Daily where possible, ideally once in the morning and once in the afternoon.

How long does a physiotherapy program typically last?

Around 2 to 6 months, depending on the condition and progression of the patient.

2.8. Conclusions to chapter

Due to the high morbidity and the vast number of stroke survivors left with physical disabilities, stroke is a serious disease.

The main physical deficits suffered by stroke patients are weakness, poor coordination, spasticity and reduced range of motion. The overall aim of physiotherapy is to increase patient independence. It has been found that recovery can continue into the chronic stages of stroke. Many studies have shown both healthy people and stroke patients can benefit greatly from receiving extrinsic feedback during motor learning.

According to literature and particularly the stroke physiotherapists interviewed, the fundamental elements of interaction from the physiotherapist to stroke patients are:

- Instruction of exercises
- Information of performance
- Information of how to improve
- Information of improvements for motivation

Since physiotherapists guide movements, an aim of this guidance seems to be to allow stroke patients to reproduce target movements. Since the aim of regular physiotherapy is to improve, the aim could also be considered as to allow target movements to be conformed to more closely than if physiotherapy was performed by the patient on their own. In this way independence, the overall aim of stroke physiotherapy, is improved by improving performance during physiotherapy, as a result of conforming more closely to target movements. This is achieved by guidance provided by the physiotherapist which enhances motor learning.

Although many forms and formats of feedback exist, no consensus has developed regarding which are optimal. Similarly, a large number of disability and functional measures exist as well as parameters that can be assessed during exercise. It therefore seems that a level of judgement must be made when catering for the individual learner and situation.

Feedback given frequently containing error correction information has been shown to result in dependency. However, it has also been shown that feedback given frequently containing information about the fundamental elements of the movement is necessary in early learning. Therefore it again seems that a level of judgement must be made when catering for the individual learner and situation.

It has been found that the cost of home rehabilitation with physiotherapists is similar to the cost of hospital rehabilitation, but less costly than day-care. Home stroke physiotherapy has been shown to be effective.

There are no clearly defined conditions that patients must reach before discharge from hospital care. Although guidelines for stroke treatment exist, in many cases they are not followed. This is largely due to limited resources and number of clinicians. Communication with patients and carers upon discharge appears limited. Treatment in many cases is insufficient to allow patients to reach their full potential of physical recovery.

From existing systems which aim to provide a means to further rehabilitate within the home, the following characteristics seem important:

- Lightweight, compact, non-intrusive
- Easy to use, understandable, fun, motivating
- Tele-rehabilitation, information of performance from patients to clinicians and of exercises and feedback from physiotherapists to patients, via telephone line or internet
- Ability to guide functional exercises relating to ADLs
- Ability to detect movements at individual DOFs including the hand

Systems exist that aim to treat the upper limb in a similar context as outlined by the hypothesis of this research. This is perhaps due to function of the upper limb playing a part in all the ADLs listed in the BI, and because sitting up and walking seems to be given a first priority during physiotherapy. It therefore seems beneficial to further rehabilitate the upper limb.

Although systems that aim to treat the upper limb have been identified, little is specified in terms of the method of interaction during the session. In regular stroke physiotherapy, patients are able to pause between attempts to reproduce target movements and then continue when they were ready. Although no existing systems are described as allowing this, it is considered important for the comfort of patients and to allow enough time to contemplate and remember feedback.

It has been shown that graphical feedback of a patient's movements and target movements can guide exercise. It has also been shown that knowledge of improvements increases motivation during learning. The rotating tabletop handle feedback system (Winstein, Merians & Sullivan 1998) displays a figure proportional to the extent of deviation from the target movement combined with graphical feedback. However, no existing systems quantitatively inform patients of their improvements combined with graphical feedback.

Systems such as the Feedback Training System (FTF) (Kohler, Schmitz-Rode & Disselhorst-Klug 2010) appear to provide guidance of one DOF only. This may lead to consideration of

movements in terms of the end effector only. No existing systems investigate the effects of feedback on other DOFs which also move during movements. Consequently, it may be that only the DOF for which the guidance is provided improves in conformance to target movements.

Reduced movement coordination is a common physical deficit after stroke, as the information to allow for coordinated movements can be lost due to the infarction. Restoring movement coordination through repetitive practice is performed during regular stroke physiotherapy. Detecting movement coordination during physiotherapy may therefore be useful to monitor patient performance and optimise physiotherapy programs. However with existing systems, little emphasis has been placed on the detection of coordination of movements during physiotherapy. There appears to be no widely agreed method of defining movement coordination or movement synergism, although in one study it has been considered in terms of the times of peak velocities and accelerations and decelerations of DOFs (Alazmani et al. 2008). The extent of movement synergism could also be defined as the extent that two or more DOFs were moving simultaneously. This definition seems to be the simplest method of defining movement synergism in the way in which it relates to movement coordination.

There are existing systems that aim to provide a means to further rehabilitate within the home, which suggests a need for such systems exists. None of these systems have been developed and tested enough to be used in a widespread, routine or commercial fashion. The increase in use of gaming consoles and their technology in stroke rehabilitation suggests that such refined user-friendly systems can be beneficial.

A range of sensors such as those used in game console technology are now available for low costs. Also, DAQ systems are available for low costs. Software environments are also available which allow for signal processing and generation of feedback.

The stroke physiotherapists interviewed agreed that the system outlined by the hypothesis of this research could potentially be useful, stating the following aspects as particularly important:

- Motivating patients to perform exercises on their own
- Being able to detect whether or not exercises are being performed
- Being able to gain more detailed information about movements
- Detecting small movements and improvements in patients with severe impairments

The findings from this chapter, along with the hypothesis and research questions formed the basis for further discussion and development of system objectives and a design specification for a prototype system in the following chapter.

CHAPTER 3. PROTOTYPE DEVELOPMENT

3.1. Introduction to chapter

This chapter describes the design and construction of a prototype system for testing. The findings from the information review along with the hypothesis and research questions lead to establishment of design requirements. This includes description of an initial system concept, further discussion, considerations, observation of movements and the development of a simplified model of the upper limb. All of this leads to establishment of system objectives and a design specification, which together describe the established requirements for the system. Concepts are generated and evaluated against the identified requirements for the hardware for reading movements and software for generating and providing feedback. The DAQ systems and software identified in the information review are also evaluated and testing of sensors is performed. From the system objectives, design specification, concept evaluation and testing of sensors, a prototype system for testing is then established and constructed.

The system objectives and design specification are listed per requirement and the concepts and description of the prototype system are evaluated per feature. It was felt that this was the clearest and most concise method of reporting. The system objectives, design specification, the prototype system itself, hypothesis, research questions and findings from the information review then provided the basis for generation of objectives for the tests of the prototype system in the next three chapters.

3.2. Establishment of design requirements

3.2.1. Initial system concept

The idea was conceived for a system that would enable regular guided and monitored therapeutic exercises in the home to provide a means for stroke patients to achieve a higher level of physical rehabilitation (see Figure 3.2.1). The system would facilitate independent physiotherapy in addition to regular physiotherapy through feedback which would provide guidance.
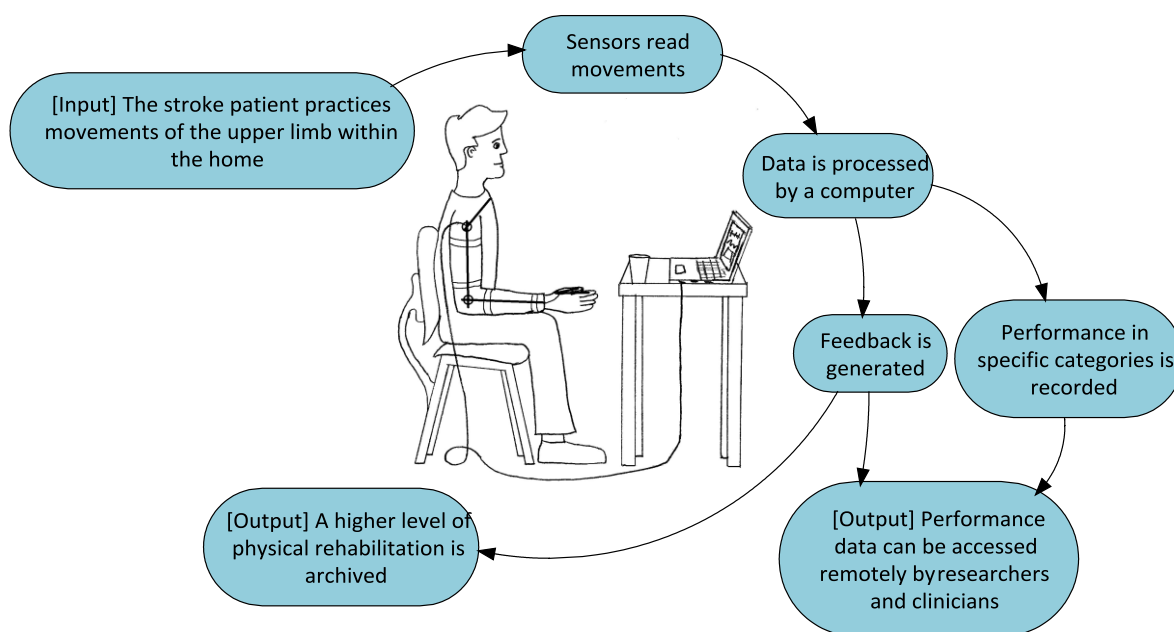
Figure 3.2.1. Mechanisms of the initial system concept

The initial system concept was used to give an initial perspective. However, it was not considered as a final solution or an optimal approach to take in terms of its design.

3.2.2. Observations of movements

Although literature concerning movement characteristics had been reviewed, it was decided to visually observe movements in order to gain a further understanding. To identify a relevant movement to observe, the BI ADLs (Mahoney, Barthel 1965) identified in the literature review were considered. Reaching and grasping was chosen for observation, because it was noted that this movement was required for the majority of the ADLs, particularly in activities such as feeding and dressing. Five people were then asked in turn to sit at a desk and reach for a cup from the surface. Dimensions and positions of the chair, desk and cup were to allow the participants to be comfortable and to simulate everyday conditions. Participants were asked to reach for and grasp the cup, and to withdraw it towards the body as they would under normal circumstances. Each of the participants was asked to perform the movement approximately five times. It was noted that in all cases, the fingers and thumb were active with extension and flexion, as well as the elbow and shoulder

also with extension and flexion. Also, opening of the hand began from the onset of movements. The duration of an individual movement was approximately one second.

The ranges of displacement during the movement and the full ranges of movement at the DOFs which moved were then measured using a goniometer at the shoulder and elbow joints. Shoulder displacements were measured from the body to the upper arm, and elbow displacements from the upper arm to the forearm. Since opening and closing of the hand involved movement of many DOFs of the hand, for simplification it was considered in terms of a linear displacement. This was taken as the distance from the centre of the proximal phalanx of the thumb to the centre of the middle phalanx of the forefinger. This was done because it appeared to describe opening and closing of the hand and allowed for definition of points to measure between. This measurement was taken using a standard tape measure and is referred to here as 'grip distance'. Participants were asked to pause during the movement whilst measurements were taken, and then to extend and then flex the same DOFs whilst measurements were again taken. From this, mean displacements and then ranges of movement were calculated and are shown in Table 3.2.2a:

Table 3.2.2a. Ranges of movement during the reach and grasp movement and full ranges of movement

	Mid range of movement during the reach and grasp movement		Full Range of movement	
	Start position to end position	Range	Start position to end position	Range
Grip distances (mm)	42-80	38	30-110	80
Elbow extension and flexion angles (degrees)	88.5-144.5	56	51-177	126
Shoulder extension and flexion angles (degrees)	0-42	42	0-136	136

It was found that the elbow had the largest range of movement. The velocities of these movements were also calculated. As described, the movement took approximately one second to perform and consisted of a reach and then a return movement. The values for ranges from Table 3.2.2a were therefore multiplied by two and results are shown in Table 3.2.2b:

Table 3.2.2b. Estimates of velocities of the DOFs which moved during the movements

Grip distance velocity (mm/second)	76
Elbow extension and flexion velocity (degrees/second)	112
Shoulder extension and flexion velocity (degrees/second)	84

3.2.3. Model of the upper limb

As identified in section 2.3.1, the upper limb (including the hand) consists of 38 DOFs. A model of the upper limb was created in the form of a drawing of a simplification of the DOFs and joint segments of the human arm. This was to allow the upper limb to be visualised in a concise form to aid the design process. Simplification was performed by identifying and eliminating DOFs which seem to have little effect on movements or which are not used as often. This was achieved by considering anatomy of the upper limb (as identified in section 2.3.1), the observations of movements and the BI ADLs (Mahoney, Barthel 1965). For example the humeroulnar and humeroradial joints are together responsible for extension and flexion at the elbow. This results in slight translation as well as rotation during movement. However, it is rotation which is by far the most pronounced, so translation was excluded from the model. Also, the simplification of hand movement described in section 3.2.2 was again adopted. The model of the upper limb is shown in Figure 3.2.3:
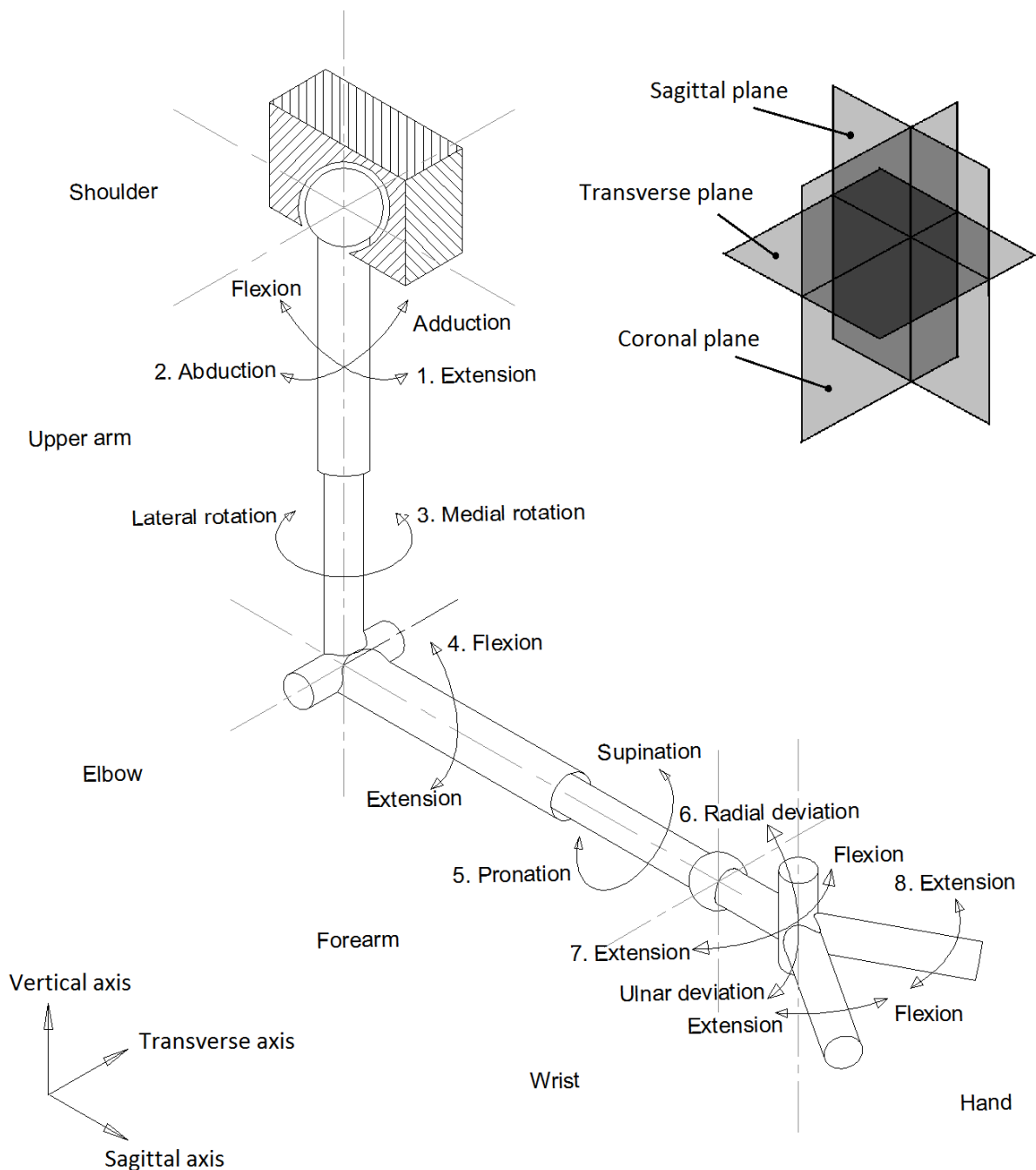
Figure 3.2.3. Model of the upper limb

The model is of the right arm, where the upper block depicts the connection of the shoulder with the torso. The upper limb was simplified to the eight DOFs shown in Table 3.2.3, which were referred to as the major DOFs of the upper limb. These DOFs allow movement in multiple planes, or in other words, 3D movements.

Table 3.2.3. The major DOFs of the upper limb

Location	Movement type
Shoulder	1. Extension and flexion
	2. Abduction and adduction
	3. Lateral and medial rotation
Elbow	4. Extension and flexion
Hand	5. Pronation and supination
Wrist	6. Radial and Ulnar deviation
	7. Extension and flexion
Hand	8. Extension and flexion (opening and closing)

3.2.4. Discussion of design requirements

This section describes discussion of some further issues regarding the design.

Difficulties in measuring human movement

As identified previously, the upper limb is a complicated appendage. To aid the design process, a list of difficulties in measuring human movement was generated:

- People are of different sizes and dimensions

- People have different skin types, for example dry skin/moist skin

- People have different builds, for example body fat percentage

- Hairs can be present in some cases

- Bone locations and centres of rotation are difficult to locate

- Skin can move relative to the bone

- People give off heat and sweat

- People can be distracted in noisy or busy environments

- Levels of fatigue and arousal can vary

Outcomes to avoid

As well as identifying requirements, to give an alternative perspective, outcomes to avoid were contemplated and are listed below:

- The system becoming overly complicated

- Causing pain, being invasive, irritant

- Difficult or time consuming to mount and dismount

- Requiring high voltages

- Low signal to noise ratio in signals

- Sensors moving relative to skin during movements

- Low sensitivity, high variability

- Requiring time consuming calibration

- Requiring a large space to operate in

- Incapable of accommodating people of different sizes

How active or passive the system should be

Since the hypothesis entailed an ability of the system to provide guidance, how active or passive the system should be was contemplated. The subject was considered in terms of the following elements:

- How in control the patient should be, for example whether or not they should determine what movements are performed during physiotherapy

- How independent a patient should be, for example whether or not they should determine what exercise sessions are performed and when during physiotherapy

- The level of mental effort required by the patient

- How easy it is for the patient to understand what to do and the extent of their understanding

It was thought that the patient should be in control to the extent that motivation will be high, but not to the extent that it is unclear what they must do in order to optimise the process of learning a movement. Also, the patient should be independent to the extent that motivation will be high to allow physiotherapy to be considered less of a chore. However, it was thought that they should not be independent to the extent that they will not know what to do in order to optimise the process of learning a skilled movement. It was thought that requiring less mental effort would lead to the exercises being considered less of a chore. This in turn would lead to greater motivation. A patient should therefore be required to make minimal mental effort. Patients should have an understanding that allows them to

feel involved and motivated. However, overly time consuming educating in specialised subjects such as the principles of motor learning may be unnecessary and should be avoided.

The objectives and physical phenomena that occur during movement

Similar to the objective of physiotherapy, the objective of movement seems to be to allow an independent and fulfilled life to be lived. In terms of movements this is achieved through locomotion and object manipulation, which allows for ADLs such as eating, dressing and toileting. The objectives of movement could therefore be considered to exist in a hierarchical structure. In order to help the identification of methods of reading movements, the physical phenomena that occur during movements were considered:

- Neural activity during planning, execution and control of movements
- Signals to muscles via neurones
- Movement of joints
- Movement of limb segments
- Signals transmitting proprioceptive feedback from muscles

Neural activity is electrically based and occurs in the CNS and muscles. Movement of joints and limb segments is rotation or translation based. Proprioceptive feedback is also electrically based and occurs in the muscles of the limb. Behaviour of these phenomena relates to the level of motor skill present.

Movement synergism

As well as the hierarchy structure of the objectives of movement, the phenomena that occur during movements can be considered a hierarchy. Initially there will be cognitive identification for the need for movement, followed by response selection. Once the movement is underway, it will follow a given pattern with measurable characteristics. Movement synergism is a form of movement characteristic or parameter. As proposed in section 2.8, the extent of movement synergism could be defined as the extent that two or more DOFs are moving simultaneously. This definition seems to be the simplest method of

defining movement synergism in the way in which it relates to movement coordination. Movement synergism is a form of movement coordination and as a motor program develops, movement coordination improves as the control process transforms from cognitive to automatic. As identified in section 2.4.2, motor programs are essential for control of movements and are often lost during a stroke. Rebuilding of the motor programs is therefore an essential part of rehabilitation. Detection of the extent of movement synergism present during learning may therefore give insight into the process of motor learning. This could allow the development of motor programs to be investigated specifically by studying the extent of movement synergism in sessions over time. This could allow the efficacy of treatment methods to be investigated by clinicians and researchers. It could also allow for optimisation of treatment methods, for example by varying parameters of a physiotherapy program and noting which ones resulted in efficient development of the motor program. As concluded in section 2.8, although many forms and formats of feedback exist, no consensus has developed regarding which are optimal. Detection of movement synergism could therefore help with the optimisation of treatment regimes, which could greatly benefit stroke patients.

Estimation of performance requirements for the prototype system

Required sensitivity was estimated based on a linear displacement at the hand from an object estimated as sufficient to cause a failed grasp. Based on the anthropometric dimensions of the fingers and hand, and the respective dimensions which were estimated to constitute a failed grasp, the linear displacement was estimated as 20 mm. The resultant angle at the shoulder when the arm was outstretched and when a 20 mm displacement at the hand was made, was then calculated. To do this, the anthropometric dimensions of the upper and lower arms were considered. The mean of the 5th percentile female and 95th percentile male upper arm and forearm lengths are 350 and 455 mm respectively (Pheasant 1990), giving a total arm length of 805 mm. This gave:

$$\frac{20}{2 \times \pi \times 805} \times 360 = 1.4 \text{ degrees}$$

Required digital resolution was then estimated based on the largest measured full range of motion and the estimated required sensitivity. The largest range was measured at the shoulder as 136 degrees. This gave:

$$\frac{136}{1.4} = 97 \text{ levels}$$

$$2^7 = 128 > 97$$

This gave an estimated required digital resolution of 7 bits or more. The required maximum velocities readable by the system was also estimated by considering the movements which were observed in section 3.2.2. The DOF whose angular velocity was estimated as highest was considered which was 112 degrees per second. The estimate for linear velocity was also considered which was 76 mm per second. These values were considered as estimates for the maximum readable velocities.

From the estimated required maximum angular velocity and the estimated required angular sensitivity, the required sample rate was estimated:

$$\frac{112}{1.4} \approx 80 \text{ Hz}$$

The maximum cost that the system could be whilst still being suitable for private purchase was estimated to be approximately £500. This was based on what was thought would be possible based on the costs of item of similar complexity such as computers or stair lifts.

These estimates of performance requirements were included in the design specification.

3.2.5. System objectives

The system objectives were established in relation to the hypothesis, research questions, information review findings, observations and discussion in section 3.2. They are split into a prototype objective, which relates to the scope of this research, and general objectives

which describe broader requirements of the system. Also, specific objectives are given which describe more specific requirements established from findings of the information review.

Prototype objective

Allow tests to be carried out and investigation to be performed to allow the hypothesis and research questions to be addressed.

General objectives

1. Be capable of enabling regular guided and monitored therapeutic exercises in the home to provide a means for stroke patients to achieve a higher level of physical rehabilitation
2. Focus on rehabilitation of the upper limb
3. Be low enough cost to be affordable for private purchase (less than £500)
4. Be useable within the home (compact, easy to set up and safe)
5. Be useable independently by patients and carers
6. Be capable of informing clinicians and researchers of performance of specific kinematic parameters
7. Be capable of remotely informing clinicians and researchers of patient performance.

Specific objectives

1. Provide guidance which, as when provided by physiotherapists, allows target movements to be conformed to more closely. (This is because it was identified that physiotherapists adopt this approach to increase motor performance during a session to increase motor learning).

2. Allow movements to be performed in a similar way to how they would be during a regular physiotherapy session, where pausing between movements and continuing when ready is possible. (This was identified as important for patient comfort and to allow enough time to contemplate and remember feedback, but no existing systems are described as allowing this).

3. Provide quantitative information to patients of their personal improvements during physiotherapy, combined with graphical feedback of their movements and the target movements. (This is because both of these elements were identified as important, but such a combination has not been explored).

4. Include an ability to detect movement synergism. (This is because restoring movement coordination through repetitive practice is performed during regular stroke physiotherapy. Detecting movement coordination during physiotherapy may therefore be useful to monitor patient performance and optimise physiotherapy programs. Also, there appears to be no widely agreed method of defining movement coordination or movement synergism. This is discussed further in section 7.3.2).

The prototype objective was to allow tests to be carried out, therefore for this research, the generation of suitable data was considered important, and refinement and aesthetics were considered less important.

3.3. Design specification

The design specification consisted of a list of identified requirements to be met (shown in Table 3.3). The design specification is therefore in some cases a break down and expansion of the system objectives. The aim of the design specification was to concisely list all requirements to be met which was then to be referred to, along with the system objectives, when generating concepts for the prototype system. Not all findings from the information review were incorporated into the design specification. For example, guidelines suggest that family members are involved in physiotherapy, however, it may not be beneficial to aim for the system to incorporate features specifically to meet this criterion. Instead, requirements were established based on what was considered to allow the system to be most useful. Similarly, although broad subjects such as how much information to give were specified, more specific subjects such as whether to give internal or external feedback were not specified. This was done in order to allow important information to be specified whilst minimising limitation to creativity during concept generation. The design specification was orientated to the scope of this research, where generation of suitable data was considered

important, and refinement and aesthetics were considered less important. The design specification was divided into hardware and software sections. The hardware section states the specification regarding reading movements which forms the input to the system, and the software section states the specification regarding feedback which forms the output of the system. 'M' is stated where a specification was considered mandatory, and 'D' where desirable.

Table 3.3. Design specification

Hardware/input/method of reading movements:		
Medium to measure	Movement at major DOFs	Measuring movement at one or more major DOFs: M Measuring movement at all major DOFs: D
Sensitivity	Within 1.4 degrees or less	D
Resolution	Outputs of analogue resolution as high as possible or digital resolution of 7 bits or more	D
Maximum readable velocities	Angular: 112 degrees/second Linear: 76 mm/second	D
Sample rate	80 Hz or more	D
Variability	Be as low variability as possible	D
Linearity	Signal responses as linear to inputs as possible	D
Cost	Be as low cost as possible so as to be suitable for private purchase for home use (less than approximately £500)	M
Required expertise	Be useable by stroke patients or carers themselves once set up	M
Movements to be performed	Functional movements or a simulation of BI ADLs (Mahoney, Barthel 1965), open and closed control, repetitive training, small movements in the case of severe impairment	M
Safety	Must not: cause pain, be invasive, be irritant, operate at high voltages, cause bodily damage to patients or carers	M
Flexibility/comfort/ circulation	Any items mounted to the patients should be flexible to allow movements to be performed naturally and comfortably. Any items mounted should not impede patient circulation	M
Putting on and taking off	If items are to be taken on or off patients, for example sleeves, it should be possible for patients or carers to do so unassisted. Must fit people of different anthropometric dimensions	M

Table 3.3. Design specification (continued)

Space	Be sufficiently compact to allow home use	M
Weight	Be light enough to be manoeuvrable by patients and carers. Any items mounted to patients should be light enough to allow movements to be performed naturally and comfortably	M
Appearance	Be simple, subtle and non-invasive	D
Sound	Operate at low enough volume to avoid patient discomfort and distraction	M
Software/output/method of providing feedback:		
Information to feed back to patients	Instruction, for example of a target movement to perform. Information of how patients are performing. Information of how to improve where necessary. Information of improvements where present for motivation	Feedback of one or more items: M Feedback of multiple items: D
Information to provide to clinicians and researchers	Performance of kinematic parameters including for example range of movement or peak velocity. Also, improvement in performance of kinematic parameters	Provision of one or more parameters: M Provision of multiple parameters: D
Amount of information to provide to patients	Not provide too much information at a given time that would be confusing and distracting	M
Complexity of information to provide to patients	Not provide information in an overly complex form that would be difficult to understand	M
Ease of reading	Be clear and sized to allow easy reading	M
Provision of information to patients during movements	Not give information that would be distracting and confusing	M
Dependency	Avoid giving feedback during or immediately after movements or upon every movement	D
Safety	Not give flashing images that may cause epilepsy, not be overly bright that would dazzle patients	M
Required expertise	Be useable by patients or carers themselves once set up	M
Appearance	Be simple and subtle. Avoid dazzling graphics	M

3.4. Design

This section describes the design concepts which were generated and the evaluation which was performed. To be concise, only the main concepts are described, and some ideas for specific aspects of the system, sketches and calculations are omitted. Also, evaluation is summarised. Some of the concepts in part use mechanisms used in existing systems. The novelty of the prototype system was summarised in section 1.6, and is described in more detail in section 7.4.

3.4.1. Hardware concepts and evaluation

Optical skin marker hardware concept

This concept utilises reflective markers attached to the skin of the upper limb (see Figure 3.4.1a). The markers would be identified by one or more webcams as identified in section 2.6.1, which through image processing would identify the relative coordinates of the markers. This is similar to the VICON optical system described in section 4.3.1 but would use readily available hardware.
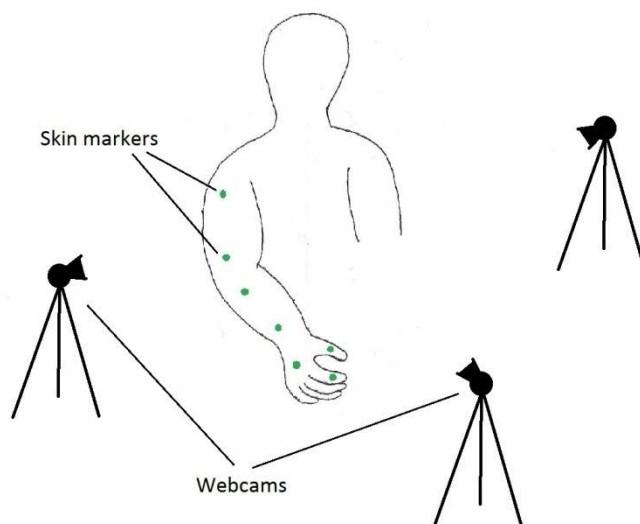
Figure 3.4.1a. Optical skin marker hardware concept

An advantage of this concept is that the markers are lightweight meaning movement restriction would be minimal. However, placing the markers in the correct positions would be time consuming, a large space would be required for operation and specialised image processing would be required if standard webcams were to be used.

Flex sensor hardware concept

This concept utilises flex sensors as identified in section 2.6.7. (shown in Figure 3.4.1b). The flex sensors would be connected to a voltage divider circuit of which the signals would be connected to a computer via a DAQ.
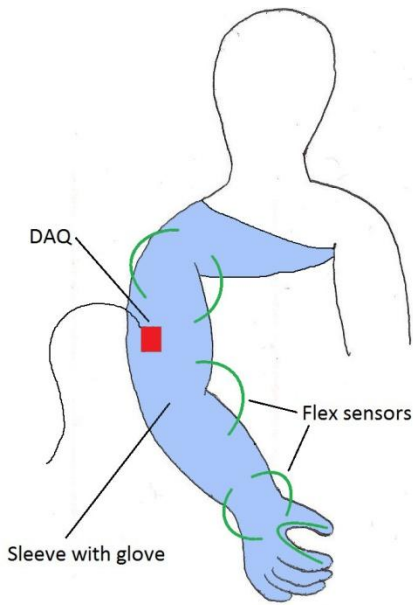
Figure 3.4.1b. Flex sensor hardware concept

Flex sensors are readily available and do not require a large space to operate within. However, measurement of certain DOFs such as shoulder abduction and adduction would be difficult.

Accelerometers hardware concept

For this concept, accelerometers and gyro sensors as identified in section 2.6.7 (see Figure 3.4.1c) are utilised. Signals from the sensors would be connected to a computer via a DAQ. Signals from acceleration and angular velocity could then be converted into displacement of the DOFs as required through integration using the computer system.
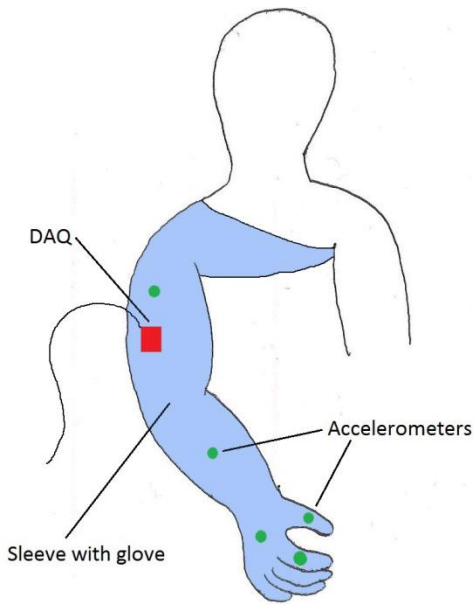
Figure 3.4.1c. Accelerometer hardware concept

Accelerometers are also readily available and do not require a large space to operate within. However, if velocity or displacement was required, signal integration could lead to drift if responses were not linear.

Exoskeleton hardware concept

Rotary potentiometers are moved by external adjustable members attached to the upper limb (shown in Figure 3.4.1d). Again, the potentiometers would be connected to a voltage divider circuit of which the signals would be connected to a computer via a DAQ.
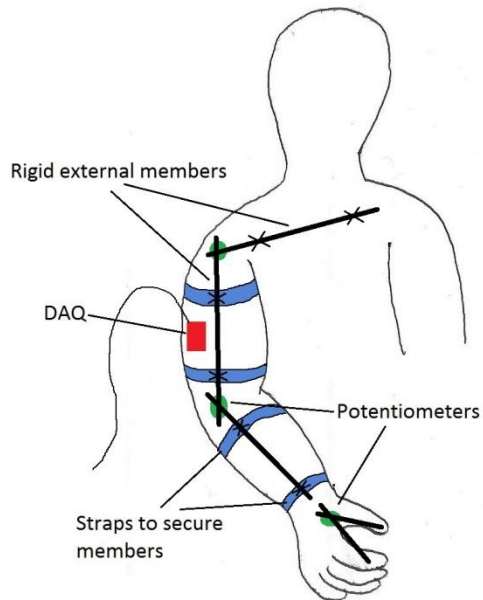
Figure 3.4.1d. Exoskeleton hardware concept

Although this concept is very simple in principle, a complicated adjustable structure would be required to accommodate patients of different anthropometric dimensions.

Sleeve system hardware concept for sensor mounting

A sleeve for attachment of sensors was constructed from neoprene from a diving suit (see Figure 3.4.1e). The sensors were contained in internal pockets and the wiring was within the sleeve (shown in Figure 3.4.1f). The sleeve incorporated straps to allow it to be tightened to fit smaller people.
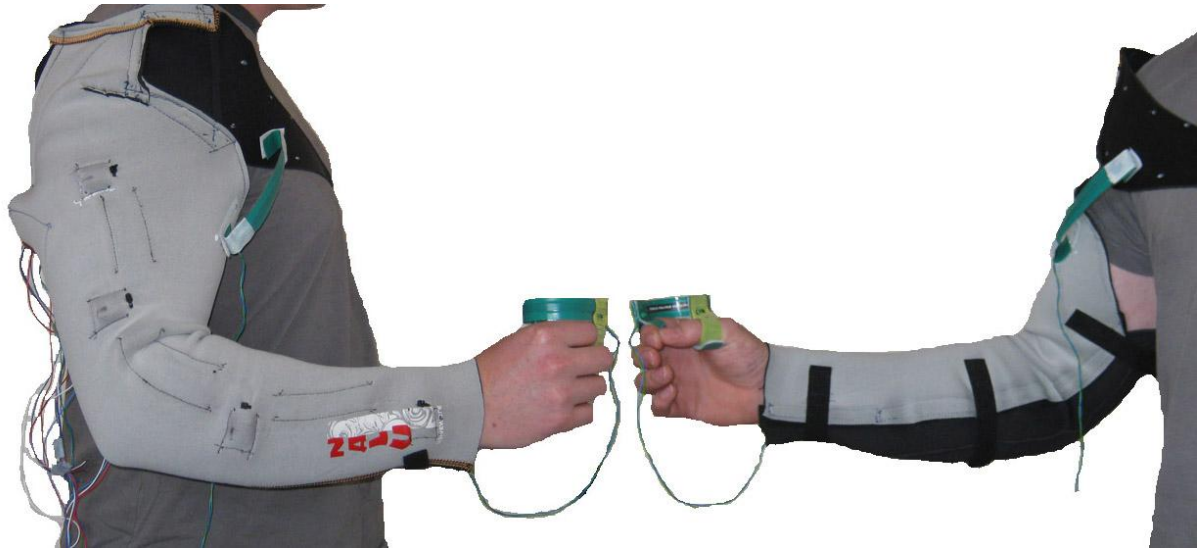
Figure 3.4.1e. Sleeve system for sensor mounting (shown from both sides)

Figure 3.4.1f. A sensor mounted inside the sleeve with internal wiring shown

With the sleeve system, it was found to be difficult to align the sensors correctly and even with the straps, adjustment to fit smaller people was very difficult. Rather than trying to fit a single garment to people of different sizes, it was thought that the sensors may be better fitted to individual straps. This would improve adjustability for size.

Evaluation of sensors

A comparison was then made between the sensors identified in section 2.6.7 (see Table 3.4.1).

Table 3.4.1. Evaluation of sensors

	SparkFun ADXL203CE Accelerometer (Analog Devices 2006a)	SparkFun LPR530AL gyro sensor (STMicroelectronics 2009)	Spectra Symbol 4.5" Flex Sensor (Spectra Symbol 2010)
Input voltage	5 V	2.7 – 3.6 V	For example 5 V (for voltage divider circuit)
Input (measured medium)	+/- 1.7 g	+/- 300 degree/second	Flexure
Output	1 V/g	0.83 or 3.33 (amplified) mV/ degree/second	60K to 110K Ohms (for voltage divider circuit)
Cost	£19 (STMicroelectronics 2009)	£15 (Active Robots 2012b)	£16 (Active Robots 2012a)

The accelerometers and gyro sensors do not impede patient movements compared to flex sensors. However, the signal integration required to obtain displacement may lead to drift and the signal may also require zeroing at periodic intervals. The velocity rating of the gyro sensor input exceeds the estimated requirement in the design specification.

3.4.2. Evaluation of DAQ systems and software

A comparison was made between the DAQ systems (Table 3.4.2a below) following which a comparison of the software identified in section 2.6.7 was made (Table 3.4.2b).

Table 3.4.2a. Evaluation of DAQ systems

	USB DAQ: USB-6009 (National Instruments 2008)	PCI DAQ: PCI-BASEII (BMCM 2012)	Wireless DAQ: NI 9201 (National Instruments 2012c)
Cost	£179 (National Instruments 2012d)	£149 (Audon Electronics 2012)	£498 (National Instruments 2012b)
Sample rate (kHz)	48	500	500
Resolution (bit)	14	16	12
Software	NI LabVIEW	N/A	NI LabVIEW
Number of analogue input channels	8	32	8

All of the identified DAQ systems exceed the minimum required sample rate and resolution of 80 Hz and 7 bits respectively, as specified in the design specification. A wireless connection method would minimise restriction of patient movements and be comfortable during sessions. However, the connection may be affected by interference to varying

extents in different environments, and the wireless DAQ is expensive. Each of the above DAQ systems has a sufficient number of channels to measure all the identified major DOFs of the upper limb. However, the USB-6009 is recognised by NI LabVIEW software and is significantly cheaper than the NI 9201 DAQ.

Table 3.4.2b. Evaluation of software

	MATLAB (MathWorks 2012)	LabVIEW (National Instruments 2012a)	Visual Studio (Microsoft 2012)
Programming language	High level	Graphical/circuit based	High level
Signal processing ability	Excellent	Excellent	Poor
Built-in signal and mathematical functions	Excellent	Excellent	Good
Integration with DAQ systems	Good	Excellent	Poor

The rating (see Table 3.4.2b) regarding signal processing ability, signal and mathematical functions, and integration with DAQ systems was based subjectively on experience and information from the respective websites. Price is not compared because site licences were available during this research and stand-alone software would be developed if a commercial version of the system was to be made.

3.4.3. Feedback concepts and evaluation

In this section, again to be concise, only the main concepts are described where many ideas for specific aspects of the system, together with sketches and calculations, are omitted.

Graph based feedback concept for the stroke patient
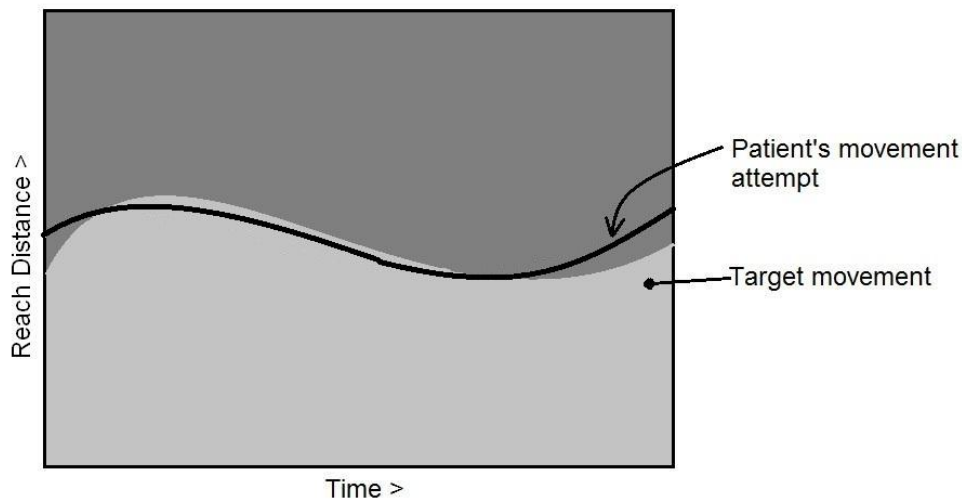
Figure 3.4.3a. Graph based feedback concept

The feedback mechanism (shown in Figure 3.4.3a) is similar to those used by Feedback Training System for guided home rehabilitation (Kohler, Schmitz-Rode & Disselhorst-Klug 2010), and the rotating tabletop handle and feedback system (Winstein, Merians & Sullivan 1998) identified in the literature review. This concept is technical in nature and instruction may be required for some patients to allow understanding. The graph can be presented in real-time or terminally.

Bar based feedback concept for stroke patients
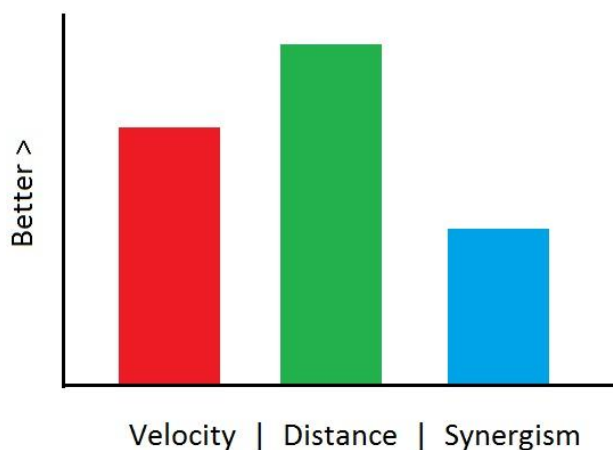
Figure 3.4.3b. Bar based feedback concept

This feedback mechanism (see Figure 3.4.3b) could have interchangeable parameters that could be selected based on the individual patient's requirements.

Worded feedback concept for stroke patients

Strength: smooth movement

Area for improvement: reach distance

Figure 3.4.3c. Worded feedback concept

This feedback mechanism (shown in Figure 3.4.3c) would be effective for communicating emotion for motivation. Also, the patient is not required to have technical knowledge.

Numeric feedback concept for stroke patients

Velocity score: 32

Distance score: 71

Improvement: 18%

Figure 3.4.3d. Numeric feedback concept

This feedback mechanism (see Figure 3.4.3d) allows precise information to be communicated which may be superior for making relative comparisons between sessions and repetitions.

A comparison was then made between the feedback concepts for stroke patients (shown in Table 3.4.3).

Table 3.4.3. Evaluation of feedback concepts for stroke patients

	Graph based	Bar based	Worded	Numeric
Provides instruction of movement	Yes	Yes	No	Yes
Advises how to improve	Yes	Yes	Yes	Yes
Informs of one's performance	Yes	Yes	Yes	Yes
Informs of one's improvement	Yes	Yes	Yes	Yes
Data types	Graphical, continuous, qualitative	Graphical, discrete (snap shot), qualitative	Worded, discrete (snap shot), qualitative	Numeric, discrete (snap shot), quantitative
Requires calibration	No	No	Yes	No

There are many parameters in which feeding back information of patient performance to clinicians and researchers may be useful. Uses include allowing patient condition, performance and improvements to be monitored in more detail and more specifically. This could allow physiotherapists to give more useful feedback to stroke patients, for example of how to improve or to inform of improvements. It could also allow exercises or programs to be prescribed based on the individual patient's condition and situation. Such information may also be of use to researchers for example to allow the efficacy of a treatment regime to be investigated and to allow for optimisation. Once data corresponding to movement has been acquired, a virtually unlimited number of possibilities regarding processing, calculations and parameters to be assessed exist. Concepts for feedback for clinicians and researchers were generated, which are described below. These concepts were not evaluated because the specific system objective to include capability of detecting movement synergism had been established. However, they were included to help the potential of the system to be investigated. Also, the objective of detecting movement synergism was expanded upon conceptually.

Range of movement feedback concept for clinicians and researchers

This could be calculated by converting acceleration data to displacement through integration, and by converting angular velocity data from gyro sensors to angular displacement. Once displacement data has been obtained, mathematical functions from the

software package could be used to obtain the range of data values, which would correlate with the range of movement in an attempt to reproduce a target movement.

Mean velocity, peak velocity and time taken feedback concepts for clinicians and researchers

If the start and finish of the movement could be defined, the mean velocity along with the time taken to perform the movement could be calculated using mathematical functions from the software package. Identifying the start and finish of a movement would allow one movement attempt to be distinguished from another. The start and finish of a movement could be defined by programming a recognition system into the software program. This could be achieved, for example, by defining a threshold of shoulder extension, to be exceeded when a patient reaches forward. The movement could be considered to be occurring whilst the threshold was being exceeded, and then to end when the start position was returned to.

Spasticity feedback concept for clinicians and researchers

An element of spasticity is shake, which in terms of displacement, velocity or acceleration profiles, is a form of noise. The software packages identified previously are able to analyse noise in terms of extent present, frequency and amplitude using mathematical functions. Functions could therefore be used to analyse spasticity in more detail than could be done through visual observation. However, to achieve this, sensitive sensors would be required along with high sample rates.

Movement synergism feedback concept for clinicians and researchers

As proposed in section 2.8, the extent of movement synergism could also be defined as the extent that two or more DOFs were moving simultaneously. To measure movement synergism in this way, the time could be counted whilst two or more DOFs were moving simultaneously during a movement. This could be taken in terms of milliseconds, or iterations of the software program to give an output in the form of counts per movement. These counts could then be divided by the total movement time to aid with comparing one movement to the other if necessary. Also, movement synergism could be considered as when both joints were moving in the same direction, for example shoulder extension and

elbow extension, or in different directions, for example shoulder extension and elbow flexion. Movement synergism could therefore be considered to occur as either positive-positive, negative-negative, positive-negative, negative-positive or as general movement synergism which could include any of these. Each of these could be calculated by considering either positive or negative velocities or accelerations. Detection of movement synergism is discussed further in section 7.3.2.

Methods of delivering feedback to clinicians and researchers

Many of the methods of providing feedback to learners identified in section 2.5 could be beneficial in feedback to clinicians and researchers. For example KR feedback could be generated based on the number of times a target on a movement was reached by patients. KP feedback could also be generated describing any of the above concepts for feedback to clinicians and researchers. This could be done per movement attempt or with a bandwidth arrangement where feedback is given only when a threshold is exceeded. Summary feedback could be given, for example in graph form, to describe performance over a series of sessions. Average feedback could also be used to summarise a patient's condition.

3.5. Testing of sensors

Of the identified sensors, gyro sensors and flex sensors were of particular interest and are tested in this section. With gyro sensors, compared with accelerometers, their radius from the centre of rotation of the DOF theoretically does not affect readings. Also, gyro sensors are not affected by static angle relative to gravity. Flex sensors are of particular interest because they allow reading of movements at complicated DOFs such as the hand opening and closing.

Both the gyro sensor and the flex sensor met the design specification according to their respective data sheets (Brock, Goldie & Greenwood 2002) (Spectra Symbol 2010). However, performance in certain categories relevant to the design specification is not stated in the data sheets, for example the output characteristics of the gyro sensor when subjected to rotation and translation simultaneously. Sensor tests were therefore performed. This also allowed the general suitability of the sensors for measuring movement to be investigated

including aspects such as the required electric circuits and the voltage ranges of the flex sensor.

3.5.1. Objectives of sensor tests

The objectives of the tests were to investigate the following:

1. The linearity of the magnitude of the gyro sensor signal to the angular velocity applied
2. The effect on the gyro sensor signal of the introduction of translation in the same plane as rotation
3. The effect on the gyro sensor signal of the introduction of translation in a plane perpendicular to the plane of rotation
4. Hysteresis in the gyro sensor signal
5. Drift in the gyro sensor signal
6. Repeatability of the gyro sensor
7. The linearity of the magnitude of the flex sensor signal to the angular displacement applied
8. The responsivity of the flex sensor signal
9. Hysteresis within the flex sensor signal
10. Drift in the flex sensor signal
11. Repeatability of the flex sensor

3.5.2. Test rig

The test rig used for testing the sensors was originally designed for analysing bell clapper dynamics and consisted of two rotating elements which swung under gravity when released from angles other than the resting angles (see Figure 3.5.2a). The rig featured two rotating elements: an upper bell element (referred to as rotating element two) hinged from an 'A' frame, and a lower clapper element (referred to as rotating element one) hinged from the bell element. The rotating elements were connected to rotational potentiometers (referred to as potentiometer one and two) whose resistance varied in correlation to the angles applied. When supplied with a voltage through a voltage divider circuit, a varying voltage in

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correlation to angles applied was obtained. After calibration, this allowed angles with time to be measured using an oscilloscope.

Figure 3.5.2a. Bell clapper test rig in its original form

Modifications to the test rig

In order to allow the effects of an introduction of translation in a plane perpendicular to the plane of rotation to be analysed, the test rig was modified to allow rotating element one to swing in the plane perpendicular to that of rotating element two. The test rig was measured and five components were designed and constructed to allow this modification (shown in Figure 3.5.2b):

Figure 3.5.2b. Components constructed and sourced for modifications to the test rig

A simple bracket was also constructed to allow square and secure mounting of the gyro sensor to the test rig, either at zero radius relative to the axis of rotating element one, meaning the axis of rotation is central to the gyro sensor, or at an adjustable radius, resulting in translation in the same plane as rotation (in-plane translation).

Figure 3.5.2c. Test rig after modifications showing rotating element one in motion

Figure 3.5.2d. Test rig after modifications showing rotating element two in motion

As shown in figures 3.5.2c and 3.5.2d, rotating element one was rotated through 90 degrees about a vertical axis. The test rig was also modified to allow mounting of the flex sensor with dimensions to simulate the human hand, and the simplification of hand movement described in section 3.2.2 was again adopted. To achieve this, a zip tie, G-clamp and spacer were used (see Figure 3.5.2e). Rotating element two was secured with a second G-clamp during all flex sensor tests.
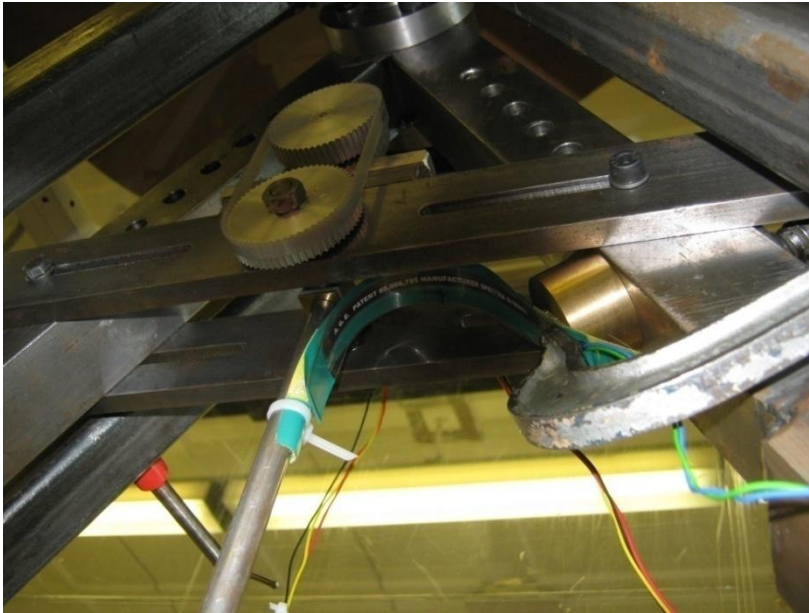
Figure 3.5.2e. Flex sensor mounted to test rig

Figures 3.5.2f to 3.5.2i show the test rig after modifications.
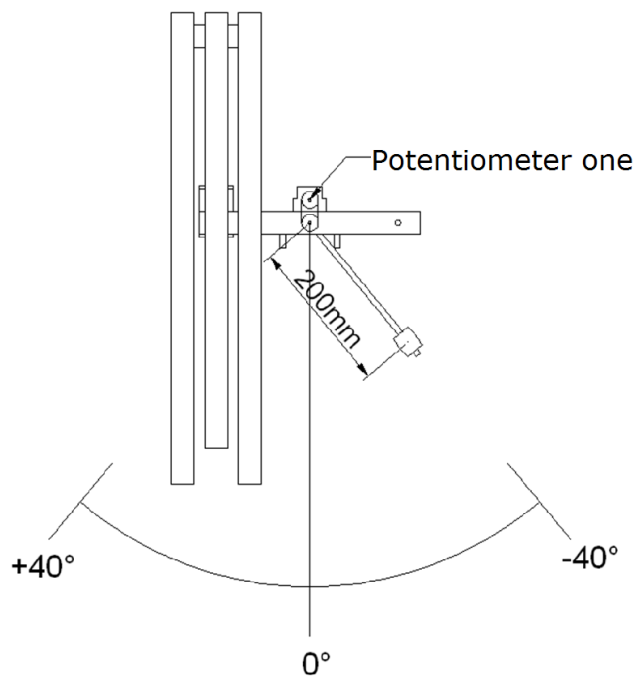
Figure 3.5.2f. Test rig after modifications for gyro sensor tests showing rotating element one at -40 degrees, the location of potentiometer one and the radial distance which the gyro sensor can be mounted at
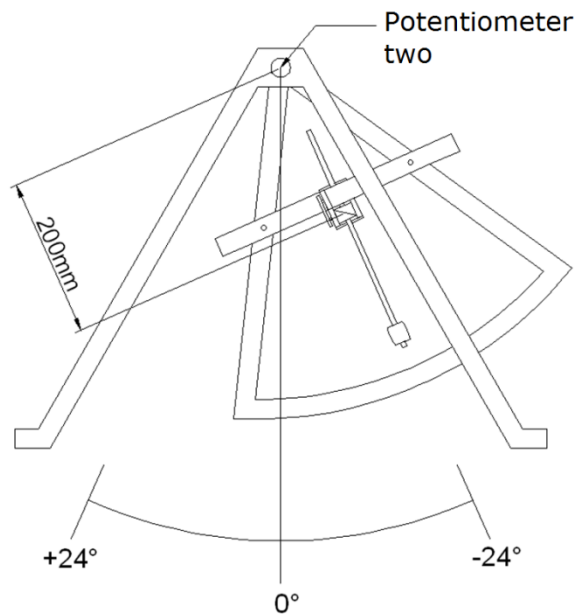
Figure 3.5.2g. Test rig after modifications for gyro sensor tests showing rotating element two at -24 degrees, the location of potentiometer two and the radial distance of element one from element two
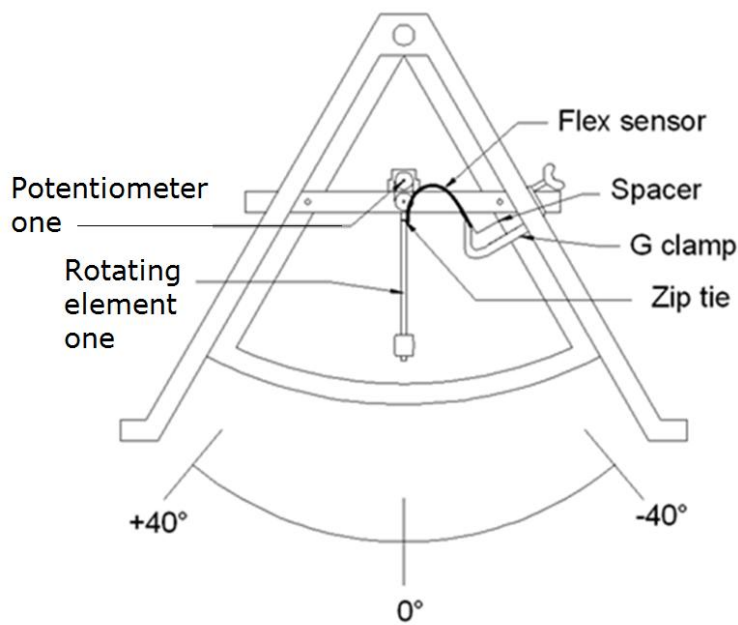
Figure 3.5.2h. Test rig after modifications for flex sensor tests showing rotating element one resting at zero degrees and rotating element two fixed

It can be seen that rotating element one rotates in plane one and rotating element two rotates in plane two (shown in Figure 3.5.2i). The corresponding responses of the gyro sensor are shown in Figure 3.5.2j.
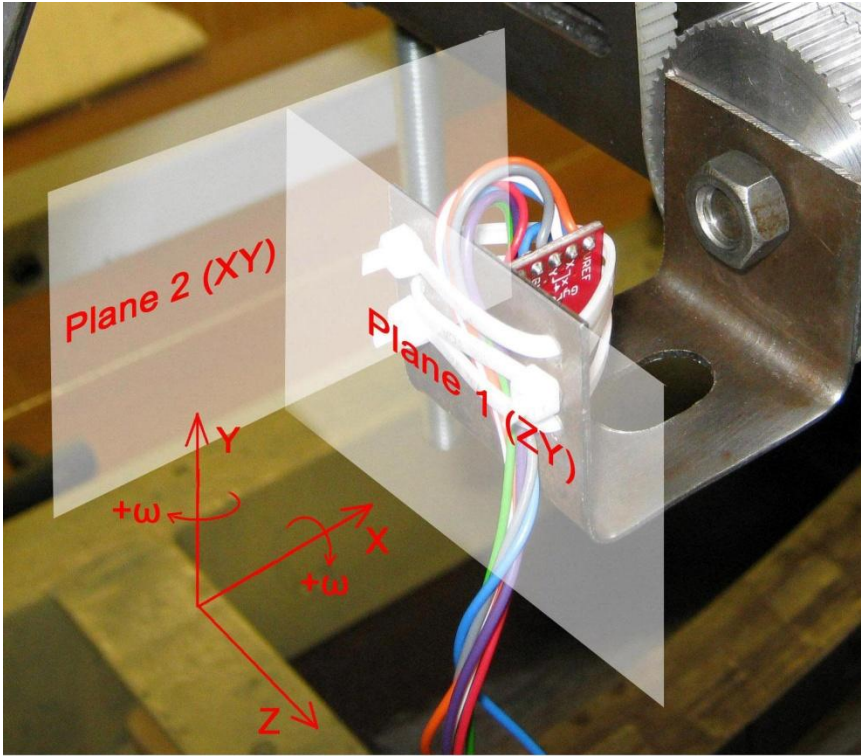
Figure 3.5.2i. Gyro sensor mounted at zero radius, plane one, perpendicular plane two, axes and rotational inputs sensed by the gyro sensor relative to test rig
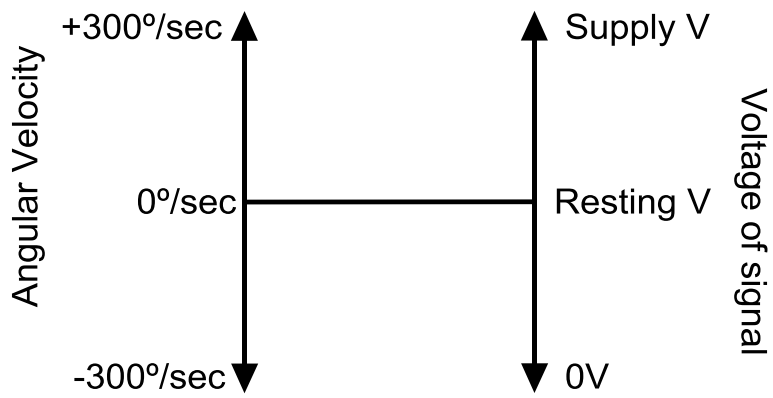
Figure 3.5.2j. Angular velocities inputted to the gyro sensor and the corresponding signals (Spectra Symbol 2010)

Electrical test circuits

Electric circuits were designed and constructed. Characteristics sought during designing the circuits were simplicity, noise minimisation and consistent supply voltage to the sensors. The electric test circuit for the gyro sensors is shown in Figure 3.5.2k.
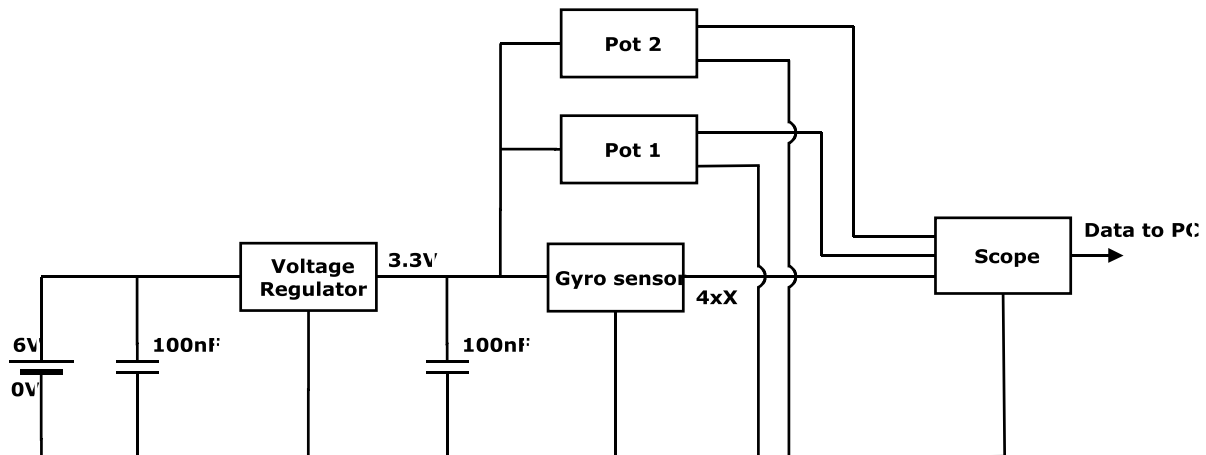
Figure 3.5.2k. Gyro sensor electrical test circuit

The power supply and potentiometers in the gyro sensor electrical test circuit allow a signal to be generated during rotation. The capacitors act as a buffer to minimise noise and the voltage regulator ensures voltage consistency at 3.3 V and prevents accidentally applying too large a voltage to the sensor and potentiometers. The oscilloscope records output signals with time from the gyro sensor and potentiometers. A photo of the circuit for the gyro sensors is shown in Figure 3.5.2l, and the electrical test circuit for the flex sensors is shown in Figure 3.5.2m.
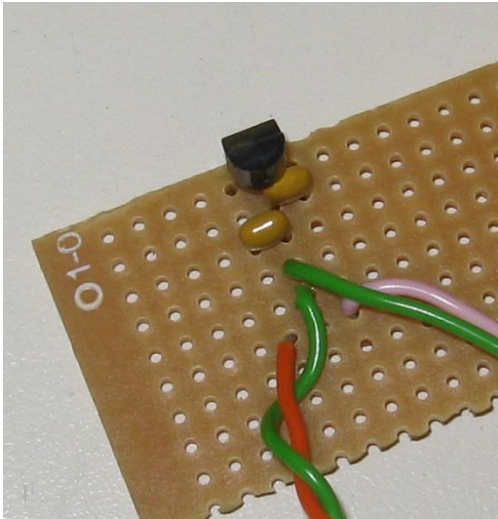
Figure 3.5.2l. Voltage regulator and capacitors soldered to a breadboard in the gyro sensor electrical test circuit
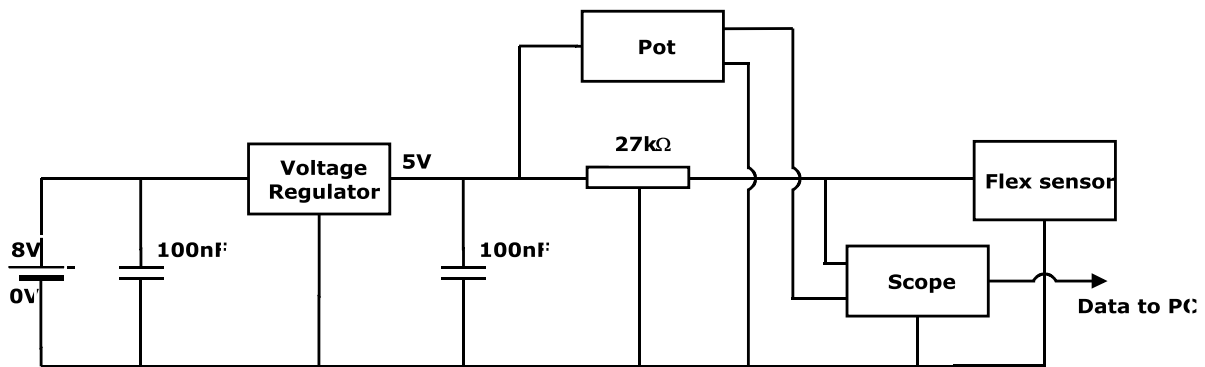
Figure 3.5.2m. Flex sensor electrical test circuit

The flex sensor electrical test circuit was similar to that of the gyro sensor. A 5 V voltage regulator was specified in this case, in order to increase the range of the output voltage. A simple voltage divider arrangement was implemented. A resistor whose value was as close to the middle of the range of resistance of the flex sensor as possible was selected. This again allows the largest range of output voltages. The resistance of the flex sensor was measured using a multi-meter at -40 degrees as approximately 36kΩ and at +40 degrees as approximately 14kΩ. 36 + 14 = 50. 50/2 = 25kΩ. The closest single resistor available was a 27kΩ resistor which was considered close enough to 25kΩ to allow for a linear output. The equipment used during testing of the sensors is listed in Table 3.5.2, and the test rig set up for testing the gyro sensor is shown in Figure 3.5.2n.

Table 3.5.2. Equipment used during the sensor tests

Equipment	Model
Gyro sensor	Sparkfun LPR530AL Dual Axis 300 degree/second Breakout Board (STMicroelectronics 2009)
Flex sensor	Spectra Symbol 4.5" flex sensor (Spectra Symbol 2010)
Oscilloscope	Tektronix TDS 1014B 100MHz 4 Channel Digital Storage (2500 samples/channel)
Power supply	Skytronic Adjustable Power Supply with digital display
Voltage regulators	TSC TS2950CT-XX 150mA Ultra Low Dropout Positive (Taiwan Semiconductor Company 2003)
Potentiometers	Vishay Spectrol Precision Industrial Potentiometer Model 157 (Vishay Spectrol 2007)
Multi-meter	Edison DM 664

Figure 3.5.2n. Test rig with equipment and electrical test circuit set up for the gyro sensor tests

3.5.3. Test methodology

Initial equipment setup involved measuring the test equipment and centralising any adjustable components. The angle limits of rotating element one were also set during gyro sensor testing. The supply voltage was set to 6.0 V during gyro sensor testing and 8.0 V during flex sensor testing. This is due to the higher rating of the voltage regulator used during the flex sensor tests. The linearity of the potentiometers was assessed by measuring

potentiometer voltages at both extreme angles and at resting angles. The voltages from potentiometer one were:

- At -40 degrees: 1.560 V
- At 0 degrees: 1.935 V
- At +40 degrees: 2.304 V

The linearity of the potentiometer was checked by taking the mean of the voltage at -40 and +40 degrees, and comparing the value with the voltage at zero degrees. This gives a value relating to the non-linearity:

$$\frac{2.304V + 1.560V}{2} = 1.932\ V$$

$$\left(\left(\frac{1.935V}{1.932V}\right) - 1\right) \times 100 = 0.155\%$$

As this percentage is small, the linearity of the potentiometers was considered satisfactory.

The resting voltages were measured as 3.29 V at the gyro sensor and 4.98 V at the flex sensor. The rotating elements were moved into the required starting positions and released by hand which was withdrawn fast to minimise interference with the resulting pendulum motion. The oscilloscope was set to take a rolling sample and was paused manually at a time appropriate to capture the required data. This allowed data from the channels to be recorded from within the same time period. 2500 voltage readings were taken at each channel during each recording sequence. The sample interval was varied depending on the duration of recording required. Data was then transferred from the oscilloscope via USB as Comma Separated Variables (CSV) format files. Mathematical and graphical analysis was then carried out using Microsoft Excel software. The graphs are vertically zeroed, where the resting position was vertically offset to zero, by subtracting the values of the resting voltages from all data values from the respective sensors. This aids the process of comparing the signals. Also, potentiometer data sets are vertically inverted as required, to ensure a

positive angular displacement results in an increase in signal magnitude, and vice versa. The signal from the flex sensor was also inverted for the same reason.

To allow the objectives of the tests to be achieved, the following tests were performed:

- Gyro sensor test 1. Basic response
- Gyro sensor test 2. In-plane translation
- Gyro sensor test 3. Translation in the perpendicular plane
- Flex sensor test 1. Basic response
- Flex sensor test 2. Flexed drift
- Flex sensor test 3. Extended drift

Gyro sensor test 1. Basic response

The objective of this test was to investigate the response whilst rotating about an axis central to the gyro sensor. Rotating element two was locked by inserting the G clamp. Also, the gyro sensor was mounted at zero radius relative to the axis of rotating element one. The sample interval was set to 2 ms. Rotating element one was then released from -40 degrees and allowed to oscillate under gravity. Figure 3.5.3a shows the response:
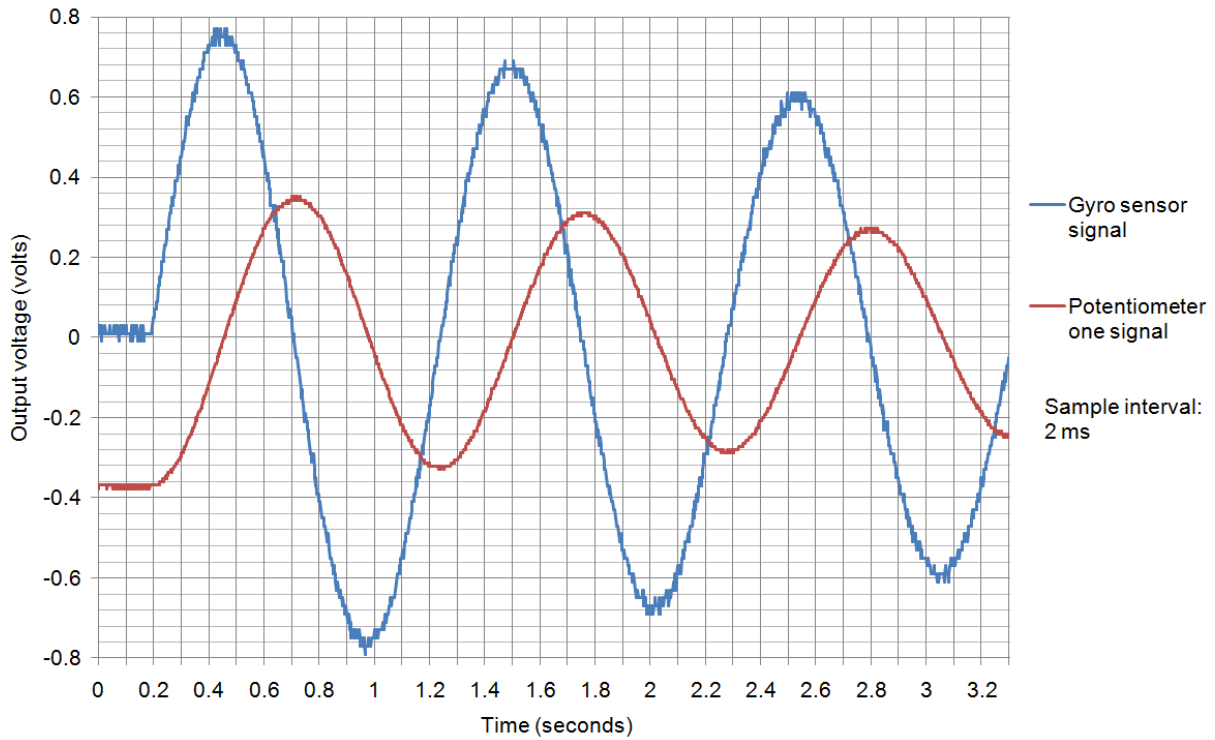
Figure 3.5.3a. Rotating element one released from -40 degrees, gyro sensor at zero radius

As expected, the decaying sinusoidal waveforms were out of phase by approximately 90 degrees due to the magnitude of the signal from the potentiometer being generated from angular displacement and that of the gyro sensor being generated from angular velocity. Also, there are three peaks and three troughs visible. To aid the process of signal comparison, the curve of the signal from the gyro sensor was then integrated to give curve of angular displacement. This was achieved by sequentially adding the data values recorded from the gyro sensor. The data was then vertically scaled to match the potentiometer signal as closely as possible (see Figure 3.5.3b):
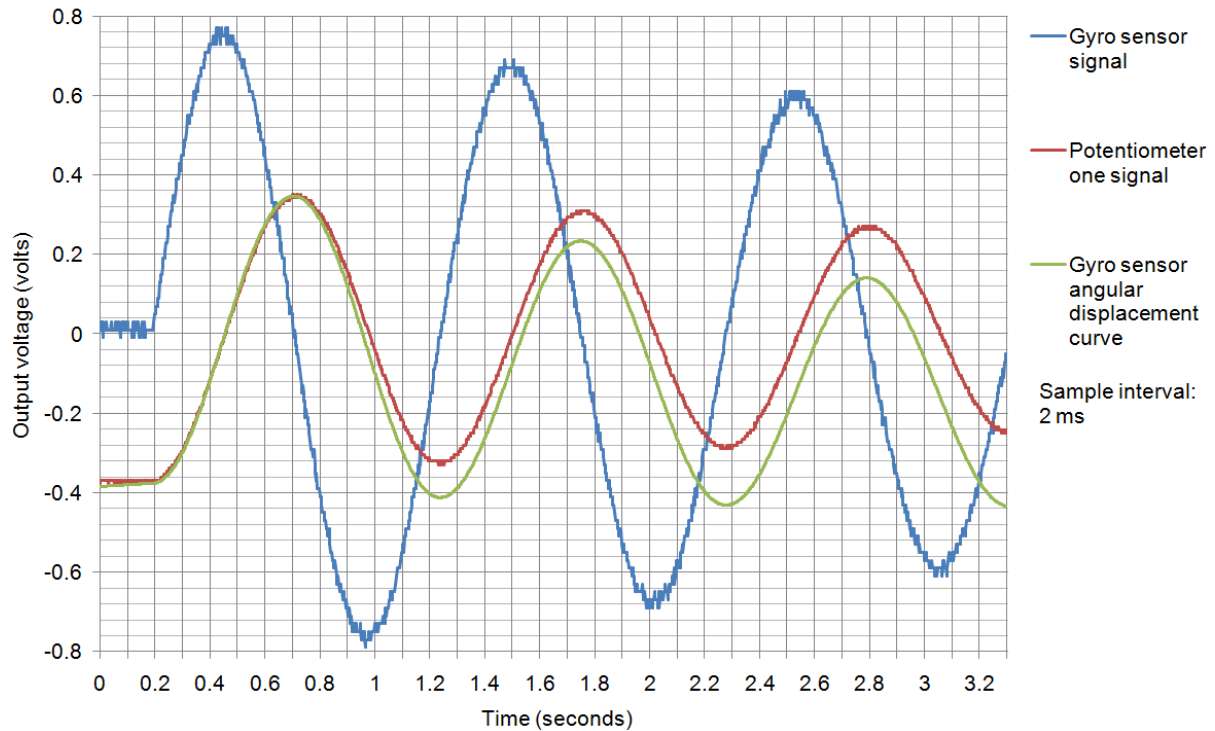
Figure 3.5.3b. Rotating element one released from -40 degrees, gyro sensor at zero radius with angular displacement curve calculated from gyro sensor data

As can be seen in Figure 3.5.3b, the gyro sensor angular displacement curve appears to drift downwards with time when compared to the curve from the potentiometer signal. This suggests that the signal from the gyro sensor is not entirely proportional to angular velocity. It was noted that integration results in errors being carried forward over the following data values.

Gyro sensor test 2. In-plane translation

The objective of this test was to investigate the effects of the introduction of in-plane translation. The gyro sensor was mounted at a 200mm radius relative to the axis of rotating element one. Rotating element one was again released from -40 degrees and allowed to oscillate. Figure 3.5.3c. shows the response:
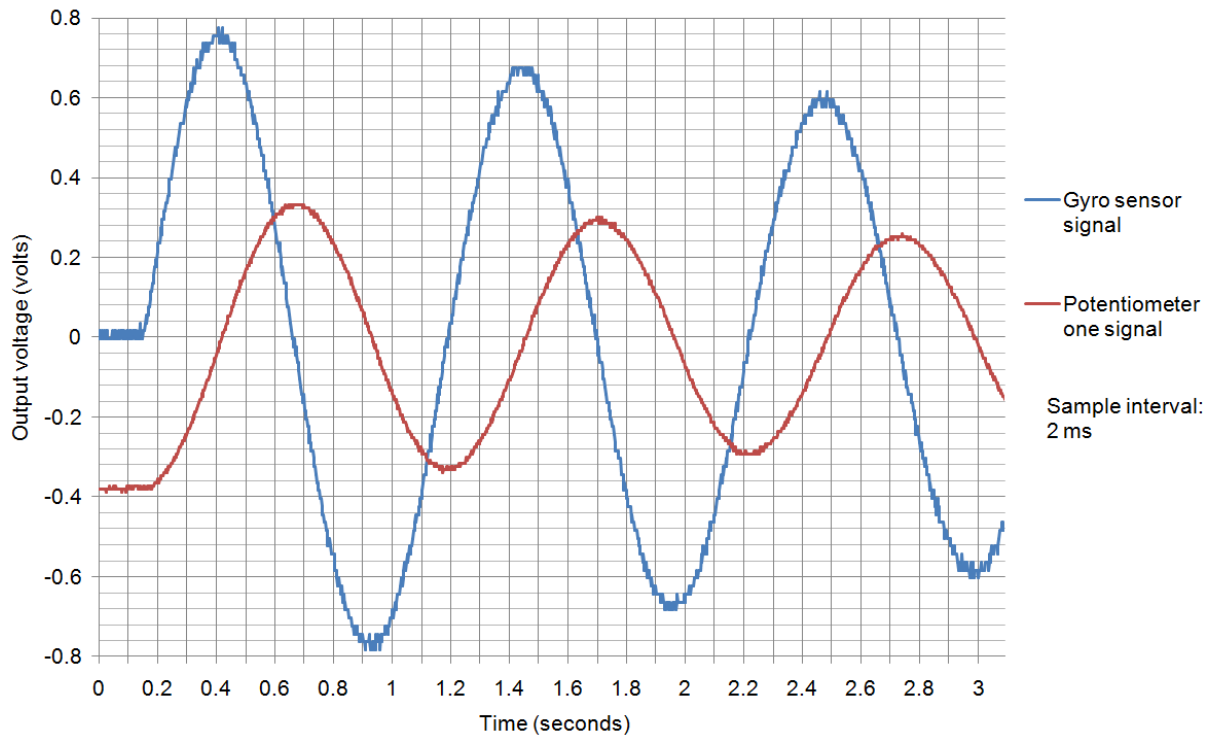
Figure 3.5.3c. Rotating element one released from -40 degrees, gyro sensor at a 200mm radius

As shown in Figure 3.5.3c, the behaviour is similar to that of when the gyro sensor was set at zero radius. The curve from the signal from the gyro sensor was again integrated to give a curve relating to angular displacement (shown in Figure 3.5.3d):
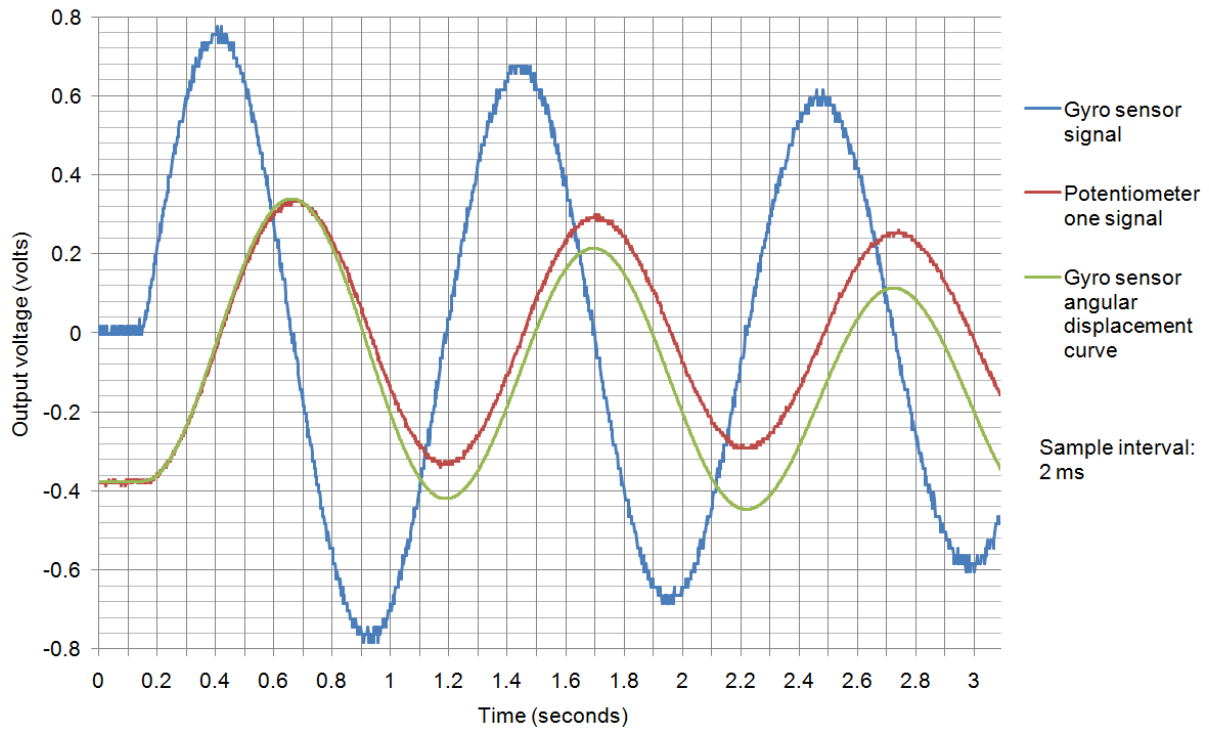
Figure 3.5.3d. Rotating element one released from -40 degrees, gyro sensor at a 200mm radius and angular displacement curve calculated from gyro sensor data

As can again be seen in Figure 3.5.3d, the gyro sensor angular displacement curve appears to drift downwards with time when compared to the curve from the potentiometer signal.

To further aid the comparison of the basic response with the response when in-plane translation is also present, the voltage trace from the gyro sensor at zero radius was overlaid onto that of the gyro sensor at a 200mm radius. The release times were then graphically synchronised by horizontally displacing the trace from the gyro sensor at zero radius.
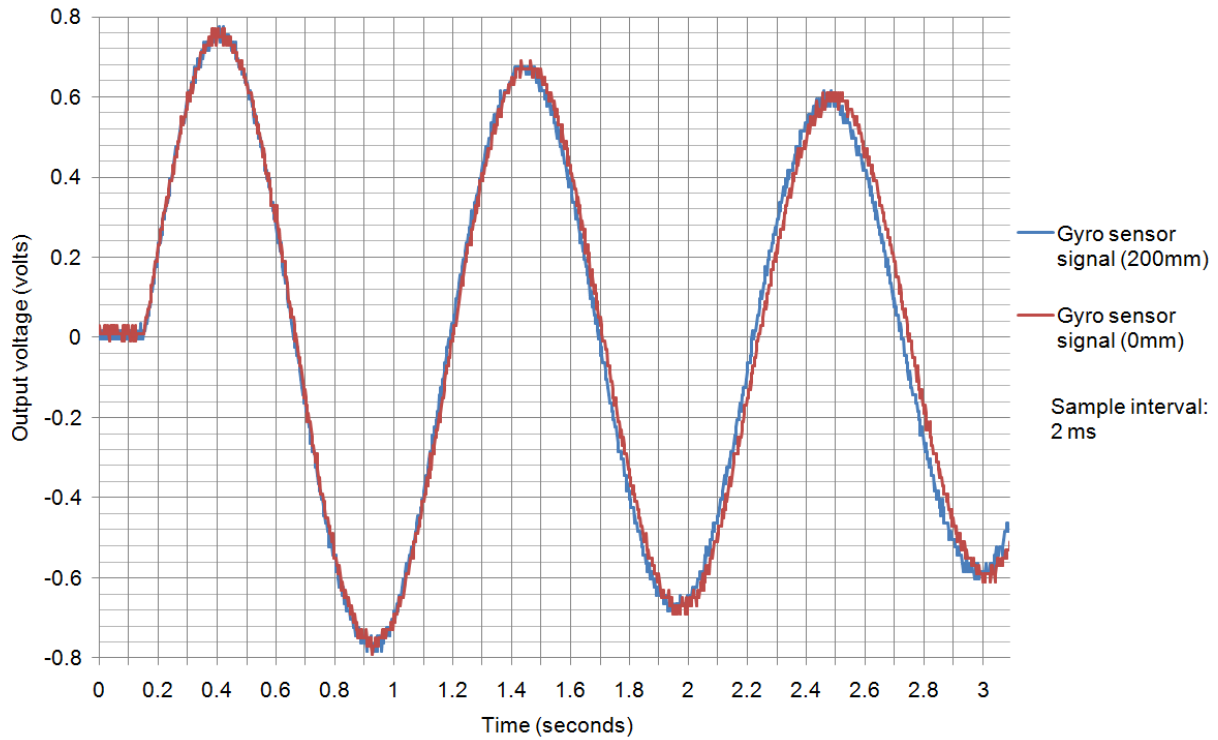
Figure 3.5.3e. Rotating element one released from -40 degrees, signal traces from gyro sensor at 200mm and at 0mm radii

Figure 3.5.3e shows that the gyro sensor outputs were largely identical, particularly during the first time period of the waveform. There appears to be none or very little interference caused by the introduction of in-plane translation.

Gyro sensor test 3. Translation in the perpendicular plane

The objective of this test was to investigate the effects of the introduction of translation in a plane perpendicular to the plane of rotation. Rotating element two was unclamped and rotating elements one and two were then released from -40 and -24 degrees respectively and allowed to oscillate.
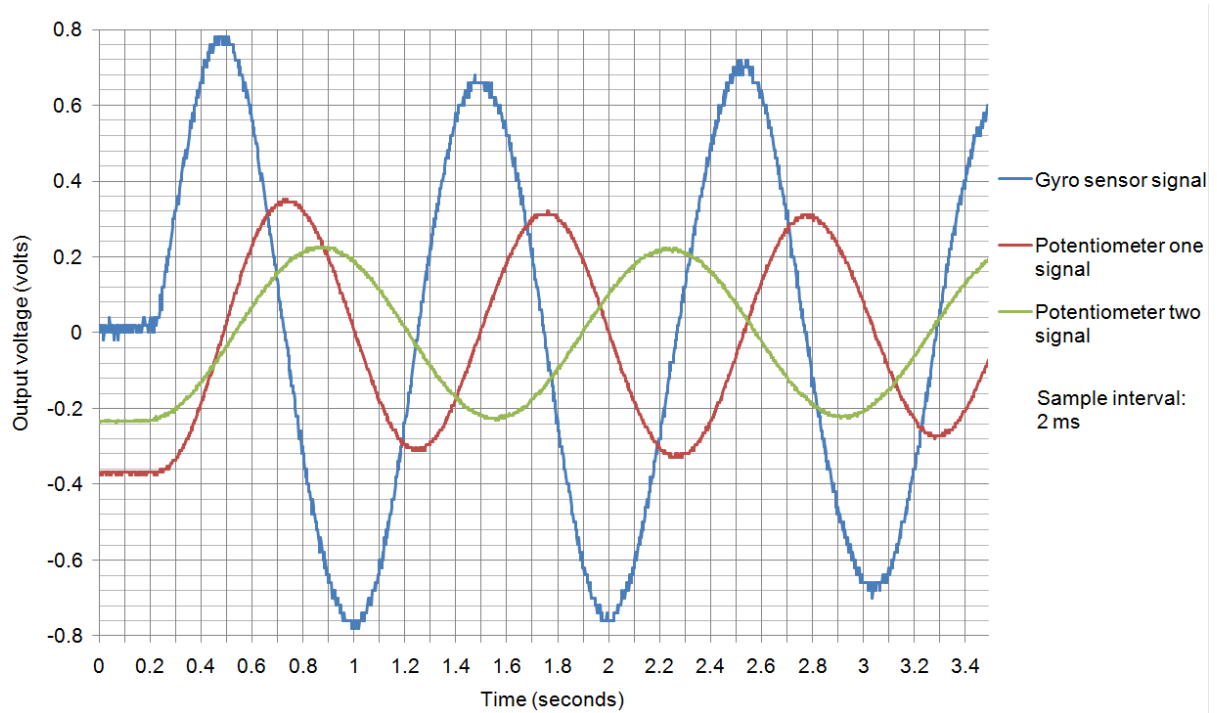
Figure 3.5.3f. Rotating elements one and two released from -40 and -24 degrees respectively, gyro sensors at a 200mm radius

It can be seen in Figure 3.5.3f that the waveform from potentiometer two is at a lower frequency. This is as expected because rotating element two has a larger distance from its axis of rotation to its centre of mass than that of rotating element one. The curve of the signal from the gyro sensor was again integrated to give a curve relating to angular displacement.
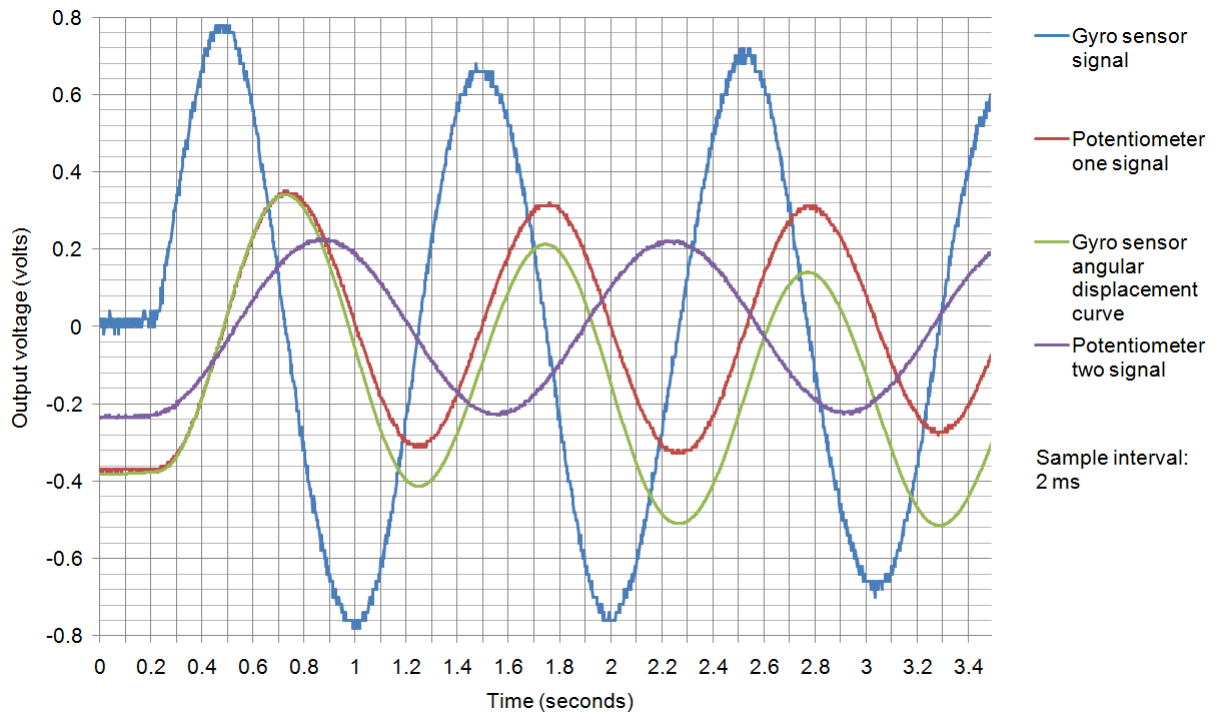
Figure 3.5.3g. Rotating elements one and two released from -40 and -24 degrees respectively, gyro sensor at a 200mm radius and angular displacement curve calculated from gyro sensor data

Figure 3.5.3g again shows that the gyro sensor angular displacement curve appears to drift downwards with time when compared to the curve from the potentiometer signal. To further aid signal comparison, the curve from the signal from the potentiometer was then differentiated to give a curve relating to angular velocity. This was achieved by calculating a moving average angular velocity over the data samples. The differentiated signal was then vertically scaled to match the gyro sensor signal as closely as possible.
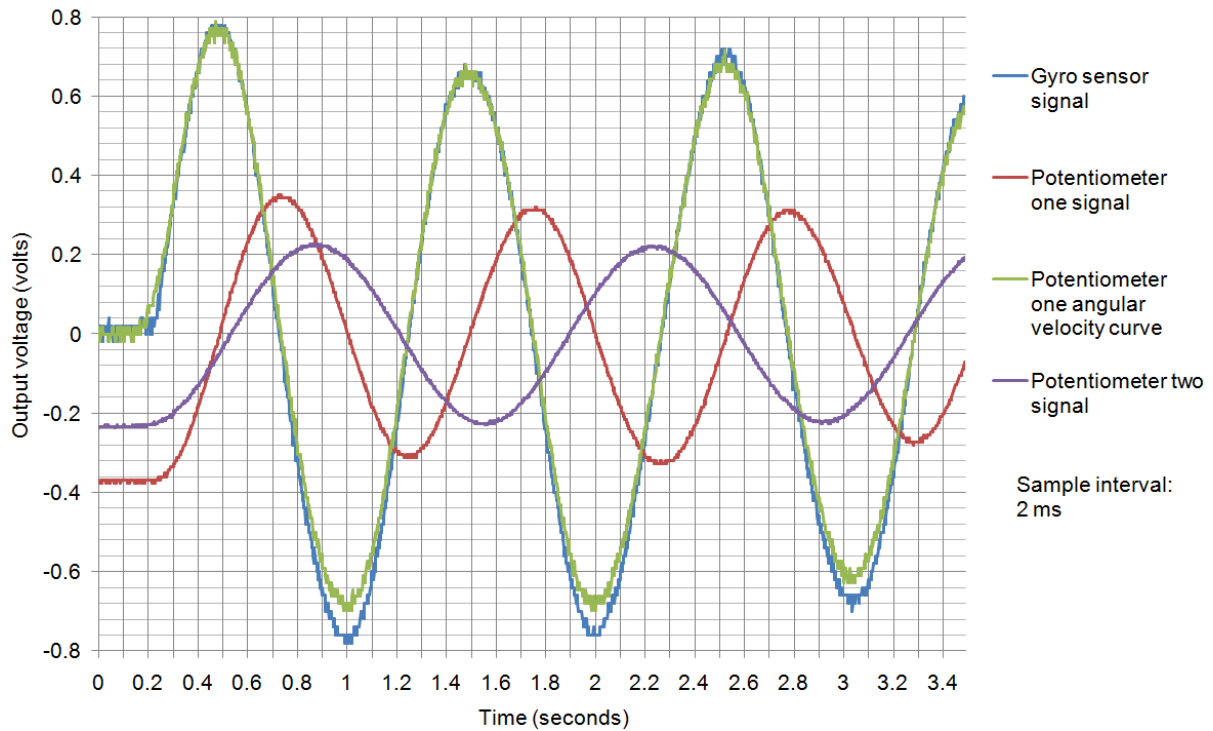
Figure 3.5.3h. Rotating elements one and two released from -40 and -24 degrees respectively, gyro sensor at a 100mm radius and differentiated angular velocity curve calculated from potentiometer one data

It can be seen in Figure 3.5.3h that the magnitude of the gyro sensor signal is disproportionally large compared to the velocity calculated from the potentiometer one data at all three troughs of the curve. The gyro sensor was therefore giving slightly disproportional responses (lower voltages) when being subjected to negative angular velocities. However, there appears to be no significant interference caused by the addition of the rotation of element two. The signal responses from the gyro sensor during movement of rotating element one and that during movement of both rotating elements were not compared to one another as it is likely that perpendicular rotation will have slightly affected the pendulum motion.

In order to highlight any unwanted signal generation from the gyro sensor during translation in the perpendicular plane, rotating element two only was then released from -24 degrees. This means that the only movement was translation in the perpendicular plane.
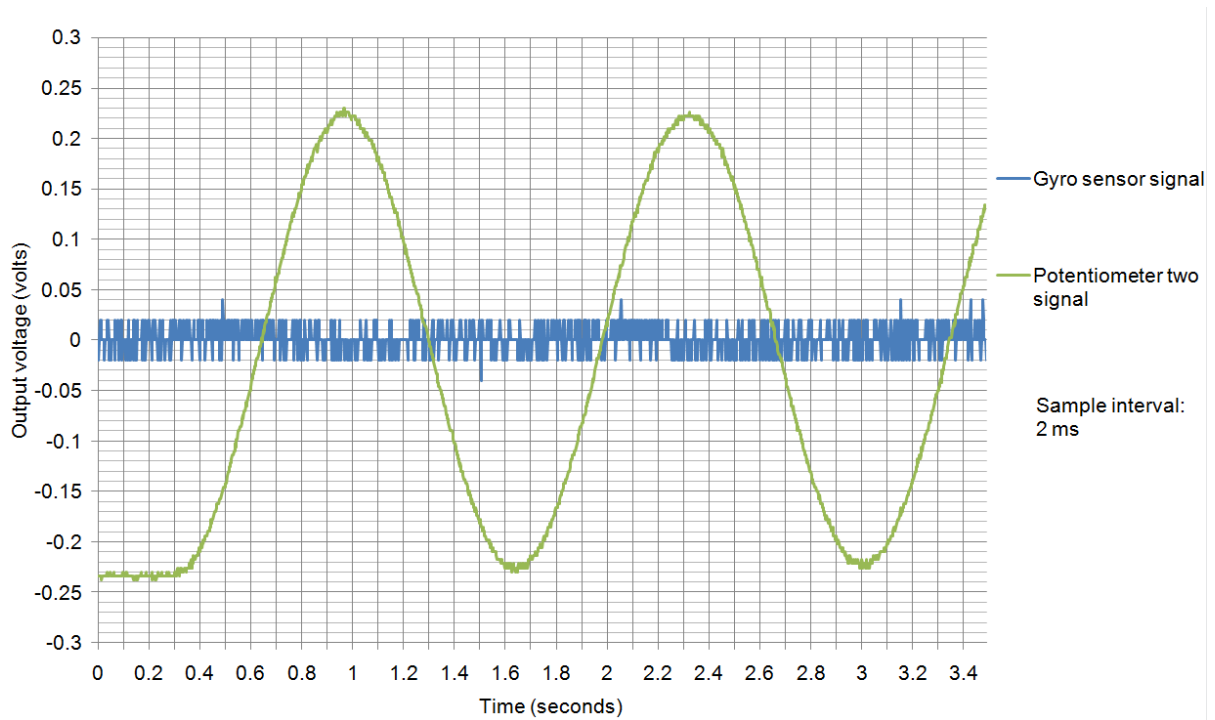
Figure 3.5.3i. Rotating element two released from -24 degrees, gyro sensor at a 200mm radius

As shown in Figure 3.5.3i that the translation in the perpendicular plane has no visible effect on the signal from the gyro sensor.

Flex sensor test 1. Basic response

The flex sensor was then inserted into the test rig as shown in Figure 3.5.2e. Rotating element one was then released from -40 degrees and allowed to oscillate.
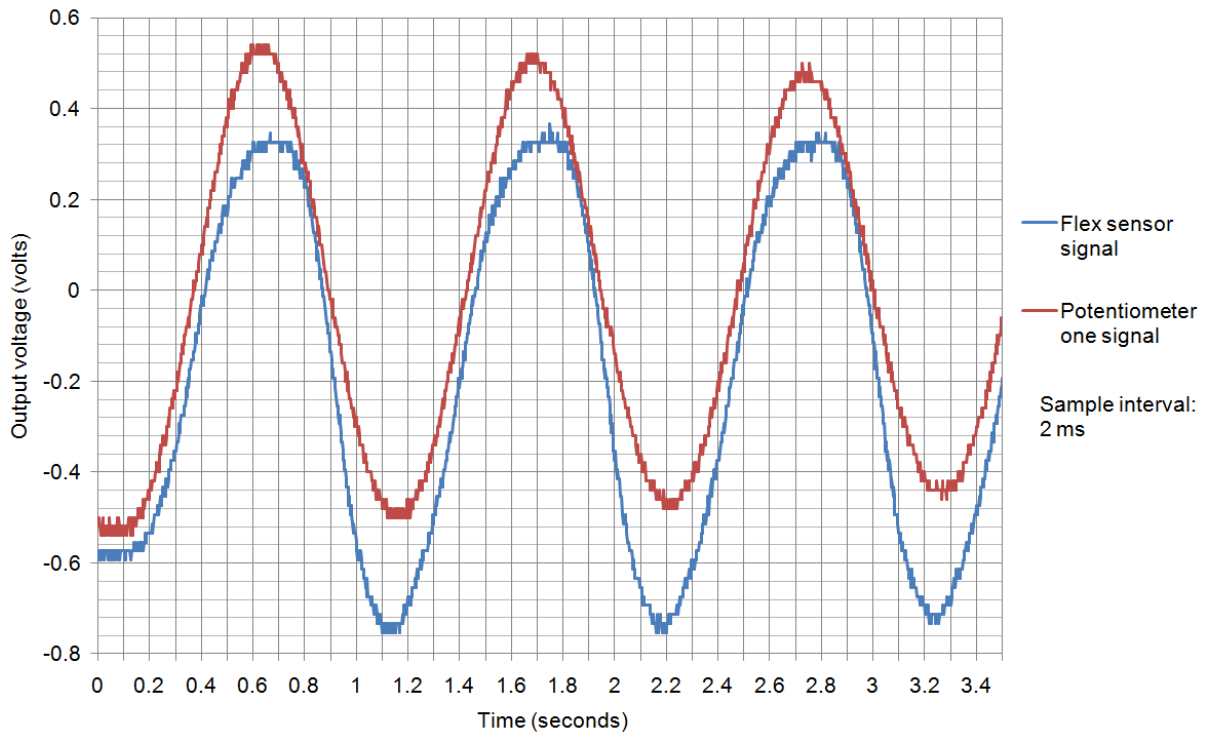
Figure 3.5.3j. Rotating element one released from -40 degrees

Both signals are in phase due to their magnitudes being generated from angular displacement (see Figure 3.5.3j). Also, there are three peaks and three troughs clearly visible. To aid the process of signal comparison, the signal from the flex sensor was vertically scaled and offset to match that of the potentiometer as closely as possible.

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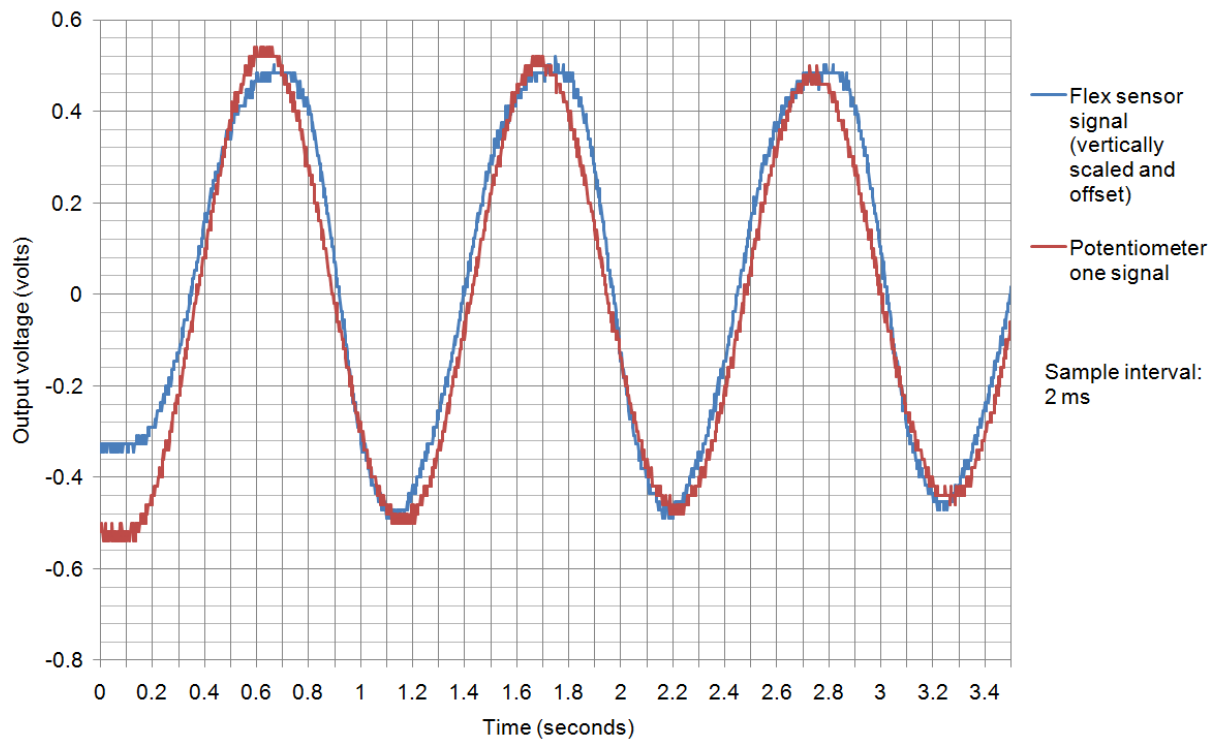
Figure 3.5.3k. Rotating element one released from -40 degrees, flex sensor signal vertically scaled and offset

As shown in Figure 3.5.3k, the flex sensor signal was early during positive displacements and late during negative displacements. These time differences appear to be consistent. Also the signal from the flex sensor is higher than that of the potentiometer before release.

The calculated angles at the start and end of the first positive phase of angular displacement were read as approximately -40 degrees and +40 degrees, giving a total angular displacement of 80 degrees. The corresponding signal samples from the flex sensor before inversion and zeroing were read as 2.70 V at -40 degrees and 1.84 V at +40 degrees giving a voltage range of 0.86 V. This gives an average change of 0.01075 V per degree, or 10.75 mV per degree.

Flex sensor test 2. Flexed drift

The sample interval of the oscilloscope was increased to 10 ms. Rotating element one was moved from 0 to -40 degrees and held at that position.
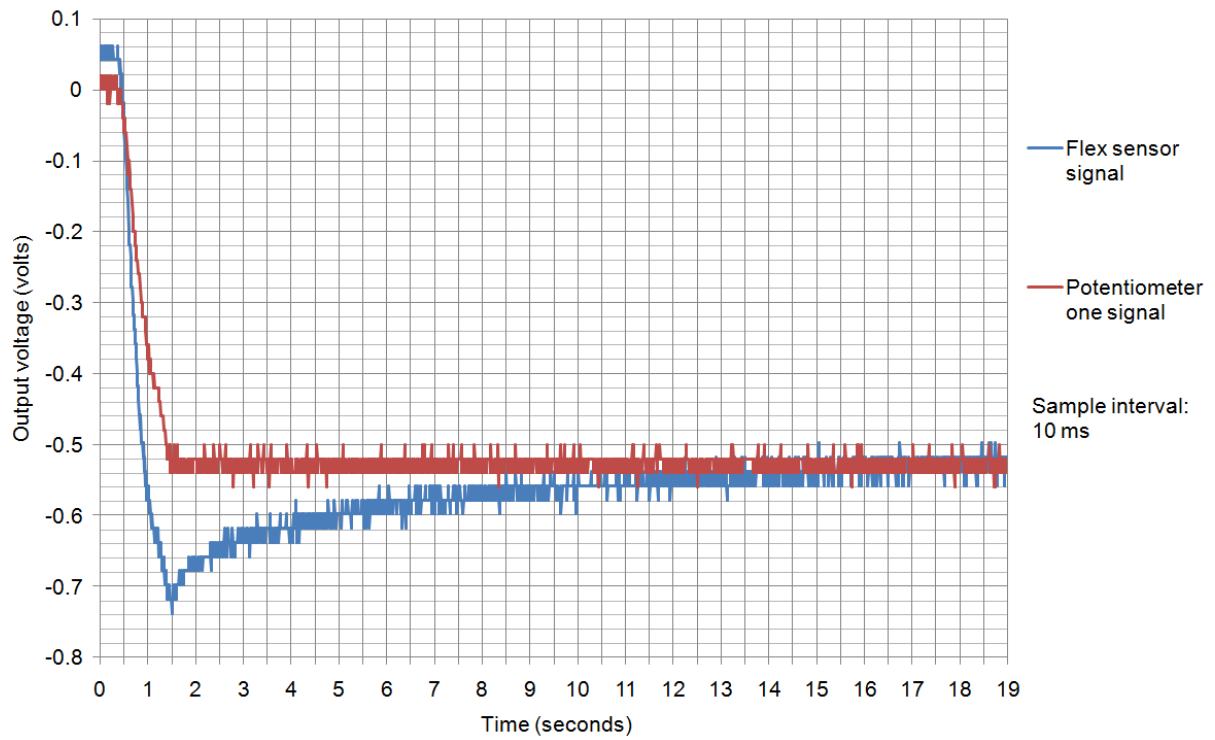
Figure 3.5.3l. Rotating element one moved from 0 to -40 degrees and held

It can be seen in Figure 3.5.3l that there is some drift which reduces over a long duration and appears to settle after approximately 16 seconds.

Flex sensor test 3. Extended drift

This time, rotating element one was moved from 0 to +40 degrees and held at that position.
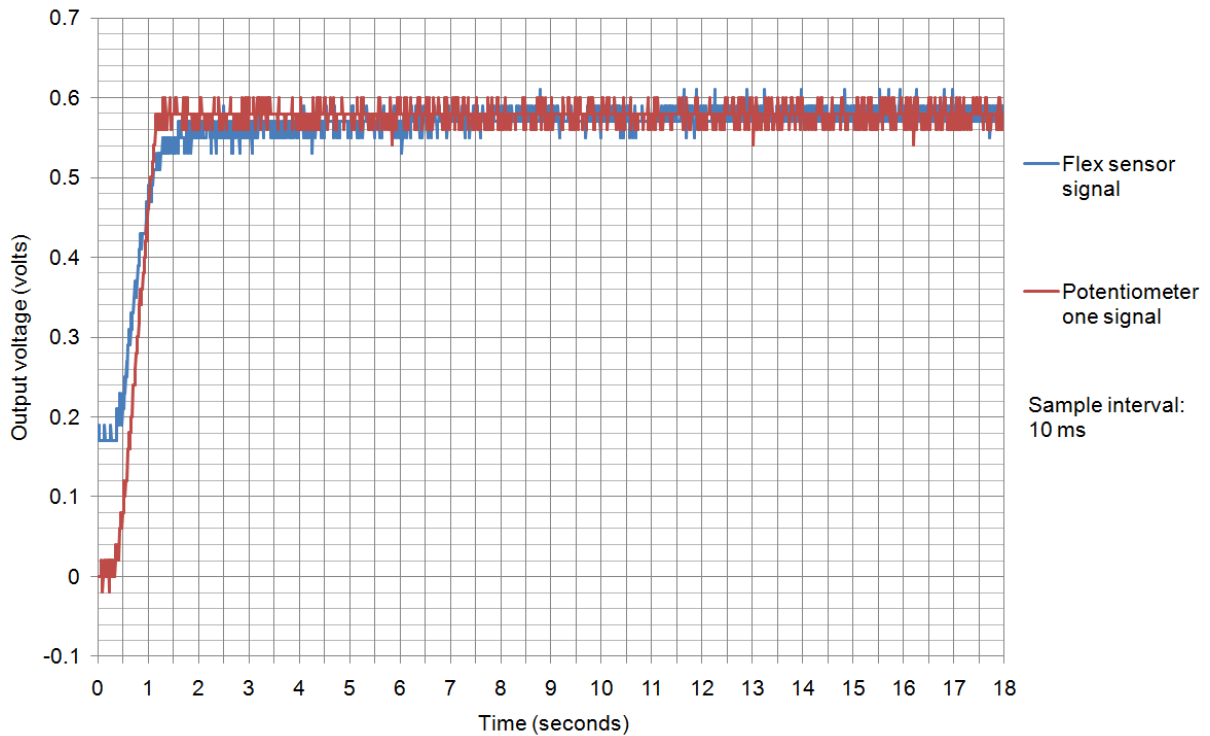
Figure 3.5.3m. Rotating element one moved from zero to +40 degrees and held

Figure 3.5.3m shows that there is some drift which reduces over time and appears to settle after approximately 8 seconds.

Limitations

- Only the X axis of the gyro sensor was tested. However, both axes are described as performing identically (STMicroelectronics 2009).

- The effect of rotating about the Y axis at the same time as the X was not tested. However, it is thought that it would cause little effect because the mechanisms are separate for each axis, and very little current is drawn by the gyro sensor.

3.5.4. Conclusions from sensor tests

This section describes the conclusions that were drawn in relation to the objectives of the tests.

1. The linearity of the response of the gyro sensor to the applied angular velocity

The magnitude of the gyro sensor signal was proportional to the applied velocity except at negative angular velocities. At this time, it was slightly disproportionally large. This could, to an extent, be compensated for mathematically if required by periodically zeroing the signal by subtracting the resting value.

2. The effect on the gyro sensor of the introduction of translation in the same plane as rotation

The introduction of translation in the same plane as rotation appeared to have no effect.

3. The effect on the gyro sensor of the introduction of translation in a plane perpendicular to the plane of rotation

The introduction of translation in a plane perpendicular to the plane of rotation appeared to have no effect.

4. Hysteresis in the gyro sensor signal

The magnitude of the gyro sensor signal was proportional to the applied velocity apart from being slightly disproportionally large at negative angular velocities. This could be considered a form of hysteresis.

5. Drift in the gyro sensor signal

When angular displacement with time was calculated, the disproportional behaviour described above resulted in a calculated angular displacement that drifted negatively with time. As stated, this could, to an extent, be compensated for mathematically if required.

6. Repeatability of the gyro sensor

When the traces were overlaid from the gyro sensor from two separate movements, the traces overlapped very closely. This suggests that outputs from the sensor are repeatable. Also, behaviour appeared repeatable over multiple oscillations of the rotating elements.

7. The linearity of the magnitude of the flex sensor signal to the applied angular displacement

The response from the flex sensor was slightly early during positive movement and slightly late during negative movement. However, it was thought that this would not affect performance negatively because the output appeared repeatable.

8. The average responsivity of the flex sensor signal

The average responsivity was approximately 0.01075 V per degree or 10.75 mV per degree. Knowing this aided the process of specifying signal multiplication factors in the software programs for the prototype system described in section 3.6.4.

9. Hysteresis within the flex sensor signal

The slightly early and late responses from the flex sensor described above could be considered a form of hysteresis. However as stated, it was thought that this would not affect performance negatively because the output appeared repeatable.

10. Drift in the flex sensor signal

Some drift was present, but appeared to settle after approximately 16 seconds when held extended, and 8 seconds when held flexed. However, the magnitude of the drift was small relative to the magnitude of the response due to movements. It was therefore concluded that the effect when measuring movements would be minimal.

11. Repeatability of the flex sensor

The behaviour appeared repeatable over multiple oscillations of the rotating element (see Figure 3.5.3k).

From these findings, the gyro sensor and flex sensor were considered to meet the requirements stated in the design specification, and were therefore concluded as suitable for use in the prototype system.

3.6. Description of the prototype system

This section describes the embodiment system, or prototype system for testing, in terms of features and advantages with respect to the system objectives and design specification. Shortcomings with respect to the design specification and completion of the system objectives are discussed in section 7.2. First, a summary of the prototype system as a whole is given, followed by more detailed descriptions of movements, hardware, feedback and software.

3.6.1. Summary of the prototype system

As concluded from the information review, because the aim of regular physiotherapy is to improve, the aim could also be considered as to allow target movements to be conformed to more closely than if physiotherapy was performed by the patient on their own. In this way independence, the overall aim of stroke physiotherapy, is improved by improving performance during physiotherapy, as a result of conforming more closely to target movements. This is achieved by guidance provided by the physiotherapist which enhances motor learning. It is by these principles that the prototype system aimed to function.
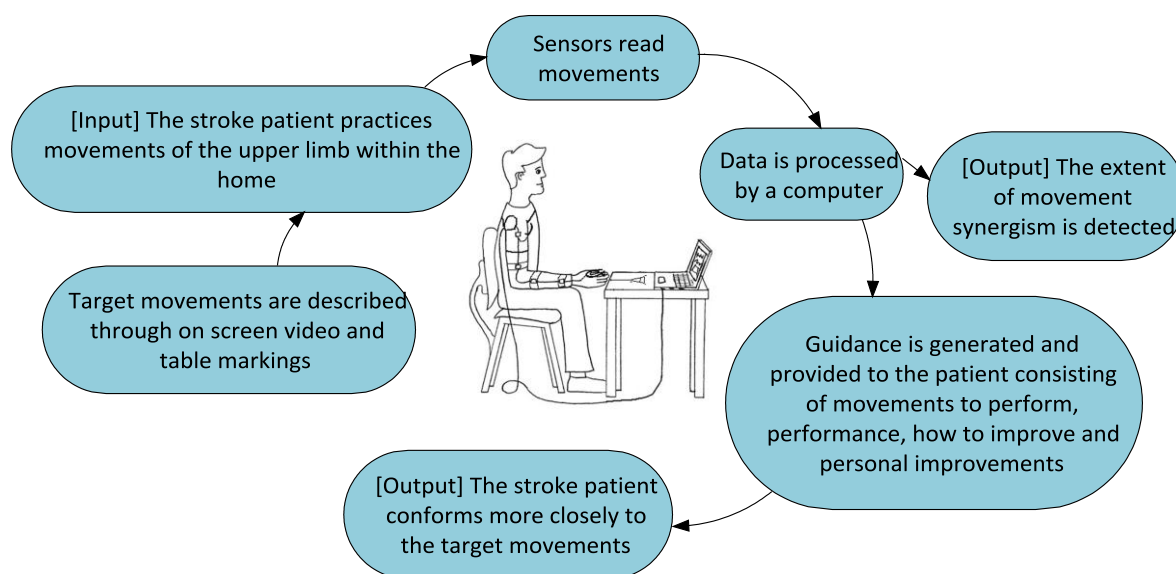
Figure 3.6.1a. Description of the main mechanisms of the prototype system

Figure 3.6.1a is an adapted version of Figure 3.2.1 which was used to describe the mechanisms of the initial system concept. Established details have been added. During

physiotherapy, patients sit at a table with a computer screen on which feedback is provided. The table also shows movement guidance markings as shown in Figure 3.6.1b. The reach distance could be varied according the user's individual anthropometric dimensions, described further in section 6.3.6.
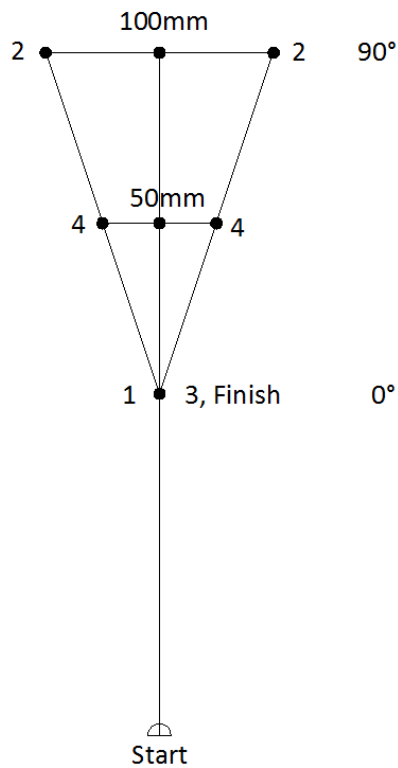
Figure 3.6.1b. Movement guidance markings shown on the table top

During physiotherapy, videos could be viewed of target movements in relation to the guidance markings shown in Figure 3.6.1b. The start position shown in Figure 3.6.1b was aligned with the edge of a table top. The numbered positions shown are then moved between and the start position is then returned to. The prototype system guided functional movements based on ADLs. Figure 3.6.1b shows markings to guide either a reach and grasp movement, or a movement involving reaching, pronation and supination, referred to as a 'turn door handle movement'.
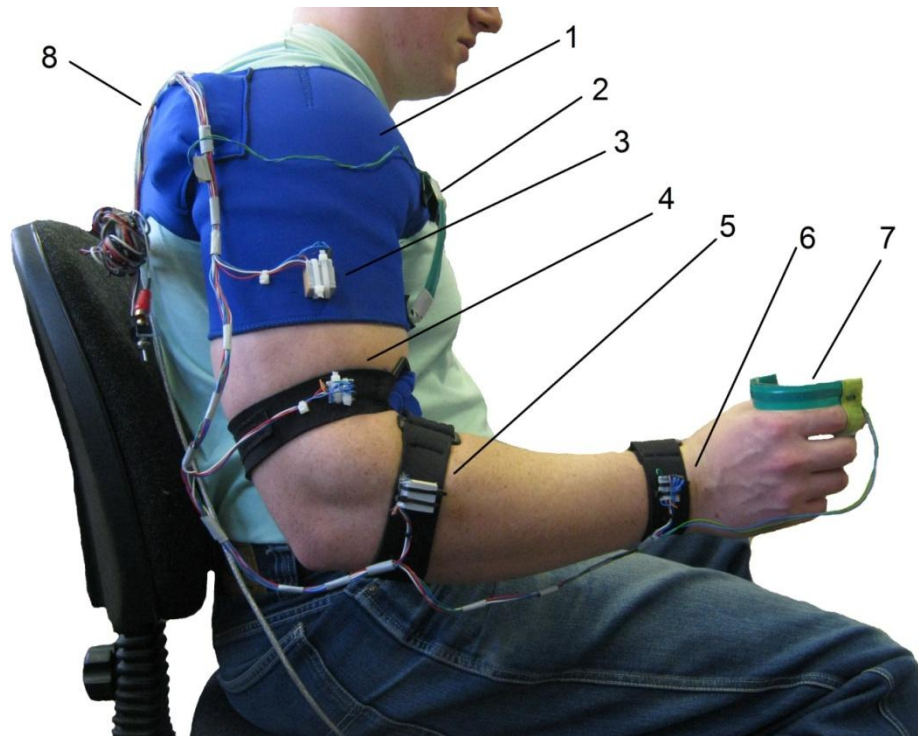
Figure 3.6.1c. Side view of the sensors and hardware of the prototype system

Movements were read using a combination of gyro sensors and flex sensors mounted to the patient using straps. In Figure 3.6.1c, item 1 is a shoulder strap constructed from neoprene, item 2 is a Spectra Symbol 4.5" Flex Sensor (Spectra Symbol 2010) for reading shoulder extension and flexion and item 3 is a SparkFun LPR530AL dual axis gyro sensor (STMicroelectronics 2009) for measuring shoulder extension and flexion and abduction and adduction. Also, item 4 is a gyro sensor for measuring shoulder lateral and medial deviation, item 5 is a gyro sensor for measuring elbow extension and flexion and item 6 is a gyro sensor for measuring hand pronation and supination. Finally, item 7 is a flex sensor attached to the finger and thumb by a strap at each end, for measuring hand opening and closing, and item 8 indicates the position of a National Instruments USB-6009 USB DAQ (National Instruments 2008) located in a pocket on the back of the shoulder, which powered the sensors and allowed signals from the sensors to be fed into the computer. Figure 3.6.1d shows the prototype hardware from the front:

Figure 3.6.1d. Front view of the sensors and hardware of the prototype system

As movements were performed, feedback was generated on the computer screen using a program written in the software package LabVIEW (National Instruments 2012a), a screenshot of which is given in Figure 3.6.1e:
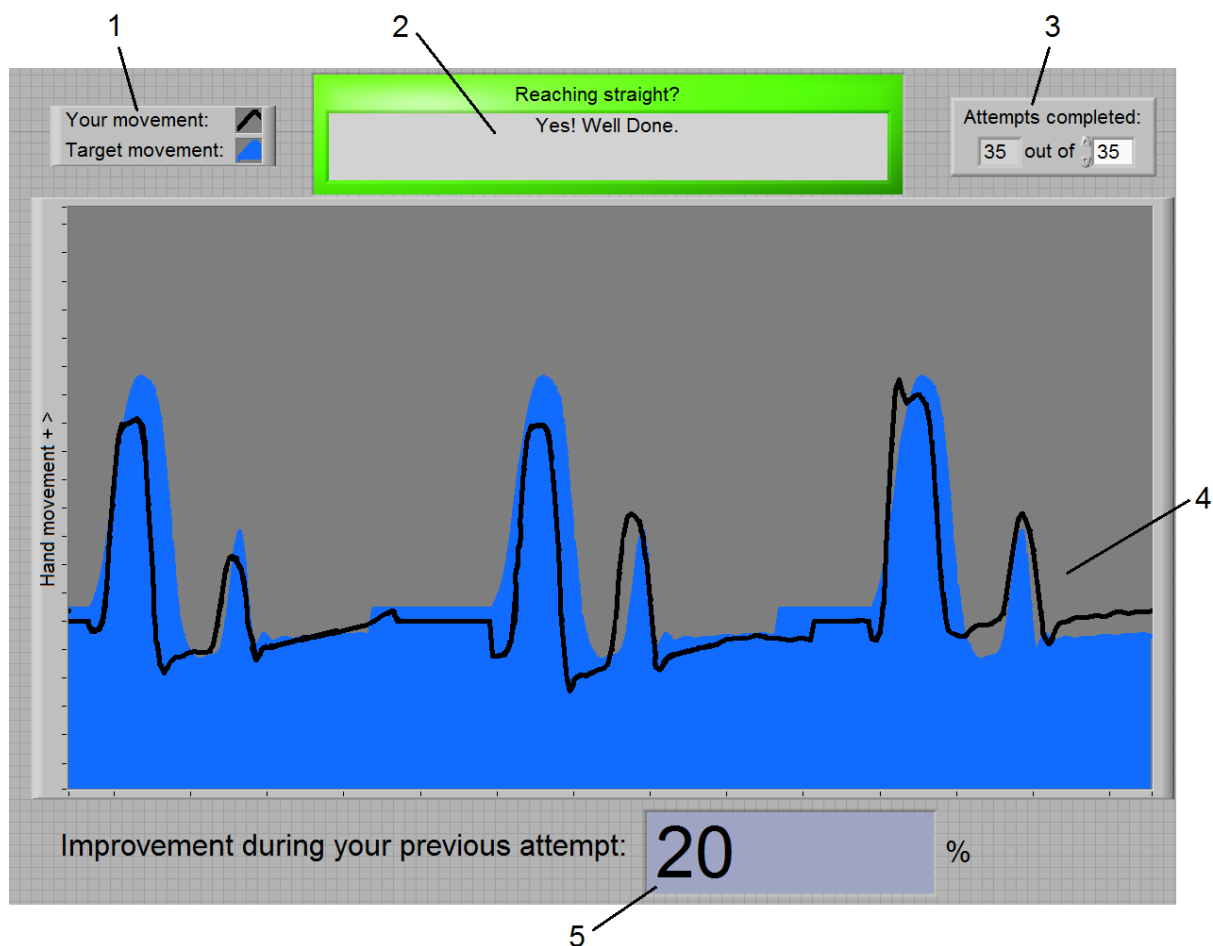
Figure 3.6.1e. Screenshot of the feedback to patients from the prototype system during use

In Figure 3.6.1e, item 1 is a legend for the graphical area, item 2 shows worded bandwidth feedback and item 3 indicates the progression through the physiotherapy session. Also, item 4 is the graphical area, in which is displayed a rolling graph of the displacement of the target movement pattern, triggered by the patient moving from the start position. The patient's movement trace is drawn in real-time. Finally, item 5 shows the patient's improvement from their initial attempt in the session, based on their extent of deviation from the target movement. As well as feedback to the patient, the extent of movement synergism present during movements was calculated from the acquired data, for use by clinicians and researchers. Movement synergism was calculated by recording the number of program iterations that occur whilst certain DOFs are moving simultaneously. Output files are generated by the feedback program containing values of extents of deviation of the patient's movement from the target movement for each movement attempt of the elbow and hand. The files also contain the number of program iterations that occurred whilst DOFs

were exceeding thresholds defined for the worded bandwidth feedback. In addition, the extent of movement synergism present amongst certain DOFs per movement attempt. This allows patient performance to be analysed in detail after a session.

The total cost of the prototype system is shown in Table 3.6.1. Costing of components of a commercial equivalent of the prototype system would differ because a custom DAQ system and custom stand-alone software program would likely be used. This may reduce the cost of production, however, the total cost to the end user would likely be similar. The prototype system had achieved the system objectives and conformed to the design specification satisfactorily. This is discussed in section 7.2.

Table 3.6.1. Cost of the prototype system

Component	Cost
DAQ	£179 (National Instruments 2012d)
Flex sensors	£16*2 (Active Robots 2012a)
Gyro sensors	£15*4 (Active Robots 2012b)
Other hardware	Neoprene material, wiring, straps, thread and buckles £20 (estimate)
Total cost	£291

3.6.2. Movements to be performed

The movements to be performed were two functional movements that simulate the movements made whilst performing the BI ADLs (Mahoney, Barthel 1965). That is, the movements contained elements of the movements made whilst performing the BI ADLs. The movements therefore simulated the types of movements commonly practised during physiotherapy. From literature and observations of movements, the most active DOFs were identified.

Reach and grasp movement

This movement consisted mainly of shoulder and elbow extensions and flexions and the hand opening and closing.

Turn door handle movement

This movement again consisted mainly of shoulder and elbow extensions and flexions, and of hand pronation and supination to simulate turning a door handle. These movements are described further in section 6.3.4.

Since the movement was to be practised at a table with a screen, to allow for comfort and alignment with the guidance markings, patients sit during physiotherapy. To help minimise movements of the trunk, patients were provided with a back support. The start position for movements was with the hand at the edge of the table at the start mark. This was a comfortable and natural position with the elbow at approximately 90 degrees. Figure 3.6.1b shows the guidance markings for both the reach and grasp movement and the turn door handle movement, where some relative dimensions and hand positions are shown. The guidance markings therefore described the spatial elements of the target movements. Markings of different scales were required for participants of different anthropometric dimensions, which is described further in section 6.3.6. Videos of the target movements could be viewed on the screen at any time during the session. The videos show the target movements being performed relative to the guidance markings. The videos were of the target movements being recorded by the 'target recording program' (described below), from directly above the movement for clarity. Even if patients are severely impaired, the prototype system was designed to still be of benefit, because it is thought that the feedback system would still operate correctly, which is discussed further in section 7.3.3. It is the patient's initiation of a movement that triggered 'playback' of the target movement profile in the graphical area, by moving forward from the start position. Patients could pause for as long as they wish between movements, and then continue to practise when they wish, allowing time to contemplate and remember feedback. If the start position was returned to prior to the duration of the target movement lapsing, the movement attempt would be ignored and the count of attempts completed will not be incremented. This allowed accidental movements to be ignored. The prototype system therefore allowed for repetitive training as is performed in regular physiotherapy, where the start position is returned to in-between movements. The aim of this was to allow movements to be relearned through brain plasticity. The movements described are closed-loop controlled, but the prototype

system was designed to guide open-loop controlled movements also which is discussed further in section 7.3.3.

3.6.3. Hardware of the prototype system

The hardware of the prototype system accommodated the right arm. This is because the researcher was right handed which made building and testing the prototype easier. The DOFs for which movement was read by the prototype system is shown in Table 3.6.3. The prototype system was capable of recording movements in multiple planes. The reaching element of the reach and grasp movement involves movement in the sagittal plane, and the opening hand element involves movement in the transverse plane. Also, the pronation and supination element of the turn door handle movement involves movement in the coronal plane.

Table 3.6.3. DOFs for which movement was read by the prototype system

DOFs	Movements	Sensors used to measure
Shoulder	Extension/flexion	Gyro sensor (also flex sensor for trigger mechanism)
	Abduction/adduction	Gyro sensor
	Lateral/medial deviation	Gyro sensor
Elbow	Extension/flexion	Gyro sensor
Hand	Supination/Pronation	Gyro sensor
	Extension/flexion (opening/closing)	Flex sensor

As for the sensor tests described in section 3.5, a voltage regulator circuit was used to power the gyro sensors and a voltage divider circuit was used to allow varying voltages from the flex sensors. The DAQ provided the standard USB voltage of 5 V to the voltage regulator and flex sensors. Signals from the sensors were wired to the analogue inputs of the DAQ, which were then digitised at 14 bit resolution. The flex sensor at the shoulder measured extension and flexion independently of the gyro sensors. This allowed one movement attempt to be distinguished from another by noting the point at which a predefined extent of shoulder extension is exceeded. This allowed patients to pause between movements as described, and allowed for resetting of integration calculations between movements. This is

referred to as the 'trigger' mechanism. The DAQ was mounted in a pocket on the rear of the shoulder to avoid restricting movement and to allow the USB cable to exit from the rear. To allow correct operation of the gyro sensors, wooden blocks were attached to allow correct alignment with axes where necessary. Also, to allow the flex sensors to flex evenly and to allow straps to be attached, plastic strips were taped to the flex sensors as shown in Figure 3.6.3:
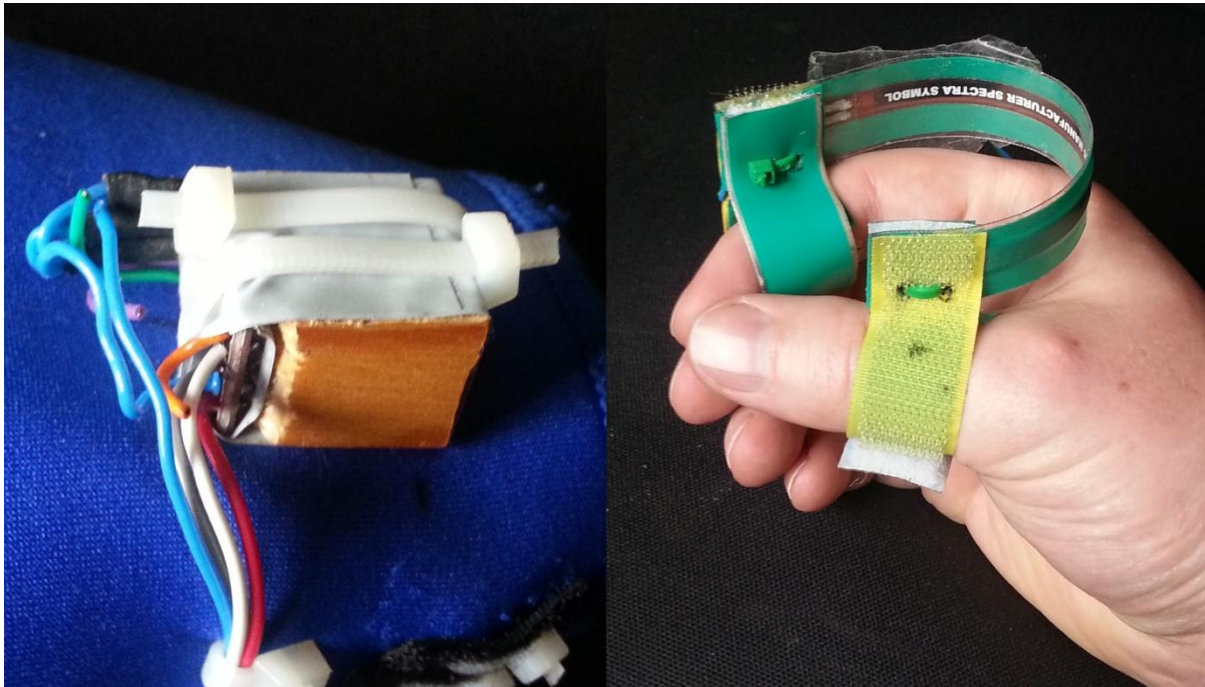
Figure 3.6.3. Wooden block attached to gyro sensor and plastic strips attached to flex sensor (not to scale)

The prototype system consisted of individual straps which allow accommodation of patients of different sizes. This, combined with secure fastening of the sensors, ensured that sensor movement relative to the patient was minimal during use. However, the sensors must be placed in the correct positions when putting the device on, and instructions may be necessary to aid independent use. The gyro sensors were placed on the distal side of the arm and the flex sensor at the shoulder from the torso to the upper arm. These positions are shown in Figure 3.6.1c. The flex sensor at the hand was attached at one end at the centre of the proximal phalanx of the thumb and at the other end to the centre of the middle phalanx of the forefinger (see Figure 3.6.3). These are the locations described in section 3.2.2. The straps were fastened using Velcro meaning fitting is fast, and the neoprene construction allowed for comfort and minimum movement and circulation

restriction during use. The prototype system was lightweight and minimal force was required to flex the flex sensor. When not attached to patients, the hardware was compact and could be folded for convenient storage, for example in a drawer. In use, the prototype system was also compact and the space required was similar to that of a desk and computer.

3.6.4. Feedback and software of the prototype system

Three main programs were written for the prototype system. These were a 'target recording program' which records target movements to be practised during physiotherapy. A 'feedback program' was also written, which provides feedback for guidance during physiotherapy, into which the target movements are loaded. Also, a 'synergism recording program' was written which calculates and records the extent of movement synergism during physiotherapy in different categories, for use by physiotherapists and researchers. For simplicity and to aid testing, the synergism recording program was written as a separate piece of code. Similarly, separate programs were written to cater for the reach and grasp movement and the turn door handle movement. If required in future, a program could be written combining the feedback to the participant with the measurement of movement synergism, which is discussed further in section 7.3.3.

Target recording program
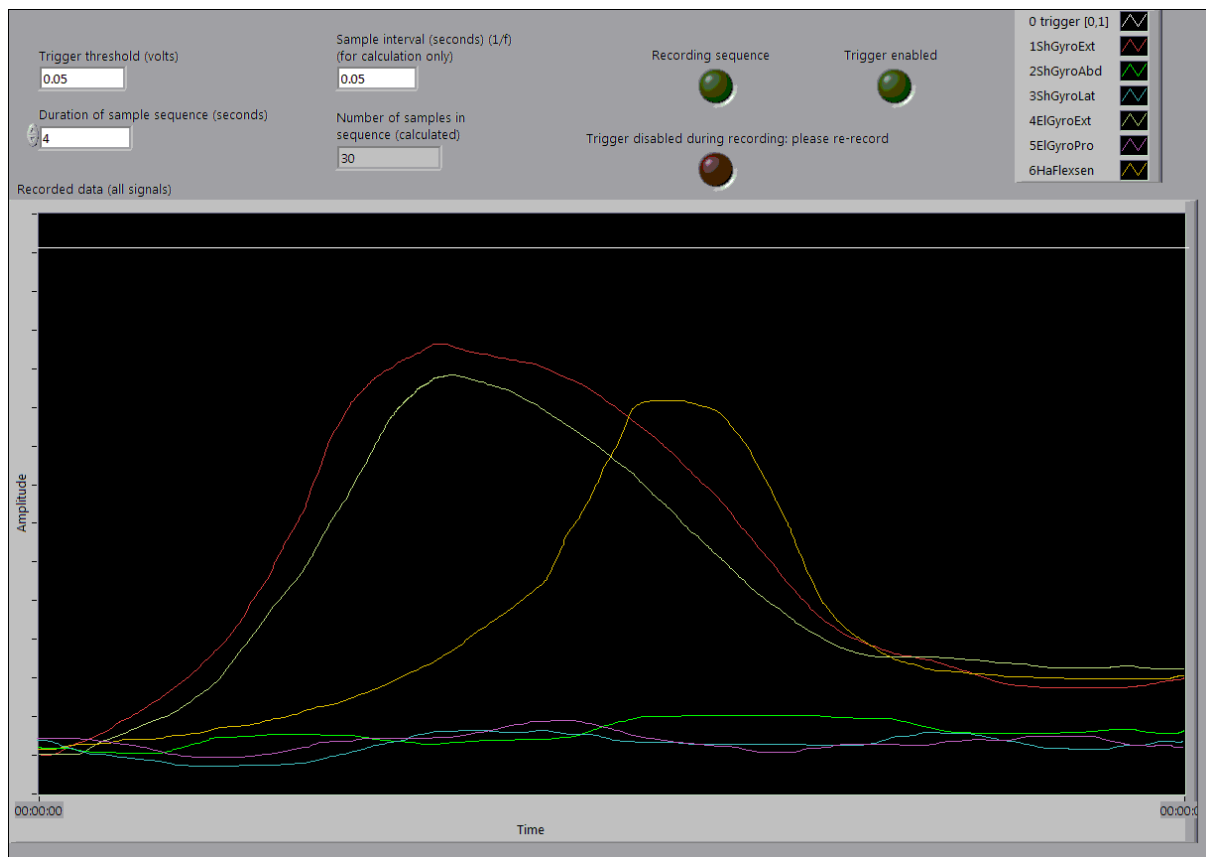
Figure 3.6.4a. Front panel of the target recording program

The front panel of the target recording program is shown in Figure 3.6.4a. The target recording program had the following features:

- Allows the file name and location of the output file to be specified
- The output file is in CSV format and contains samples of the signals from each measured DOF in separate columns
- Allows the duration of the recording sequence to be specified
- Displays the number of samples recorded for each channel when the sample interval is specified
- Allows the trigger threshold to be specified
- Indicates when the trigger is enabled
- Indicates when recording is in progress
- Starts recording the sequence automatically when the trigger is enabled

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- Stops recording once the specified duration has lapsed or if the trigger is disabled prior to this

- Warns if the trigger is disabled prior to the specified duration lapsing

- Shows a graphical display of recorded signals in the form of amplitude with time

- Shows a legend to distinguish signals from one another

For the block diagram of the target recording program, see Appendix 1. Although it was impossible to show the block diagram clearly due to its complexity, Figure 'Appendix 1' was included to describe the nature and complexity of the program. The target recording program had the following mechanisms:

- Interface with the DAQ

- Allows the sample rate to be specified

- Splitting of signal into individual channels

- Initial zeroing of signals by recording of the resting values and then subtracting them from all following respective values

- Low pass noise filters

- Trigger mechanism to allow signals to pass if the predefined threshold for shoulder extension is exceeded

- Subtraction of shoulder extension/flexion signal from elbow extension/flexion signal and shoulder abduction/adduction signal from hand pronation/supination signal to allow movement of individual DOFs to be recorded

- A threshold system that allows only velocity data over or under a certain value from the gyro sensors to be considered to overcome instabilities in resting values after movements (discussed further in section 7.3.1)

- Integration of signals from the gyro sensor to allow for correlation with position

- Resetting of integration calculation when trigger mechanism is disabled between movements

- Recording of all signals and saving to an output file for the predefined recording duration

Feedback program

The feedback to patients was a multi-element prescriptive extrinsic, or augmented, feedback system that simulated the guidance provided by a physiotherapist. Where many systems use games for physiotherapy due to their availability and their ability to motivate, the prototype system guided ADLs in a game-like fashion, through the combination of the graphical area initiated by the patient's movements, and by informing of personal improvements. The prototype system provided instruction in the form of guidance markings, videos and the blue profile to follow shown in the graphical area. The prototype system provided details, in the worded feedback and graphical area, of how patients are performing and how to improve based on their performance. Patients were also informed of their improvements in the graphical area, and by the improvement percentage figure which displayed improvements in conformance to the target movement from their initial attempt.

As stated, in Figure 3.6.1e, item 2 displays the worded bandwidth feedback. This element provided worded instructions of how to improve if displacement of certain DOFs exceeded predefined thresholds during movements. These thresholds were defined as displacements from those that exist in the target movements. At all times the question 'Reaching straight?' was displayed. If no thresholds were exceeded, 'Yes! Well done.' was displayed and the frame surrounding the worded feedback area was green. If a threshold was exceeded, the frame would change to red and worded instructions would be displayed for a configurable duration of time to allow for reading. If more than one threshold was exceeded, multiple instructions would be displayed. The worded instructions for the reach and grasp movement are shown below:

- Under excessive shoulder abduction: 'No, please avoid moving your elbow outwards'
- Under excessive shoulder adduction: 'No, please avoid moving your elbow inwards'
- Under excessive elbow lateral rotation: 'No, please avoid moving your hand to the right'
- Under excessive elbow medial rotation: 'No, please avoid moving your hand to the left'
- Under excessive hand supination: 'No, please avoid rotating your hand clockwise'

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- Under excessive hand pronation: 'No, please avoid rotating your hand anticlockwise'

The worded feedback was a form of KP feedback and was qualitative. It was relatively imprecise in that the whole arm was referred to, which was considered appropriate for early learning. The words and frame colour provided positive reinforcement when movements were performed correctly, and the red colour graphically alerted the patient's attention when thresholds were exceeded. The worded feedback could be considered to be of internal or external focus, because whilst the outcome of the movement was not referred to, the arm, as opposed to individual DOFs was referred to. Since the instructions were displayed when the thresholds were exceeded and then for a period after, the worded feedback occurred concurrently to the movement and terminally. The thresholds were established by the researcher empirically as slight deviations from the target movement, but not too slight that they would trigger the feedback too easily. Whilst this approach allowed operation of the program to be confirmed, in order to be of significant benefit to patients, it was thought that a physiotherapist's assistance would be required to define thresholds that described a well performed movement. However, since this was beyond the scope of this research, it was not carried out.

In Figure 3.6.1e, item 3 shows the progression through the session. This was a form of quantitative feedback, which aims to allow patients to understand their session more fully, know that they are making progress and thus feel in control.

In Figure 3.6.1e, item 4 shows the graphical area in which, during physiotherapy, changes in displacement of the patient's hands caused changes in height of the black line. In the program for the reach and grasp movement, opening and closing the hand caused the black line to move, whereas in the program for the turn door handle movement, pronation and supination caused the black line to move. Similarly, changes in displacement of the hand in the target movement were shown by changes in height of the blue profile. The patient's objective was therefore to move so as to cause the black line to follow the blue profile. Where deviations occur, the nature of the deviations could be observed by patients, for example, opening the hand too early would result in the black line peaking too early. How to improve could therefore be observed. If the patients move so the black line follows the blue

profile with no deviations, then theoretically patients have reproduced the target movement perfectly. An aim of this element was therefore to provide an entertaining challenge and to be motivating during use. The graphical feedback could be considered a form of KP feedback or, because the objective was to follow the blue profile, as KR feedback. It was presented in a continuous and qualitative form. It allowed a large quantity of information to be presented in a way that can be easily absorbed. Due to the technical nature of graphical data, instruction may be required as was implemented in the tests performed in Chapter 6. The graphical feedback again could be considered to be of internal or external perspective. As described, the graphical feedback was given concurrently as patients attempt to reproduce the target movement. This gave patients a choice between watching their upper limb during movements, or watching the graphical feedback. The graphical feedback could also be observed terminally, because the patient's movement trace remained on the graph for a period of time before the next movement took place.

The line was drawn either by opening and closing the hand during the reach and grasp movement, or by pronation and supination during the turn door handle movement. This was so despite the movements involving reach elements as well as hand movements, in order to allow effective guidance whilst avoiding feeding back too much information to the patient. Since the graphical area provided feedback to patients of hand movements only, it was intended that the effects of guidance would also occur at other DOFs which also move during the target movements. That is, that greater conformance to target movements would occur in these DOFs also. To aid this, the guidance markings showed reach elements of the target movements which were not described by the graphical area of the feedback. This along with the videos provided allowed the target movements to be described fully to the patients. The extent of deviation from the target movement was calculated per movement attempt, which was calculated from hand opening and closing or pronation and supination depending on the target movement. This was also calculated at the elbow (extension and flexion). This was to allow the effects of feedback on other DOFs, which also move during target movements, to be investigated which is described further in Chapter 6.

In Figure 3.6.1e, item 5 indicates the patient's improvement in their latest movement attempt compared with their initial movement attempt in the session. This was based on

the extent of their deviation from the target movement of the hand opening and closing in the reach and grasp movement, or pronation and supination in the turn door handle movement. This is a form of quantitative feedback which could be considered a summary of the performance during the patient's movement attempt. This feedback was given terminally relative to movement attempts and was given at 100% frequency. The figure was given to the nearest percent in order to be precise enough to show improvements whilst not being overly complicated. It was descriptive and aimed to provide reinforcing effects and to be motivating during use. The figure was calculated by comparing the positive differences from the patient's movement to the target movement per sample of data, which is described further below.

The feedback program also included an analysis area on the front panel, accessible by scrolling down from the feedback area for patients. This area was hidden when giving feedback to participants. The analysis area was used to aid designing and testing of the prototype system and to ensure correct setup prior to sessions.

Figure 3.6.4c. Analysis area of the front panel of the feedback program showing a graphical display of the patient's elbow extension and flexion against the target movement and graphical displays of signals from all sensors during movements in the form of amplitude with time

The analysis area of the front panel of the feedback program is shown in Figure 3.6.4c. The feedback program, in particular the analysis area, had the following features in addition to those described:

- Allows the recorded target movement to be located for use during the physiotherapy session
- Allows the file name and location of the output file to be specified
- The output files are in CSV format and contain values corresponding with the conformances to the target movement of the hand and elbow per movement attempt
- The output files also contain the number of program iterations that occurred whilst DOFs were exceeding thresholds defined for the worded bandwidth feedback
- Allows the number of movement repetitions in the session before the program terminates to be specified
- Allows the duration of the target movement playback and comparison sequence to be specified
- Allows the trigger threshold to be specified
- Indicates when the trigger is enabled
- Allows the duration of time for which worded feedback is displayed to be specified
- Asks for a waiting period upon running the program to ensure all elements of the program have loaded
- Indicates when the patient's initial attempts at reproducing the target movement for future comparisons have been recorded
- Shows the initial hand (opening and closing or pronation and supination) and elbow (extension and flexion) 'summed deviation values' (explained below)
- Shows the hand and elbow summed deviation values per movement attempt
- Shows the patient's improvement in conformance at the elbow to the target movement from their initial attempts (as is done for the hand in the feedback to patients)

- Shows a graphical display of the patient's elbow extension and flexion against the target movement, equivalent to that given for the hand (opening and closing or pronation and supination) in the graphical area of the feedback to the participant

- Shows individual graphical displays of signals from all sensors during movements in the form of amplitude with time

- Shows numeric values for the signals from all sensors during movements

- The program terminates once the predefined number of movement attempts have been made

For the block diagram of the feedback program, see Appendix 2. In addition to the described mechanisms of the target recording program, the feedback program had the following mechanisms:

- Assessing displacement values of the DOFs for bandwidth feedback and enabling the worded feedback and colour change of the worded feedback frame for a predefined duration if the predefined thresholds are exceeded

- Counting the number of program iterations that occur whilst DOFs exceed the predefined thresholds for the worded feedback

- Reading the target movement when the trigger mechanism is enabled

- Subtracting the signals from the patient's movements from those of the target movement at the hand (opening and closing or pronation and supination), and the elbow (extension and flexion)

- Converting any negative differences per sample to positive

- Summing of the total differences per sample to give a 'summed deviation value' per movement attempt, of which lower values indicate closer conformance to the target movement

- Comparing the summed deviation value calculated from the patient's initial attempt with their latest attempts by dividing their initial summed deviation values by their latest summed deviation values, subtracting one and multiplying by 100 %

- Displaying any improvements in conformance as a percentage, otherwise displaying '0 %'

- Saving the summed deviation values per hand (opening and closing or pronation and supination) and elbow extension and flexion per movement attempt. This is done along with the number of program iterations which occur whilst DOFs exceed the predefined bandwidths for the worded feedback, also per movement attempt, into an output file

- Saving all signals per movement attempt to an output file. This was also to allow patient performance to be analysed in detail after a session (but was not used during testing of the prototype system for this research)

Synergism recording program
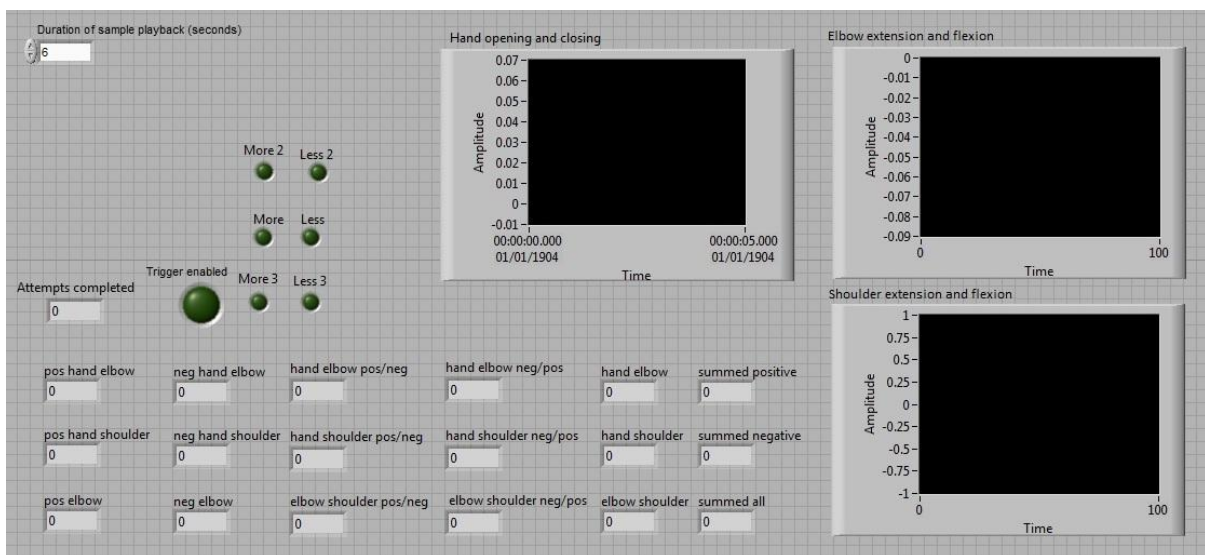
Figure 3.6.4d. Front panel of the synergism recording program

The front panel of the synergism recording program is shown in Figure 3.6.4d. The established functional movements to perform involved pronounced movements of the shoulder, elbow and hand. The synergism recording program was therefore constructed to assess movement synergism amongst these DOFs, and was based on the movement synergism feedback concept for clinicians and researchers generated in section 3.4.3. The synergism recording program had the following features:

- Allows the file name and location of the output file to be specified
- Allows the duration of the recording sequence per movement to be specified

- The output file is in CSV format and contains counts of program iterations that occurred whilst movement synergism was present in the categories shown below per movement attempt

- Indicates when the trigger mechanism is enabled

- Indicates when the shoulder, elbow and hand are moving with positive or negative velocities

- Displays the number of program iterations that occur whilst movement synergism was occurring in categories per movement attempt

- The categories included positive-positive, negative-negative, positive-negative, negative-positive and general movement synergism for each DOF combination. Also summed positive-positive, summed negative-negative and summed general movement synergism for all DOFs

- Shows individual graphical displays of signals from the sensors during movements in the form of amplitude with time

- The program is terminated manually once the required number of movement attempts have been performed

The block diagram of the synergism recording program is shown in Appendix 3. In addition to the described mechanisms of the target recording program, the synergism recording program had a positive and negative velocity threshold on the signal from the hand flex sensor. This threshold must be exceeded in order for signals to be considered. This was to avoid noise being considered as velocity when detecting movement synergism. This was not applied to the gyro sensors because, as described, velocity thresholds were already in place.

Program parameters

Values for program parameters were established with the aim of allowing optimal performance. For example the sample rate was set to 20 Hz, which is discussed further in section 7.2. This allowed for suitable detail about the movement to be obtained whilst avoiding delays in the graphical feedback on slower computer systems. This sample rate was established empirically whilst using the prototype system and observing the outputs. Many

other parameters were established in a similarly strategic manner, but to be concise are listed as bullet points. These include:

- Order for the low-pass filters: 4th order

- Trigger mechanism threshold: 0.05 V

- Velocity thresholds for gyro sensors: +/- 0.05 V

- Displacement thresholds for worded bandwidth feedback: varies per DOF

- Signal multiplication factors to allow similar ranges of responses from DOFs that move during movements: varies per DOF

- Words for worded feedback (listed above)

- Dimensions, positions and colours of the feedback (shown above)

The system objectives, design specification, the prototype system itself, hypothesis, research questions and findings from the information review provided the basis for generation of objectives for the tests of the prototype system in the following three chapters.

CHAPTER 4. VALIDATION OF THE PROTOTYPE HARDWARE USING VICON

4.1. Introduction to chapter

This chapter describes tests performed to validate the performance of the prototype hardware against VICON, an independent measure, known to be accurate and repeatable in measuring human movement. The aim of these tests was to investigate the behaviour and capabilities of the prototype hardware when movements were performed in multiple planes and with varying spatiotemporal parameters. These tests were performed to assess the suitability of the prototype hardware for performing further tests in chapters 5 and 6, and also to allow the results from the further tests to be better understood. VICON is a commercial optical measurement system designed for research use. Recordings were made simultaneously using both systems, and where differences in data appeared, the extents and causes were contemplated.

In this chapter, the objectives of the tests are established with respect to the system objectives, design specification, the prototype system itself, hypothesis, research questions and findings from the information review. VICON is then introduced and a switch mechanism developed to allow synchronisation of initiation of recording of both systems is described. LabVIEW test programs and movements performed are then described. The data recorded from two participants (participants one and two) of similar anthropometric dimensions and the test schedule are then described. Conversion of the data recorded is described and noise in the prototype hardware, the effect of out of plane movements and variability of the data recorded from VICON are analysed. The correlation between data from the prototype hardware and VICON is investigated along with the intra-variability and inter-variability of the prototype hardware. Performance when measuring at high and low velocities and through large and small displacements is also investigated. Finally, the limitations of the tests are discussed and conclusions are drawn on the level of the system objectives and the design specification. This formed the basis for discussion of the results in relation to the hypothesis and research questions in Chapter 7.

The objectives of the tests were established with the most important generally listed first, and the order of the tests and analysis was established with the most fundamental being performed first. This was considered the clearest in terms of both performing the tests and reporting the results. This applies to the following two test chapters also. To allow for consistent methodology and to minimise cumulative errors in analysis, the default number of decimal places from the software used initially was recorded. This resulted in a large number of decimal places which were then reduced as the thesis was finalised. This also applies to the following two test chapters.

4.2. Objectives of the tests

The objectives of the tests were to investigate the following regarding the prototype hardware:

- Correlation between the prototype hardware and VICON
- Intra-variability
- Inter-variability

To help address performance in these categories, the following were first to be investigated:

- The variability of VICON
- The noise present in the signals from the sensors used for the prototype hardware

To help further understand the prototype hardware, the following were also to be investigated:

- Performance of the prototype hardware when the DOFs are moved through large displacements
- Performance of the prototype hardware when the DOFs are moved at high velocities
- The minimum velocities that the prototype hardware can detect
- The smallest displacements that the prototype hardware can detect

4.3. Test methodology

4.3.1. VICON

VICON is a motion analysis tool used mainly for analysing physical performance during sport for research purposes. VICON identifies the position of reflective markers attached to a body whose motion is to be measured. The markers are in the form of small spheres with reflective surfaces. The markers are attached to the body to be measured using adhesive strips. The location of the markers on the body is dependent on the shape of the body and the movements that are to be measured. A series of cameras surround a volume within which movements can be measured. Each camera has infrared LEDs that emit in the direction of the markers. The cameras then detect light reflected from the markers and send signals to a computer system via Ethernet. The computer system then calculates the coordinates of each marker based on trigonometry in pseudo real-time. The cameras have an adjustable resolution of up to 4704 x 3456 pixels, or 16 megapixels, and an adjustable sample rate of up to 2 KHz (VICON 2009). The computer system runs the software package Nexus, which allows display of the position and movement of the markers. Nexus allows for post processing of recorded data including specification of segments from groups of markers if required. Nexus also allows for exportation of recorded data in CSV format files, which contain the coordinate data per sample of each marker. These output files therefore contain the X, Y and Z coordinate values in mm per marker. The cost of VICON is approximately £200,000. Figures 4.3.1a to 4.3.1c show components of VICON:
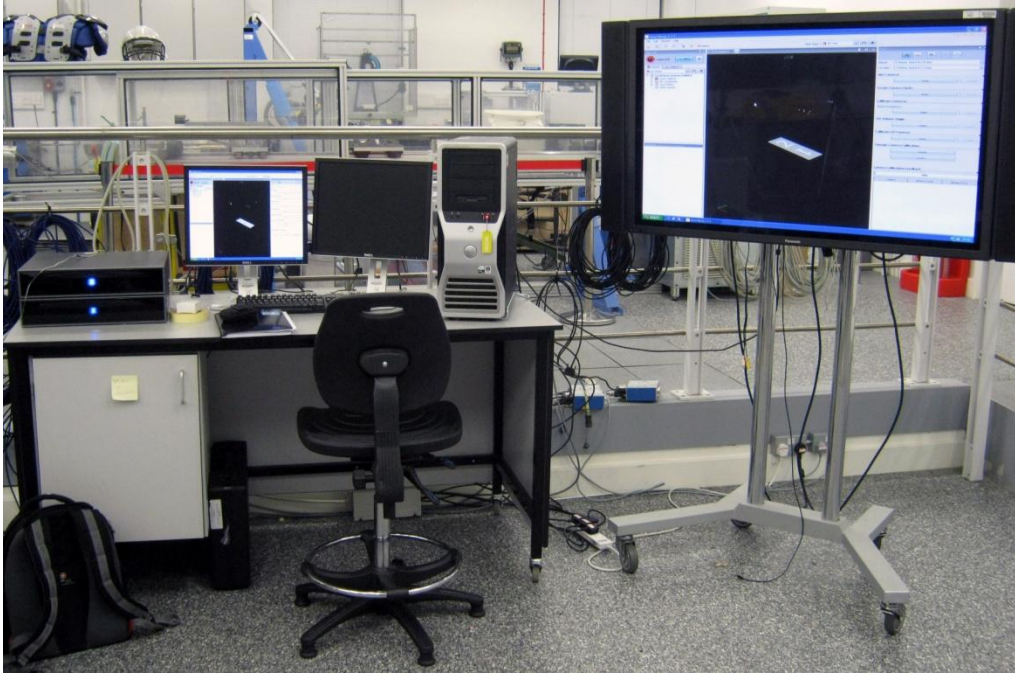
Figure 4.3.1a. VICON computer system and user interface

Figure 4.3.1b. A VICON camera with infrared LEDs and lens visible
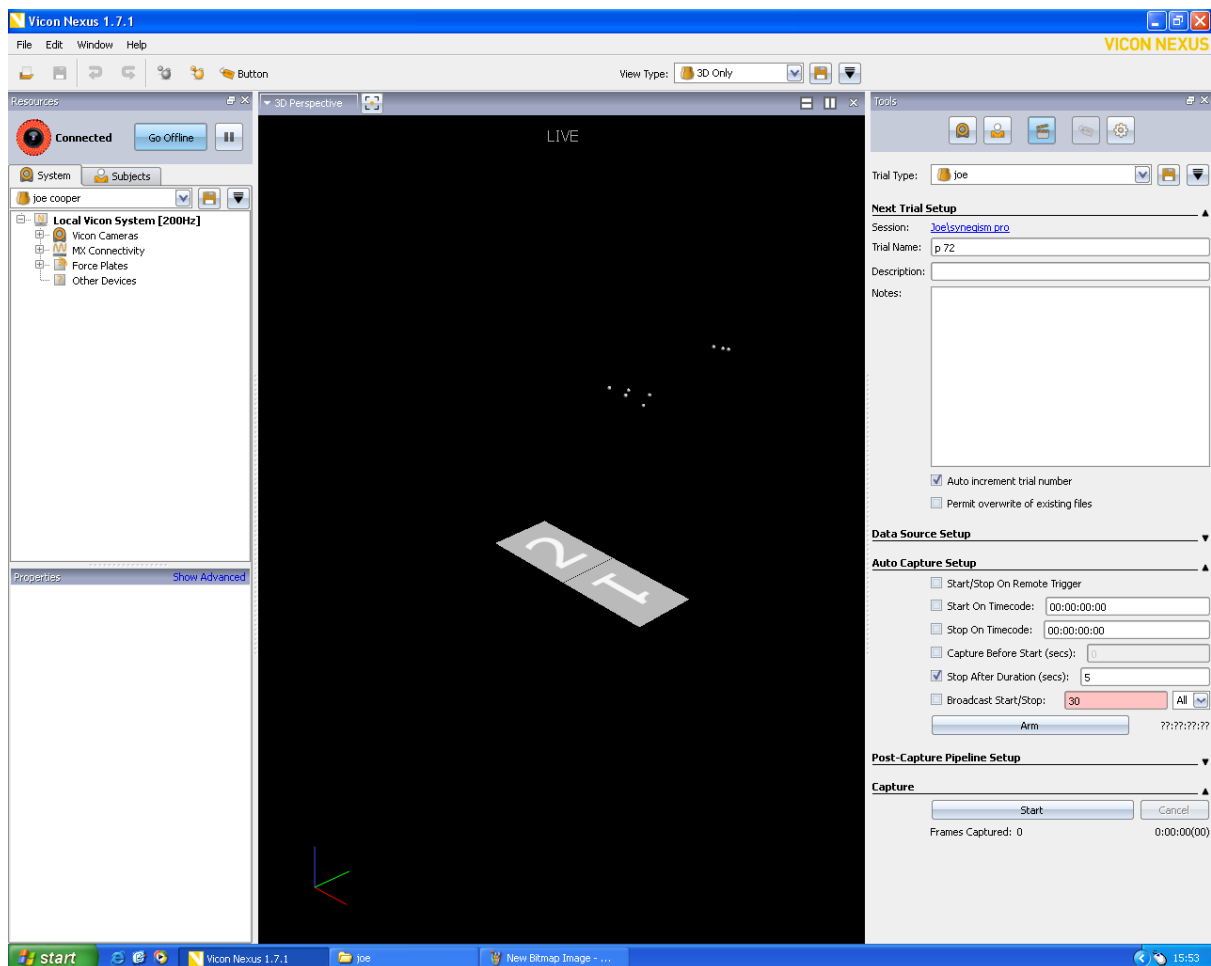
Figure 4.3.1c. A screenshot of the user interface of the Nexus software

4.3.2. Switch mechanism

In order to compare the data from the prototype hardware with the data from VICON, the data sets required time synchronisation. The VICON computer system accepts a Radio Corporation of America (RCA) connector from which a switch function was set in Nexus when the terminals close. This means that when a switch connected to the RCA connector closes, VICON will begin a recording sequence. A single switch was used to initiate both the VICON recording sequence and to create a 'mark' in the data recorded from the prototype hardware. This was incorporated into the circuit shown in Figure 4.3.2:
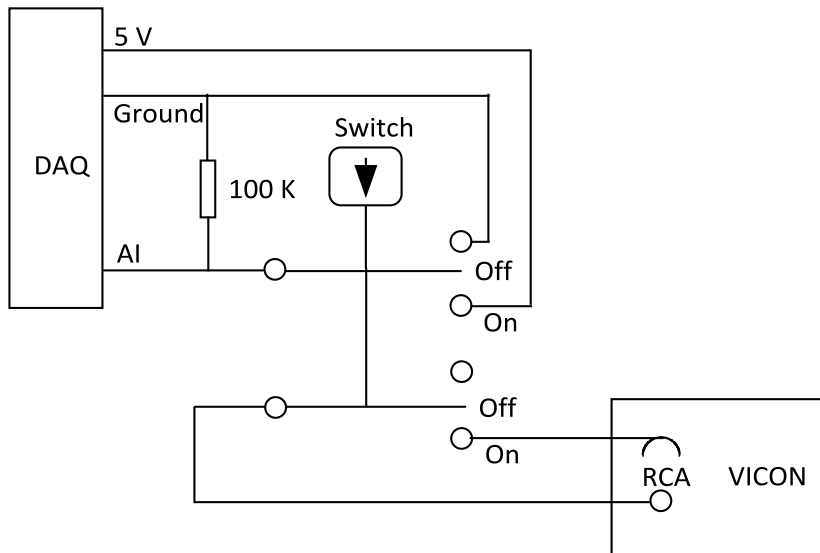
Figure 4.3.2. The electrical circuit of the switch mechanism

A double pole switch was used to isolate the systems to avoid surges or short circuits. Also, a 100 KΩ resistor was used in a buffer arrangement to reduce noise. The 5 V output from the DAQ was used to generate a signal, which was then connected through the switch to an analogue input on the DAQ.

4.3.3. LabVIEW test programs

To allow data gathered from the prototype hardware to be better understood, the ambient noise from the sensors was analysed. To allow this, two further programs were constructed in the LabVIEW software; one to read signal samples at a rate of up to 48 kHz and write them to an output file, and one to perform a Fast Fourier Transform (FFT) on the recorded data (shown in figures 4.3.3a and 4.3.3b). This allowed the noise present at different frequencies to be examined.
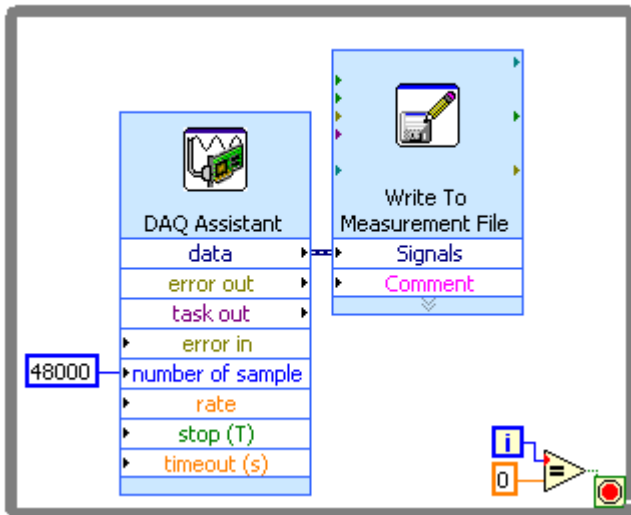
Figure 4.3.3a. Block diagram of the program to record signal samples at up to 48 kHz

The program shown in Figure 4.3.3a allows the sample rate, DAQ input channel, number of samples and the name and location of the output file to be specified.
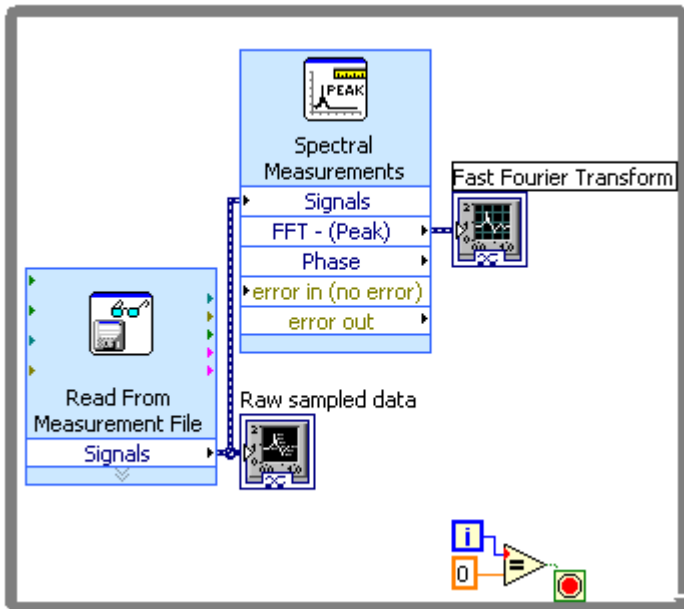
Figure 4.3.3b. Block diagram of the program to perform an FFT on the recorded data

The program shown Figure 4.3.3b allows previously recorded files to be located and loaded, FFTs to be performed and FFT charts to be produced.

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To allow data to be recorded by the prototype hardware for comparison with VICON, the target recording program described in section 3.6.4 was modified and saved as a separate program. The trigger mechanism was removed, meaning that signals were enabled and recorded from the onset of execution of the program. Also, the 5 V signal from the switch mechanism when enabled was converted to a logic '1', or from 0 V when disabled to a logic '0'. Respective '0's or '1's were then saved per sample recorded from the sensors in the output file. This was to serve as a reference to allow time synchronisation between data from the prototype hardware and VICON during data analysis.

4.3.4. Movements performed

As established in section 3.6.2, the functional movements to perform consisted mainly of movement of certain DOFs. Performance in measuring movement at these DOFs was therefore investigated. To gain a more complete understanding of the performance of the prototype hardware, performance in measuring shoulder lateral and medial deviation was also investigated. This allowed the performance of the prototype hardware in measuring movements in multiple planes to be investigated. Performance in measuring shoulder extension and flexion was not investigated, because as described in section 3.6.4, calculation of shoulder extension and flexion is involved in calculation of elbow extension and flexion. Performance in measuring the following movements was therefore investigated:

- Elbow extension and flexion
- Hand opening and closing
- Shoulder lateral and medial rotation
- Hand pronation and supination

Due to limited availability of VICON and to allow sufficient time for testing the efficacy of the whole prototype, only two participants were involved in testing the performance of the prototype hardware. The start position was as described in section 3.6.2 and guidance markings similar to those described in section 3.6.1 were used to ensure movements were performed in a similar manner between repetitions and participants. Where participants

were asked to perform more than one repetition of a movement, they were asked to attempt to perform as similarly as possible in all repetitions. Also, participants were asked to try to move only within certain planes, for example in the sagittal plane during shoulder and elbow extension and flexion. The movements listed above were performed by both participants with the characteristics shown in Table 4.3.4.

Table 4.3.4. The categories of performance investigated and the characteristics of the corresponding movements performed by both participants

Category of performance to investigate	Characteristics of movements
Correlation, intra-variability, inter-variability	10 repetitions of each movement, mid range of movement at a comfortable velocity to simulate ADLs
Performance when measuring large displacements	1 repetition of each movement, full range of movement at a comfortable velocity
Performance when measuring high velocity movements	2 sequential repetitions of each movement per recorded sequence, mid range of movement at a relatively high velocity
The minimum velocities and displacements detectable	1 repetition of each movement, mid range of movement at a relatively low velocity and progressively reducing to a stop

4.3.5. Data recorded

Data recorded for FFT noise analysis

For the FFT noise analysis tests, voltage samples from the system hardware were recorded at 48 kHz, which is the maximum sample rate supported by the DAQ, to examine high frequency noise. This allows frequencies up to 24 kHz to be analysed due to the Nyquist limitation. Samples where then recorded at 200 Hz to allow noise to be analysed closer to the sample rate of the feedback program. The programs described in section 4.3.3 were used and CSV format output files were generated. This was done from a channel with a flex sensor attached, a gyro sensor and then an empty channel. No movements were performed during this sampling. The duration of each sample was set to 1 second meaning that 3 sets of 48 000 samples were recorded and 3 of 200 samples.

Data recorded for validation of the prototype hardware using VICON

During all movements, voltage samples were recorded from the prototype hardware from all sensors at a rate of 20 Hz; the sample rate established for the feedback program in section 3.6.4. Also, the recorded data contained a '1' with samples recorded when the switch mechanism was activated. The recording sequence of VICON was set to four seconds to allow sufficient time to perform the movements whilst avoiding generating overly large output files. The program for recording from the prototype hardware had to be initiated prior to the VICON recording sequence to allow the time of the switch mechanism to be recorded. The recording sequence of the program for recording from the prototype hardware was set to a longer duration of six seconds to ensure all data from VICON could be compared. Coordinate samples were recorded from VICON at a rate of 250 Hz. This again allowed for sufficient detail whilst avoiding the generation of overly large output files. The output file from VICON therefore contained 1000 coordinate readings in mm for the X, Y and Z axes for each marker. As 52 movements were performed by two participants, 104 movements were performed in total. For each of these movements, output files were generated from both the prototype hardware and from VICON.

4.3.6. Test schedule

This section describes the activities performed in the laboratory during performance of the tests.

1. Align the table and guidance markings with the VICON axes. Markings were located on the floor to aid this process (shown in Figure 4.3.6a)

Figure 4.3.6a. Table and guidance sheets aligned with the VICON axes

2. Boot up the VICON computer system and load the Nexus software program
3. Ensure no shiny objects are causing interference with VICON and remove them if present
4. Calibrate VICON using the T-shaped bar with markers at specific positions known by VICON
5. Ensure the camera error values for each of the cameras are equal to or less than '0.25'; an aggregated figure generated by Nexus for which no units are given
6. Set the sample rate of VICON and set the "start recording" sequence method to "switch"
7. Specify file names and locations for the output files from both the prototype hardware and VICON for participant one

8. Plug the switch mechanism into the VICON computer system and test that it operates correctly

9. Mount the prototype hardware to participant one

10. Mount the markers to participant one as shown in figures 4.3.6b and 4.3.6c
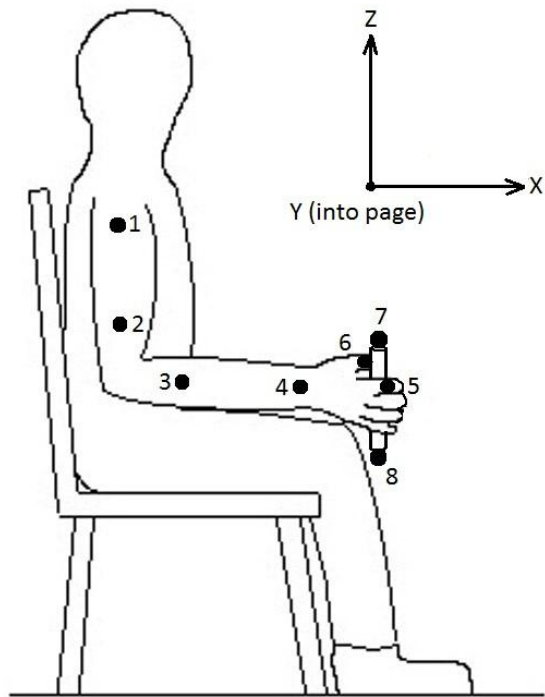
Figure 4.3.6b. Locations of markers on the upper limb with VICON axis terminology shown

Figure 4.3.6c. Prototype hardware and markers mounted to a participant

11. Participant one performs the movements described in section 4.3.4

12. Specify file names and locations for the output files from both the prototype hardware and VICON for participant two

13. Mount the prototype hardware and markers to participant two as was done for participant one

14. Participant two performs the movements described in section 4.3.4

15. Generate output files from Nexus by creating a model of the upper limb and numbering the markers as shown in Figure 4.3.6b

16. Save all output files to a portable drive

The positions of the markers shown in Figure 4.3.6b were established by aiming for as few markers as possible for simplicity whilst still allowing the displacements of the DOFs to be calculated from the coordinate data. Markers 5 and 6 were attached to the middle phalanx of the forefinger and the proximal phalanx of the thumb respectively, which were established in section 3.2.2 for the locations of measurement of the hand opening and closing. Markers 7 and 8 were attached to either end of a small bar, which was held and

rotated during hand pronation and supination and excluded during hand opening and closing movements (see Figure 4.3.6c).

4.4. Data analysis

4.4.1. Conversion of data

The coordinate data from each marker recorded by VICON was converted to displacements of the DOFs (see Figure 4.4.1):
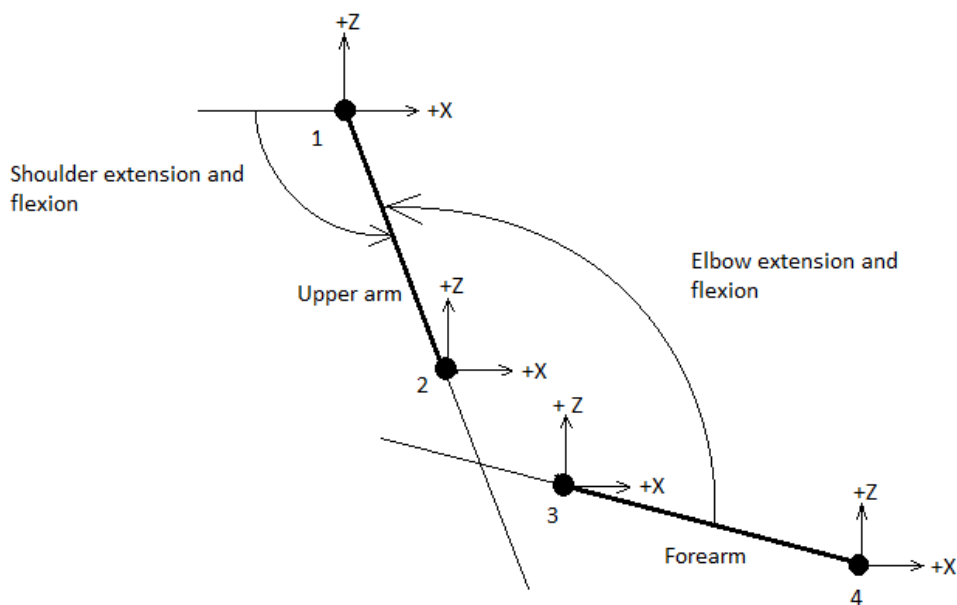
Figure 4.4.1. Markers 1 to 4 with coordinate convention and calculated displacement directions shown

Shoulder extension, $\emptyset$, was calculated as shown in Equation 4.4.1a:

$$\emptyset = \tan^{-1}\left(\frac{\partial z}{\partial x}\right) = \tan^{-1}\left(\frac{z2-z1}{x2-x1}\right) \quad \text{Equation 4.4.1a}$$

To cater for the differences in the quadrants of the circle around the shoulder to give an absolute angle from the –X axis, a logic function (Function 4.4.1a) was constructed in Microsoft Excel:

If (δx>0) Then
  + 180 degrees
If (δz>0) Then
  + 360 degrees Function 4.4.1a

Elbow extension, Ø2, was calculated using Equation 4.4.1a:

$$\varnothing 2 = \tan^{-1}\left(\frac{\partial z}{\partial x}\right) = \tan^{-1}\left(\frac{z4 - z3}{x4 - x3}\right) \quad \text{Equation 4.4.1a}$$

To calculate elbow extension relative to the upper arm, Ø3, Equation 4.4.1b was applied:

$$\varnothing 3 = \varnothing - \varnothing 2 + 180 \quad \text{Equation 4.4.1b}$$

Similar calculations were performed to find the angular displacements of the other DOFs, where the coordinates of the respective markers were referred to. The hand opening distance, D, was found by calculating the distance between markers 5 and 6. This was achieved using Equation 4.4.1c:

$$D = \sqrt{(xB - xA)^2 + (yB - yA)^2 + (zB - zA)^2} \quad \text{Equation 4.4.1c}$$

In Equation 4.4.1c, the distance between two markers A and B can be found, which were substituted for markers 5 and 6:

$$D = \sqrt{(x6 - x5)^2 + (y6 - y5)^2 + (z6 - z5)^2} \quad \text{Equation 4.4.1c}$$

Before comparisons were made between the data from VICON and the prototype hardware, the data from the prototype hardware was scaled and offset to match the data from VICON

as closely as possible. This approach allowed for variability to be investigated, but not accuracy. Instead of investigating accuracy, visual observations were made of correlations between the systems. The scale and offset values were established by overlaying the data from VICON with the corresponding data from the prototype hardware. The values were then varied and altered based on visual observations until a match as close as possible was made between the overlaid data. This was done for all the movements performed at mid range of movement at a comfortable velocity to simulate ADLs. A single mean scale value and a single mean offset value were then calculated from the values for each movement for each DOF. These values were then fixed for each respective DOF for all comparisons. Where data corresponding to velocity was required, the displacement values calculated from the data recorded by VICON were differentiated, and to allow for comparisons, the data from VICON was re-sampled to match the sample rate of the data recorded by the prototype hardware.

4.4.2. Noise analysis, out of plane movements and VICON variability

Noise analysis

Since it was thought that interference from the 50 Hz AC mains might interfere with recorded data, noise within the prototype hardware was analysed. From the data recorded at sample rates of 48 KHz and 200 Hz from the flex sensor and gyro sensor, the range of voltage and standard deviation within the samples was calculated. These calculations were also performed on the signal recorded from the channel with no sensor attached and the results are shown in Table 4.2.2a:

Table 4.4.2a. Range and standard deviation of samples recorded at 48 kHz

	Flex sensor	Gyro sensor	No sensor
Range: maximum – minimum (mV)	22.96	25.51	20.41
Standard deviation (mV)	4.28	4.51	4.36

It can be seen in Table 4.4.2a that the attachment of sensors only resulted in a small increase in noise. The gyro sensor exhibited the largest voltage range of noise at 25.51 mV. The estimated velocity which occurred at the elbow (extension and flexion) during the observation of movements in section 3.2.2 was 112 degrees per second which, according to the data sheet of the gyro sensor (STMicroelectronics 2009), would result in a signal magnitude of 372.96 mV. This range of noise as a percentage of the amplitude is approximately 7 %.

Table 4.4.2b. Range and standard deviation of samples recorded at 200 Hz

	Flex sensor	Gyro sensor	No sensor
Range: maximum – minimum (mV)	15.31	17.86	15.30
Standard deviation (mV)	4.39	4.75	3.93

As shown in Table 4.4.2b, the voltage range of noise and noise variation in the samples recorded at 200 Hz were largely the same as those in the samples recorded at 48 KHz. The slight decrease in voltage range may have been due to some of the variation being missed at the lower sample rate. Output graphs were generated from the data using the program described in section 4.3.3.
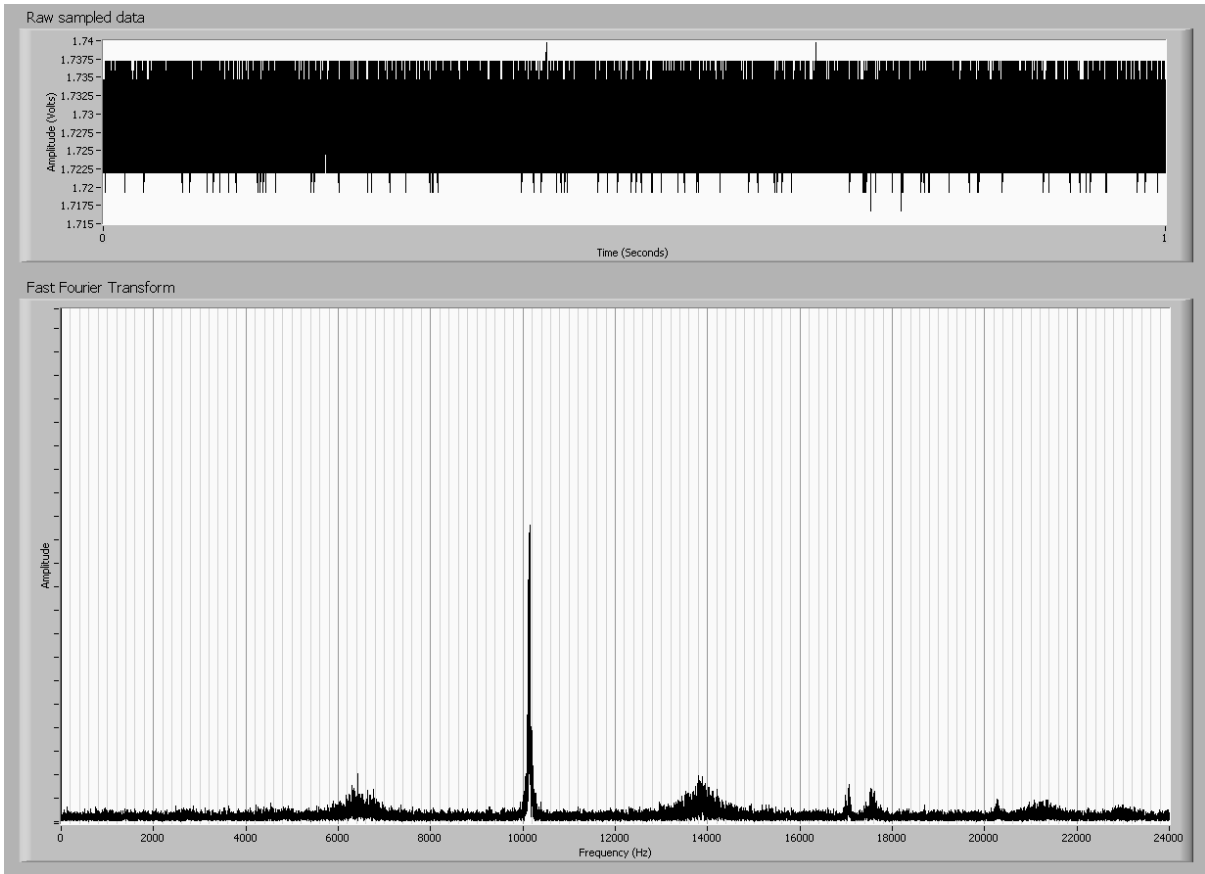
Figure 4.4.2a. FFT graph from the samples recorded at 48 KHz with a flex sensor attached
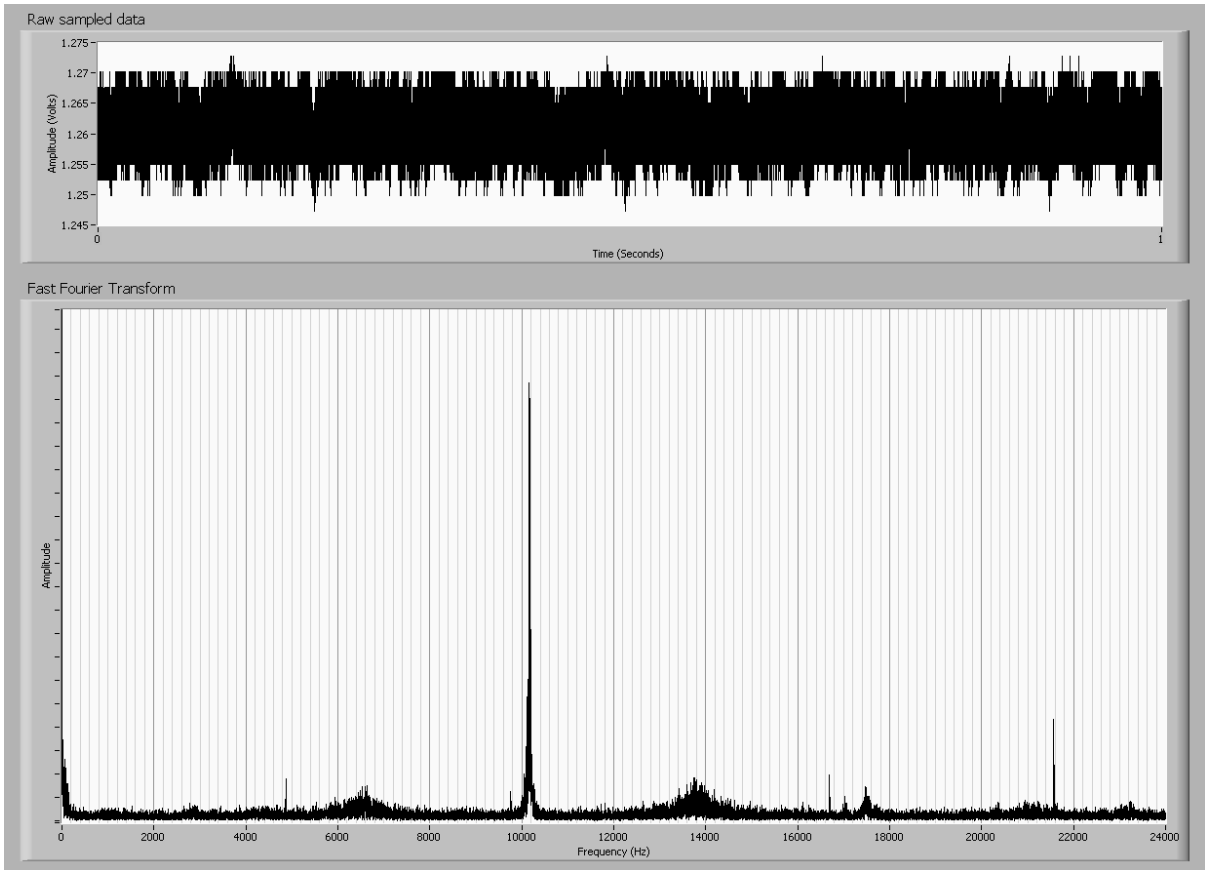
Figure 4.4.2b. FFT graph from the samples recorded at 48 KHz with a gyro sensor attached
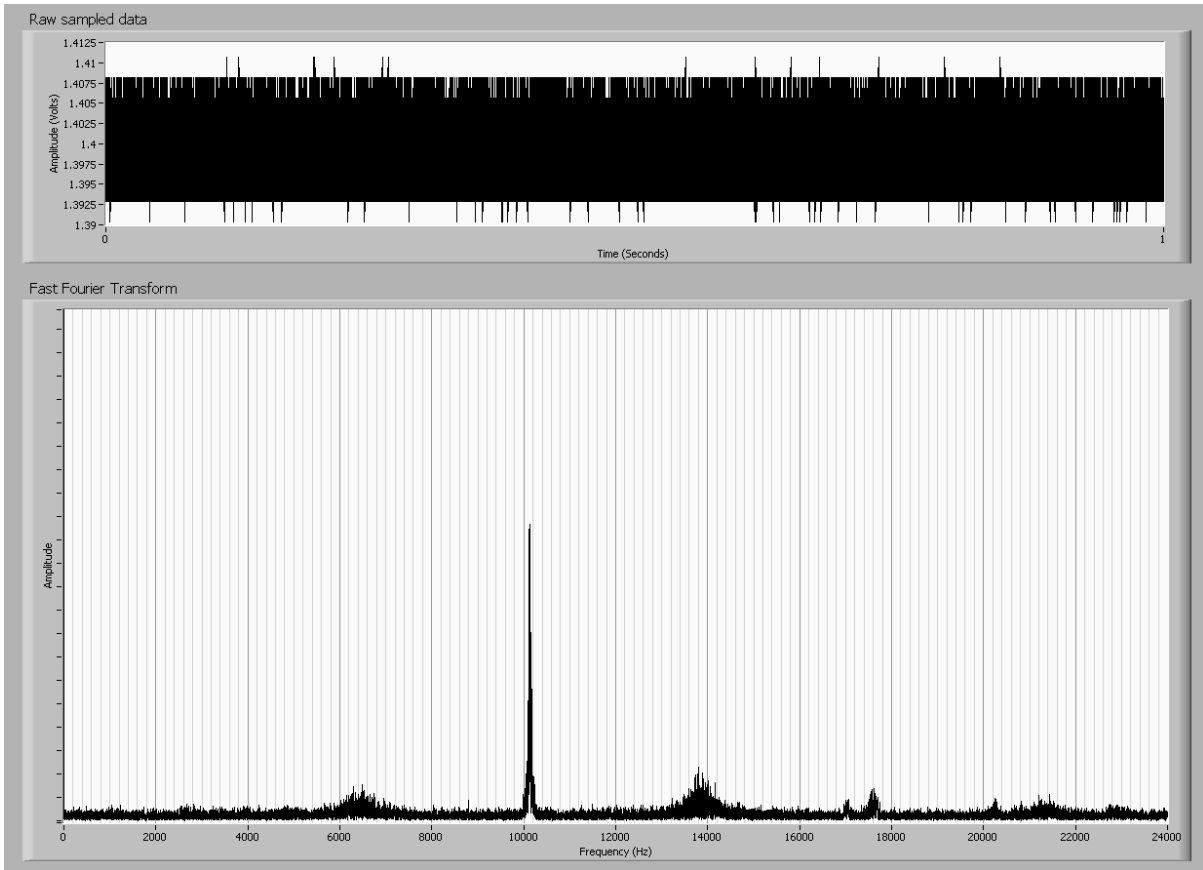
Figure 4.4.2c. FFT graph from the samples recorded at 48 KHz with no sensor attached

It can be seen from the relative amplitude in all FFT graphs from the samples recorded at 48 KHz (figures 4.4.2a to 4.4.2c) that some low amplitude noise concentrations were present at 6 and 16 KHz and a significant peak occurred at 10 KHz. The FFT graphs for the samples recorded at 200 Hz are shown below.
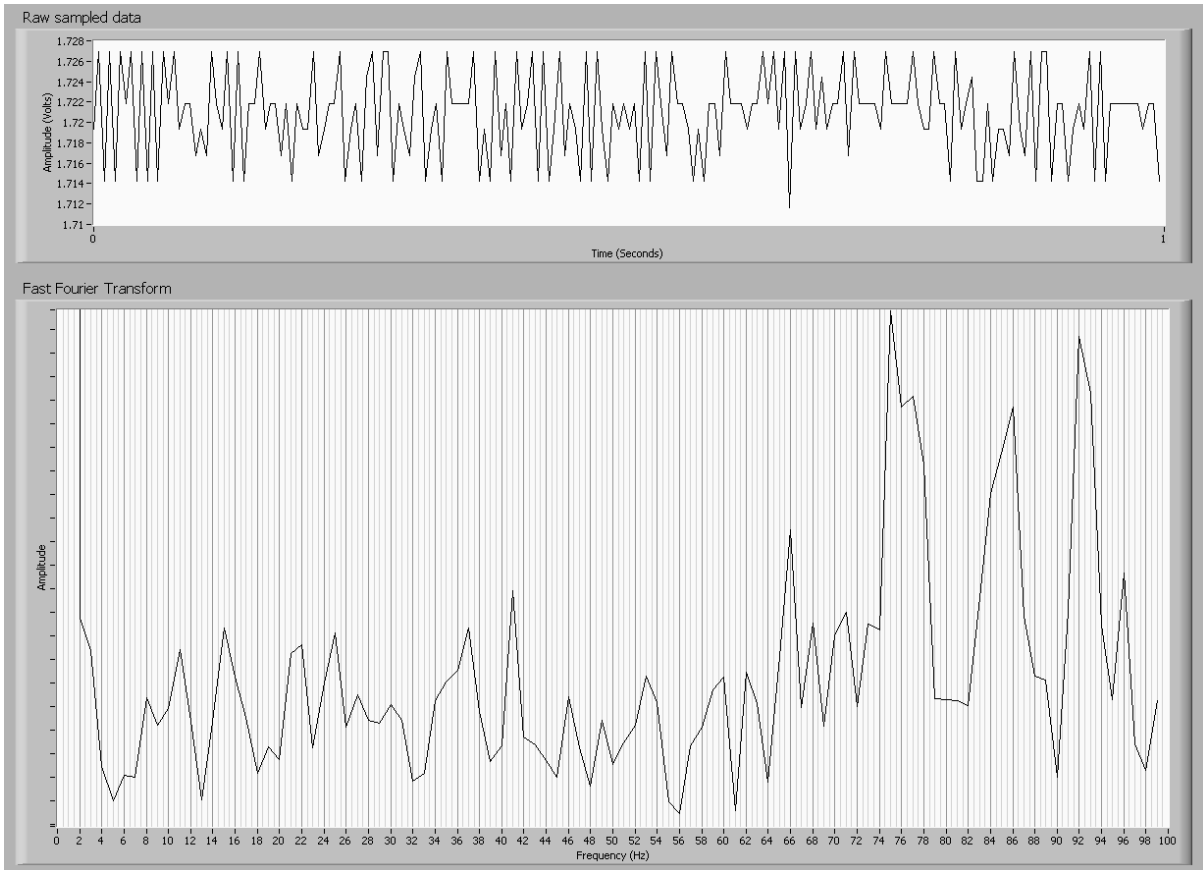
Figure 4.4.2d. FFT graph from the samples recorded at 200 Hz with a flex sensor attached
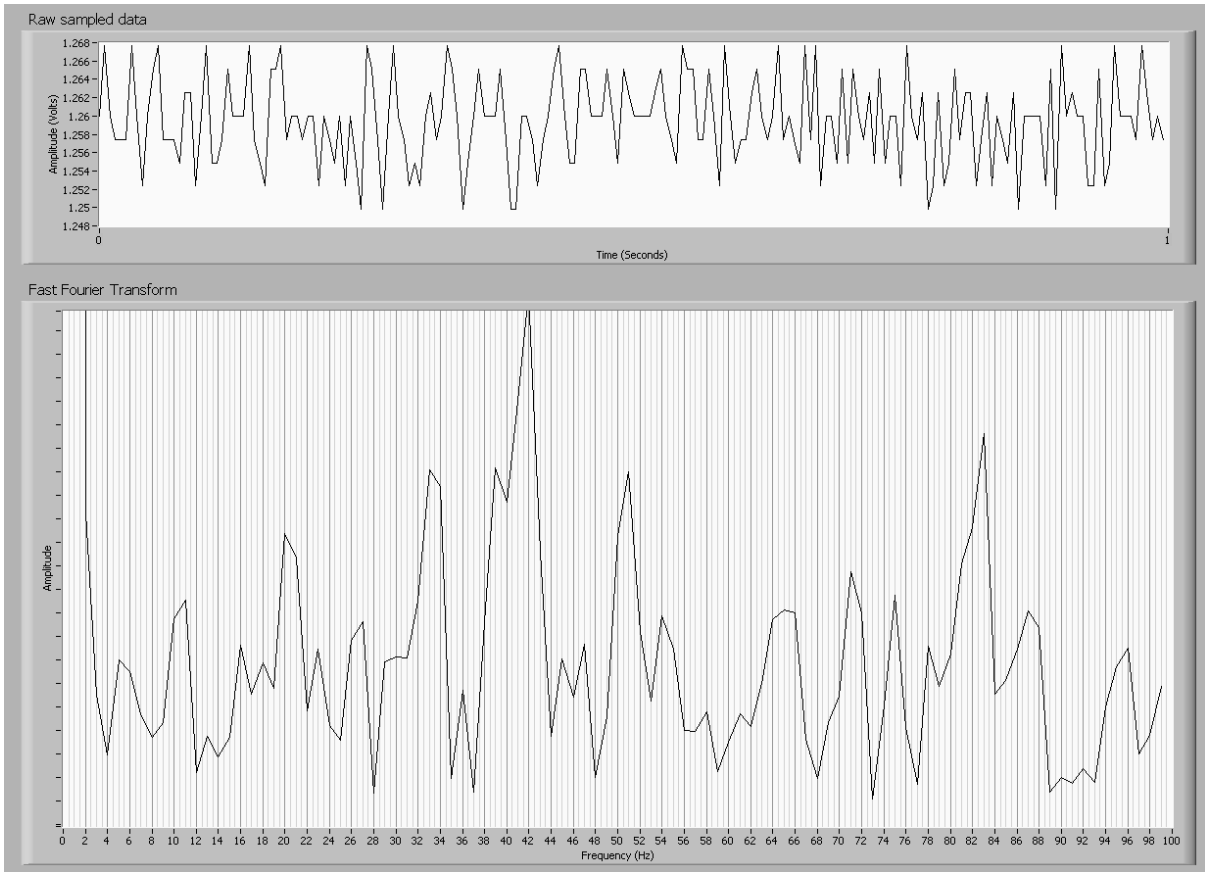
Figure 4.4.2e. FFT graph from the samples recorded at 200 Hz with a gyro sensor attached
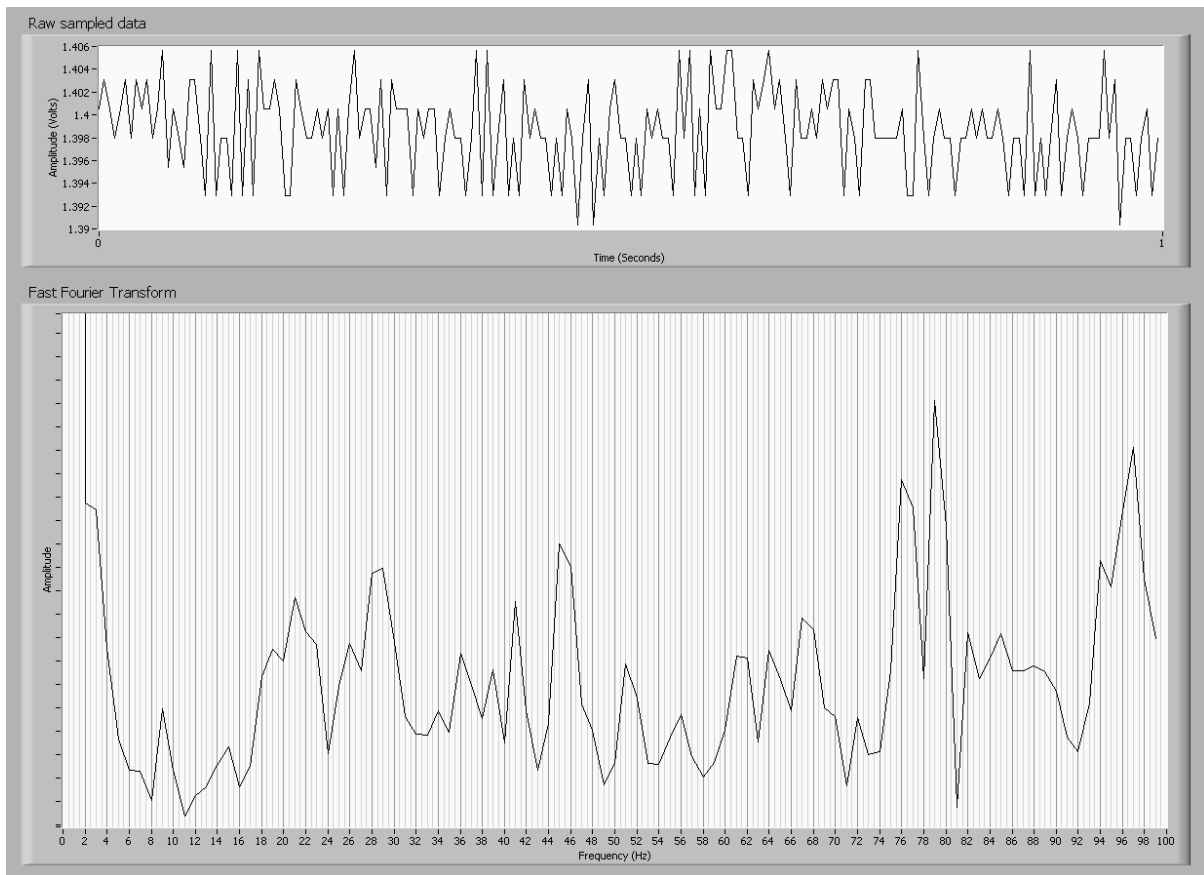
Figure 4.4.2f. FFT graph from the samples recorded at 200 Hz with no sensor attached

No concentrations of noise at 50 Hz or at any other frequency were seen in the data recorded at 200 Hz (shown in figures 4.4.2d to 4.4.2f). The source of the peak in noise at 10 kHz could perhaps be an internal clock on the DAQ. The effects of this were eliminated by implementing 200 Hz low-pass filters in the software programs for the prototype system. This was done using built-in functions applied to all signals inputting the programs.

The effect of out-of-plane movements

As stated, participants were asked to try to move only within certain planes. However, it is impossible to isolate movement totally to within certain planes, so the effect on the calculation of movements out of these planes was investigated. Since the plane moved in most often was the sagittal plane, the effect of movement out of this plane was investigated. If the movement had been purely within the sagittal plane, there would be no movement in the Y axis of markers 3 and 4. Therefore the deviation from the sagittal plane can be investigated by studying the movement in the Y axis of markers 3 and 4 that occurred during movements. This can then be equated to an error in the measurement of elbow

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extension and flexion. Since the effect of deviation from the sagittal plane was an estimate, as a time saving measure, only four of the ten repetitions of elbow extension and flexion were examined. Similarly, four of the ten repetitions of hand pronation and supination were examined because elbow extension and flexion also occurred during these movements. These movements were examined from both participants giving 16 movements in total. The difference between the Y coordinate value for marker 3 and 4 was calculated for each sample. The range of differences was then calculated for each movement. This was done rather than examining the maximum difference during the movement because differences could have existed prior to the recording of samples, caused for example by tapering of the upper arm towards the wrist. These differences would be best ignored because the centre of the arm may still align with the sagittal plane.

Table 4.4.2c. Ranges of differences between the Y coordinate values for markers 3 and 4 (mm)

Movement	Participant one	Participant two
Elbow extension and flexion 1	34.28	30.14
Elbow extension and flexion 2	44.11	20.41
Elbow extension and flexion 3	42.42	24.79
Elbow extension and flexion 4	48.29	27.46
Hand pronation and supination 1	48.29	48.00
Hand pronation and supination 2	64.46	45.21
Hand pronation and supination 3	68.62	43.90
Hand pronation and supination 4	52.03	43.11

Of the ranges shown in Table 4.4.2c, the mean was calculated as 42.85 mm. To calculate the effect of this, an elbow extension displacement between the maximum and minimum reached during performance of the reach and grasp movement was specified as 135 degrees. This was considered a nominal position for the upper arm and forearm and formed the basis of calculations of the effect of out-of-plane movements. The relative lengths of the upper arm and forearm were then estimated based on the distances between markers 1

and 2 and between markers 3 and 4 of samples from VICON. This was again achieved using equation 4.4.1c. The same was done for both participants and means were calculated. The mean distance between markers 1 and 2 was 181.50 mm and between 3 and 4 was 168.02 mm.
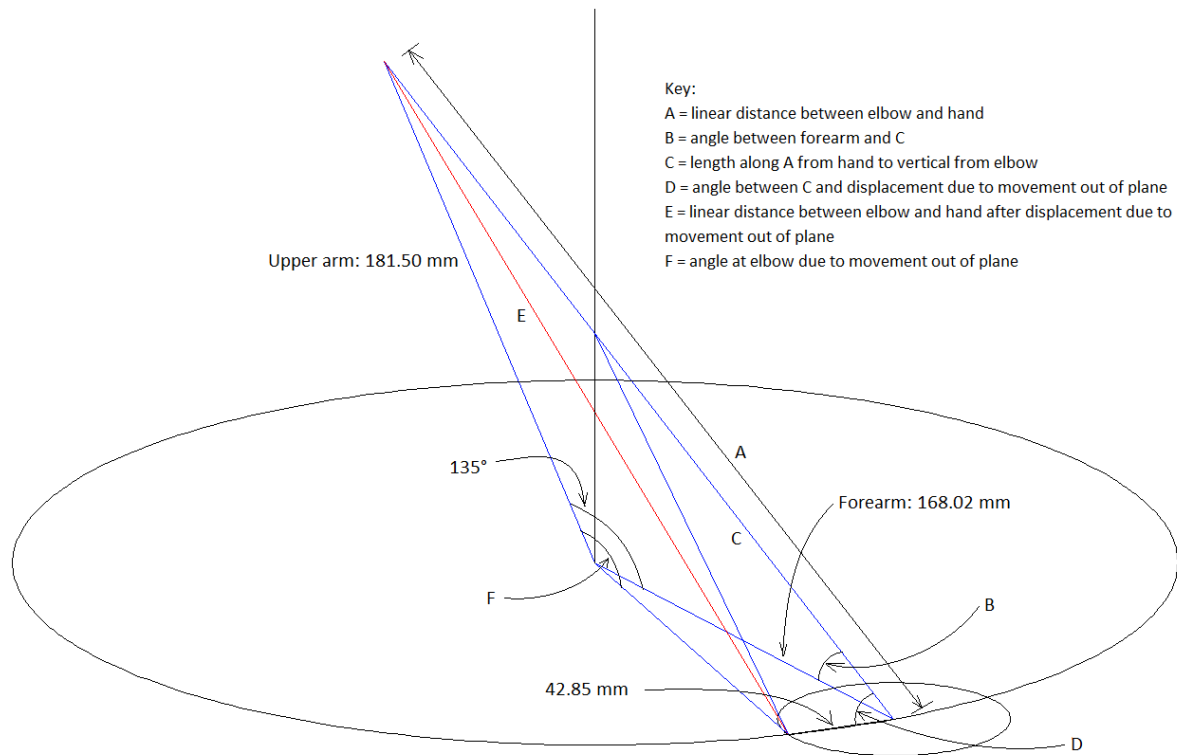
Figure 4.4.2g. Dimensions of the nominal position of the upper arm and forearm with the out-of-plane movement shown

The effect of the out-of-plane movement identified above was then calculated using trigonometry, see Appendix 4, where the angle F in Figure 4.4.2g was calculated as 133.17 degrees. The difference between this and the assumed displacement of 135 degrees is 1.83 degrees. The average range of movement at the elbow and shoulder during the reaching and grasping movements was calculated as 69.25 degrees (which is explained further in section 4.4.7). The displacement was then calculated as a percentage of the range of movement as 2.65 %. That is to say, the estimated maximum error due to movements out of the sagittal plane was 2.65 % of the mean range of movement. This shows that movements were mainly within the specified planes, which supports the validity of the tests.

Variability in the data recorded from VICON

To further understand the data from the tests, the variability of the data gathered from VICON was investigated. To do this the two markers at a fixed distance from one another, markers 7 and 8 attached to either end of the bar shown in Figure 4.3.6c, were considered. The distances between markers 7 and 8 were then calculated per sample from the data recorded by VICON during the hand pronation and supination movements where the bar was rotated. These movements were chosen because they were thought to be most likely to result in variability as the markers move in multiple planes. Equation 4.4.1c was used again to find the distance between markers 7 and 8. These calculated distances were then checked for anomalous values and the range of distances was calculated for each of the hand pronation and supination movements. Considering the range gave a worst case estimate of the performance of VICON, however, because no anomalous values were present, it was considered a valid approach. The standard deviation of the calculated distances was also calculated and the values are shown in Table 4.4.2d:

Table 4.4.2d. Ranges and standard deviations of calculated distances between markers 7 and 8 during the pronation and supination movements

Participant one		Participant two	
Range of distances (mm)	Standard deviation (mm)	Range of distances (mm)	Standard deviation (mm)
3.05	0.67	2.91	0.50
2.50	0.43	2.71	0.46
3.24	0.56	2.70	0.59
2.73	0.43	2.83	0.51
2.73	0.35	2.87	0.53
2.71	0.30	2.88	0.50
2.52	0.54	3.18	0.61
2.41	0.46	3.04	0.60
2.66	0.52	3.17	0.58
2.88	0.57	3.25	0.56

The mean range of distances (of both participants) was then calculated as 2.85 mm. The maximum range was also identified as 3.25 mm. The mean standard deviation of the distances was also calculated as 0.51 mm. That is to say, the variability in the data recorded by VICON was 0.51 mm. These values are small relative to the distances moved through by the participants, which supports the validity of the tests.

4.4.3. Correlation between the prototype hardware and VICON

The correlation was investigated by graphically overlaying data from the prototype hardware with data from VICON recorded during the ADL movements. An example of each ADL movement is shown in figures 4.4.3a to 4.4.3d:
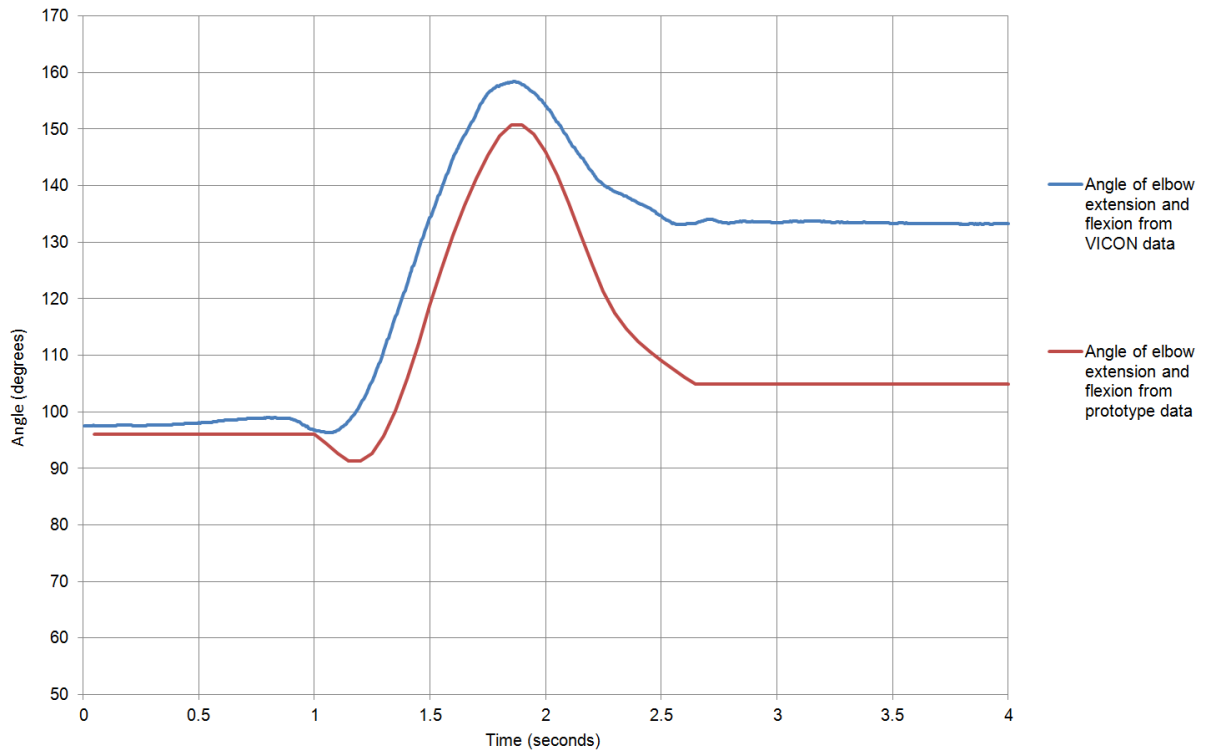
Figure 4.4.3a. Overlaid data from the prototype hardware and VICON during an example ADL movement examining elbow extension and flexion
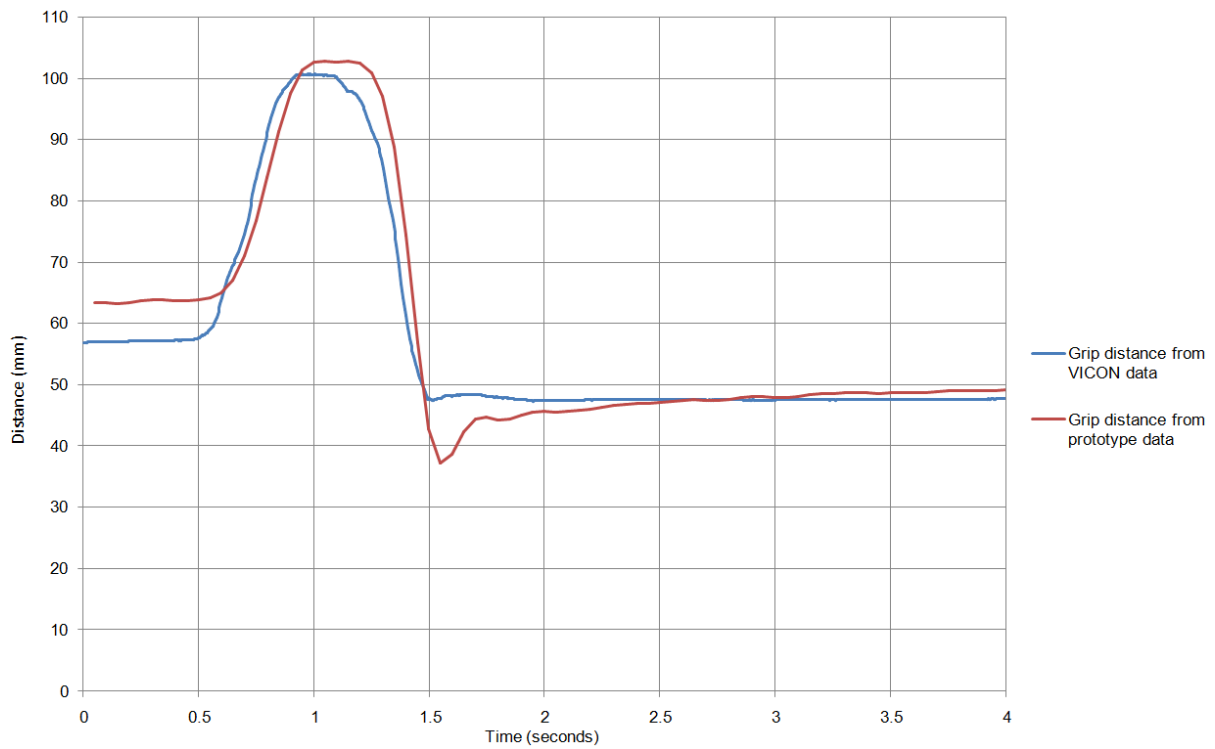
Figure 4.4.3b. Overlaid data from the prototype hardware and VICON during an example ADL movement examining hand opening and closing
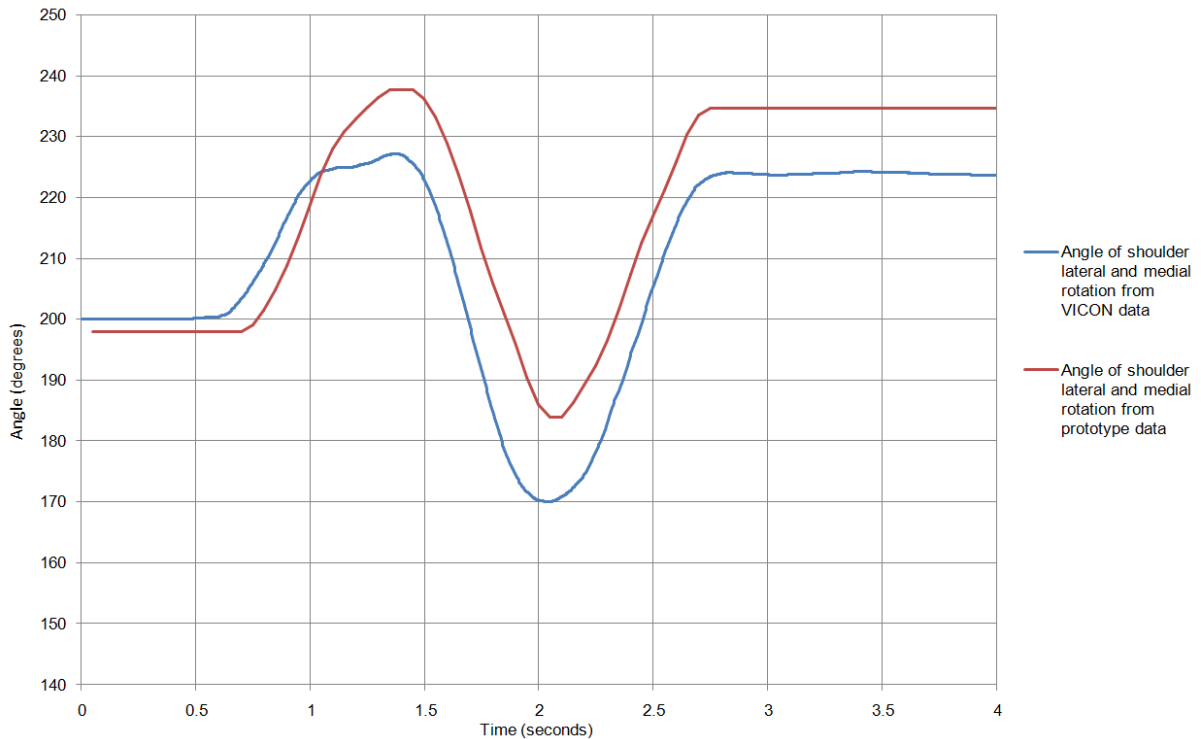
Figure 4.4.3c. Overlaid data from the prototype hardware and VICON during an example ADL movement examining shoulder lateral and medial rotation

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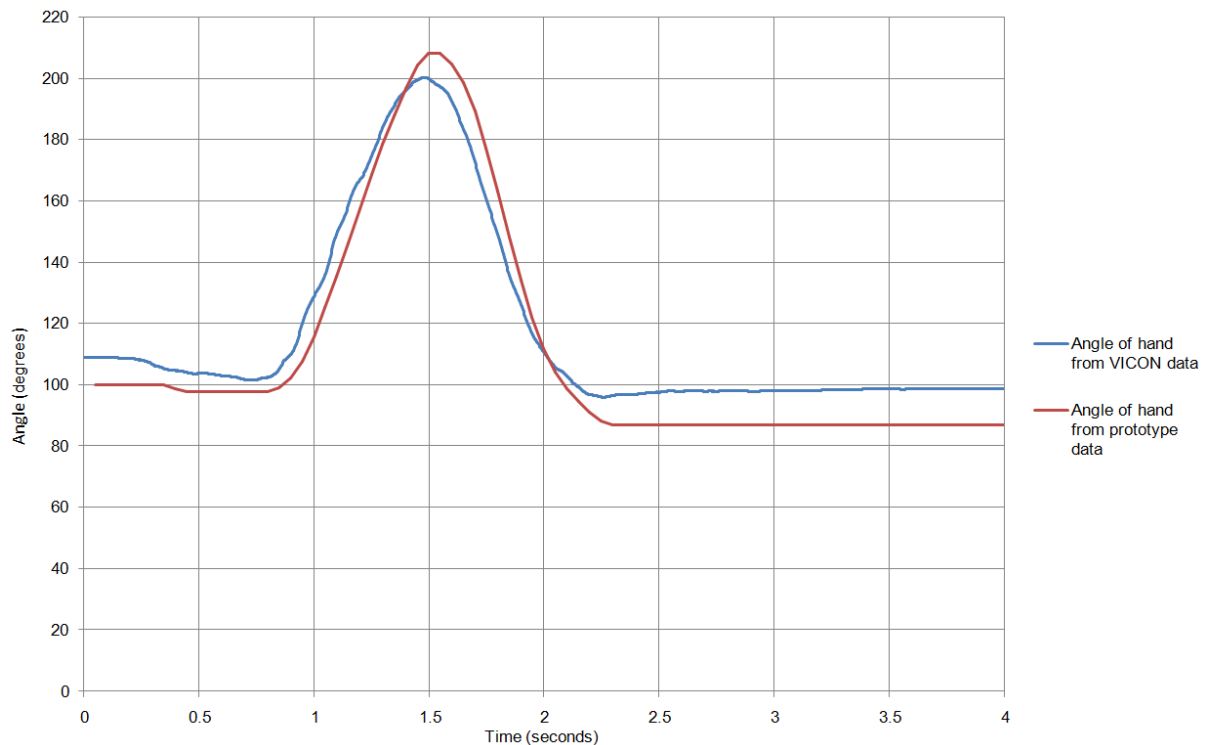
Figure 4.4.3d. Overlaid data from the prototype hardware and VICON during an example ADL movement examining hand pronation and supination

Although, to be concise, only four example movements are shown in figures 4.4.3a to 4.4.3d, the response of the prototype hardware was similar during other ADL movements. In all movements, correlation between data from the prototype hardware and VICON can be seen. Differences are in some cases are greater towards the end of the movement. This was thought to be due to accumulation of errors, caused by integration of the data from the gyro sensors. Also, in all cases, a very slight delay of the data from the prototype hardware occurred. This may be caused by the low pass filters included in the software for the prototype hardware.

4.4.4. Performance when measuring large displacements

This section investigates the behaviour of the prototype hardware when the DOFs were moved through full ranges of movement. Data from the prototype hardware was again overlaid with data from VICON.
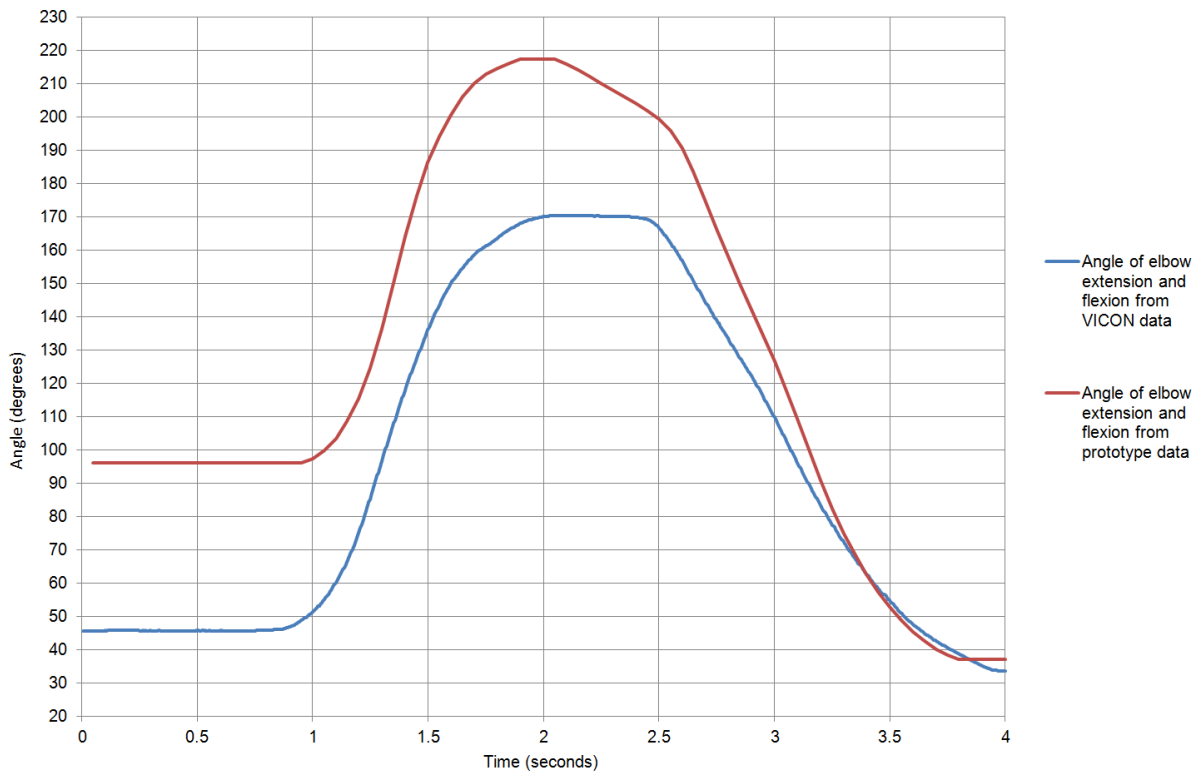
Figure 4.4.4a. Elbow full extension to full flexion

The maximum and minimum displacements of the movement in Figure 4.4.4a from the VICON data were 170.39 and 33.61 degrees respectively, giving a range of 136.77 degrees. The same was done for the other movements through large displacements.
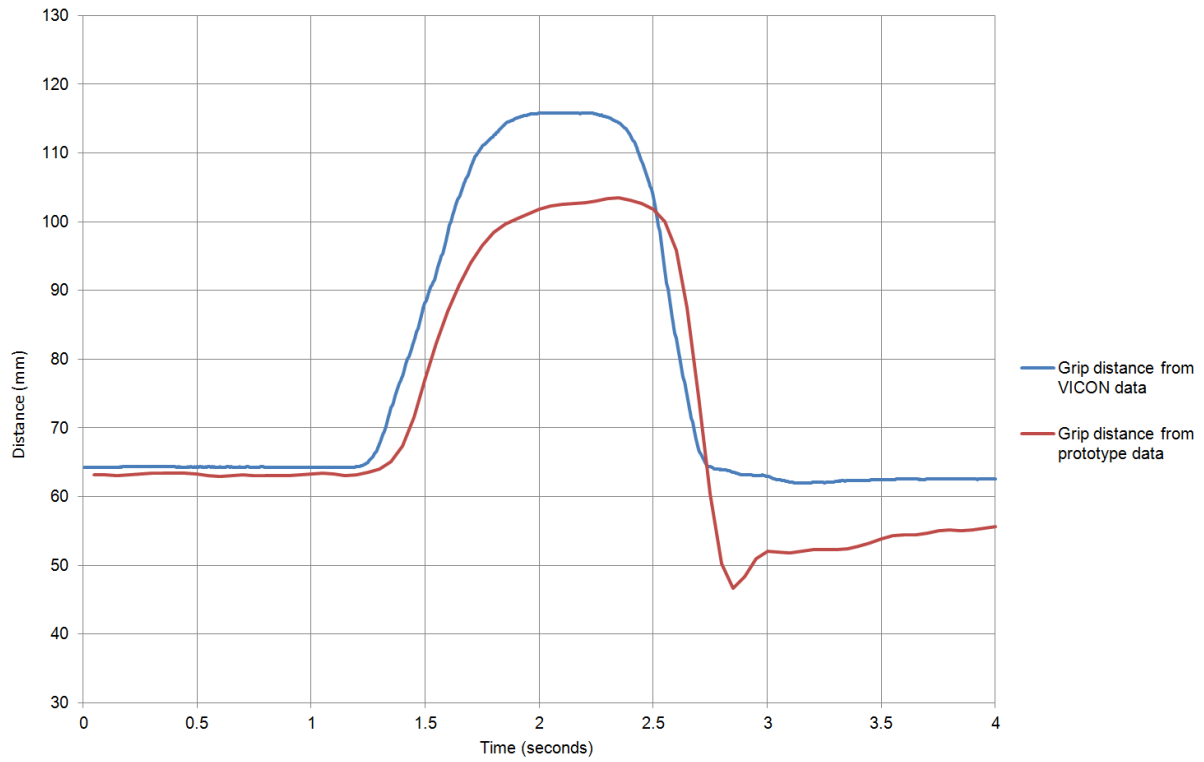
Figure 4.4.4b. Hand fully closed to fully open
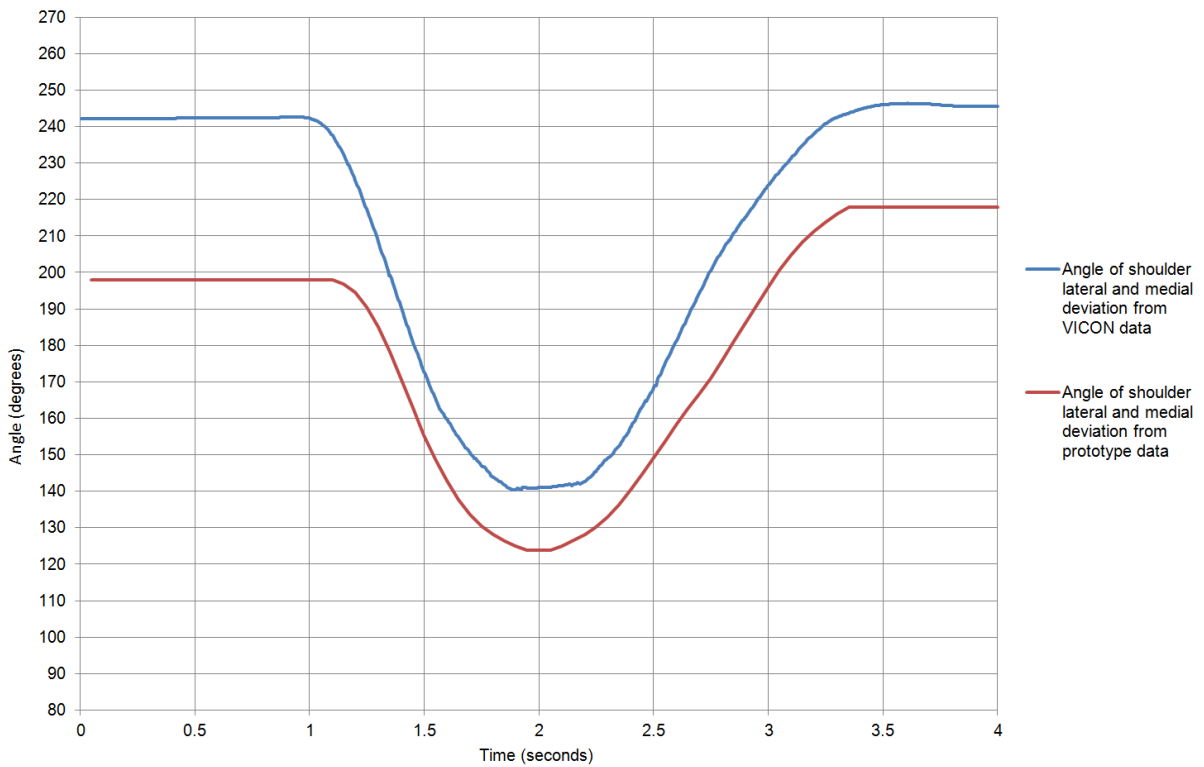
Figure 4.4.4c. Shoulder full medial rotation to full lateral rotation
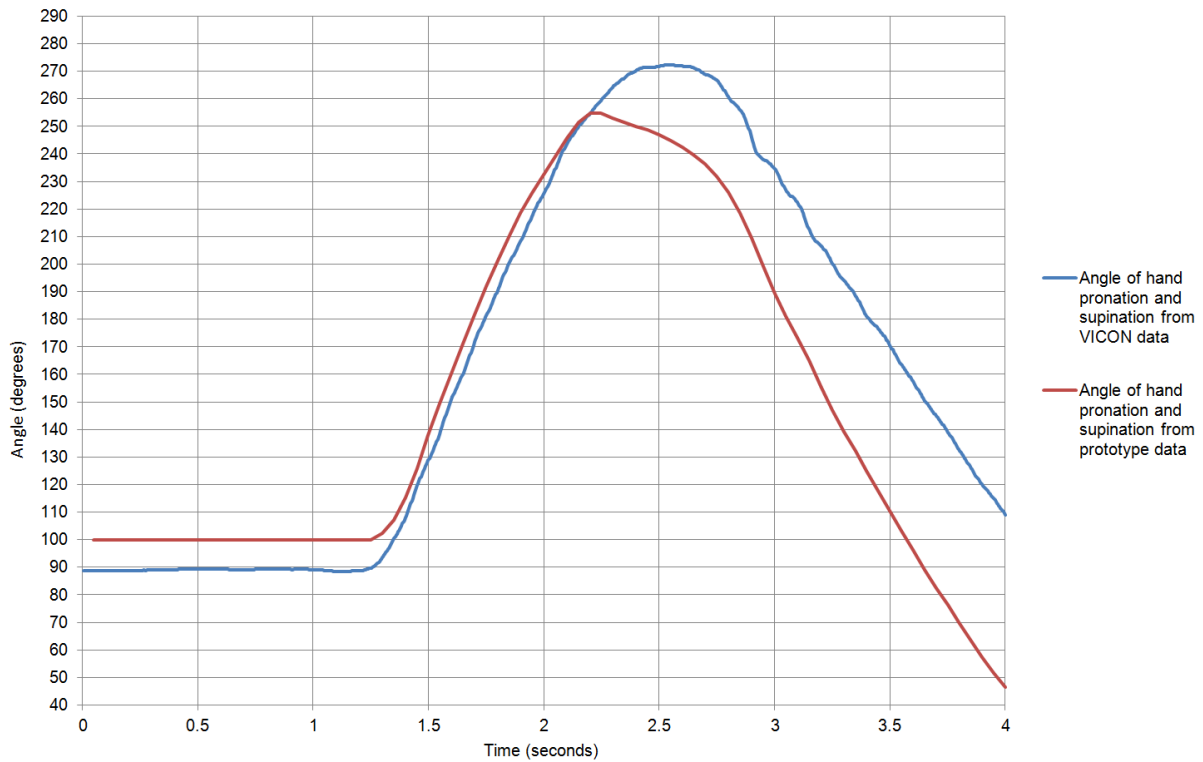
Figure 4.4.4d. Hand full pronation to full supination

Figures 4.4.4b to 4.4.4d. show that the differences between data from the prototype hardware and from VICON were greater when moving at high velocity than when performing the ADL movements. This may be due to there being more displacement moved through and thus a greater chance of errors occurring. Large differences appeared at the start of movements as shown in figures 4.4.4a and 4.4.4c. This is likely due to the scale and offset values for the data for VICON being established only from examination of the ADL movements. Figures 4.4.4a to 4.4.4d show data recorded by participant one. The responses from participant two were similar.

Table 4.4.4. Maximum and minimum displacements and ranges of displacement

	Elbow full extension to full flexion (degrees)	Hand fully closed to fully open (mm)	Shoulder full medial rotation to full lateral rotation (degrees)	Hand full pronation to full supination (degrees)
Maximum displacement	170.39	115.85	246.39	272.33
Minimum displacement	33.61	61.92	140.29	88.35
Range of displacement	136.77	53.93	106.10	183.98

Table 4.4.4 shows that the maximum range of displacement was 183.98 degrees during pronation and supination. At this displacement, correlation between data from the prototype hardware and VICON can still be seen (Figure 4.4.4d).

4.4.5. Performance when measuring high velocity movements

This section investigates the behaviour of the prototype hardware when the DOFs were moved at higher velocities than when performing the ADL movements.
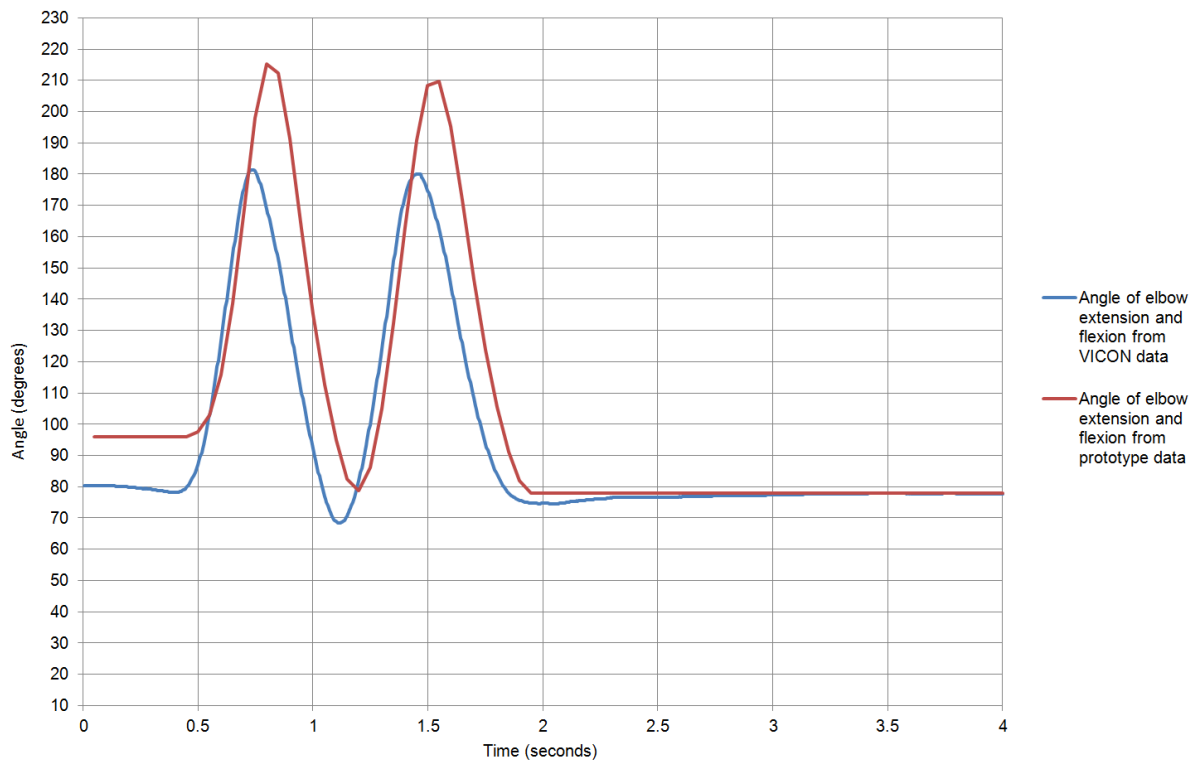
Figure 4.4.5a. Elbow extension to flexion at high velocity

To calculate the velocity of the movement shown in Figure 4.4.5a, the displacements calculated from the data from VICON were differentiated. From this, the maximum velocity was then identified as 577 degrees per second or approximately 96 RPM. The same was done for other movements investigating performance at high velocities.
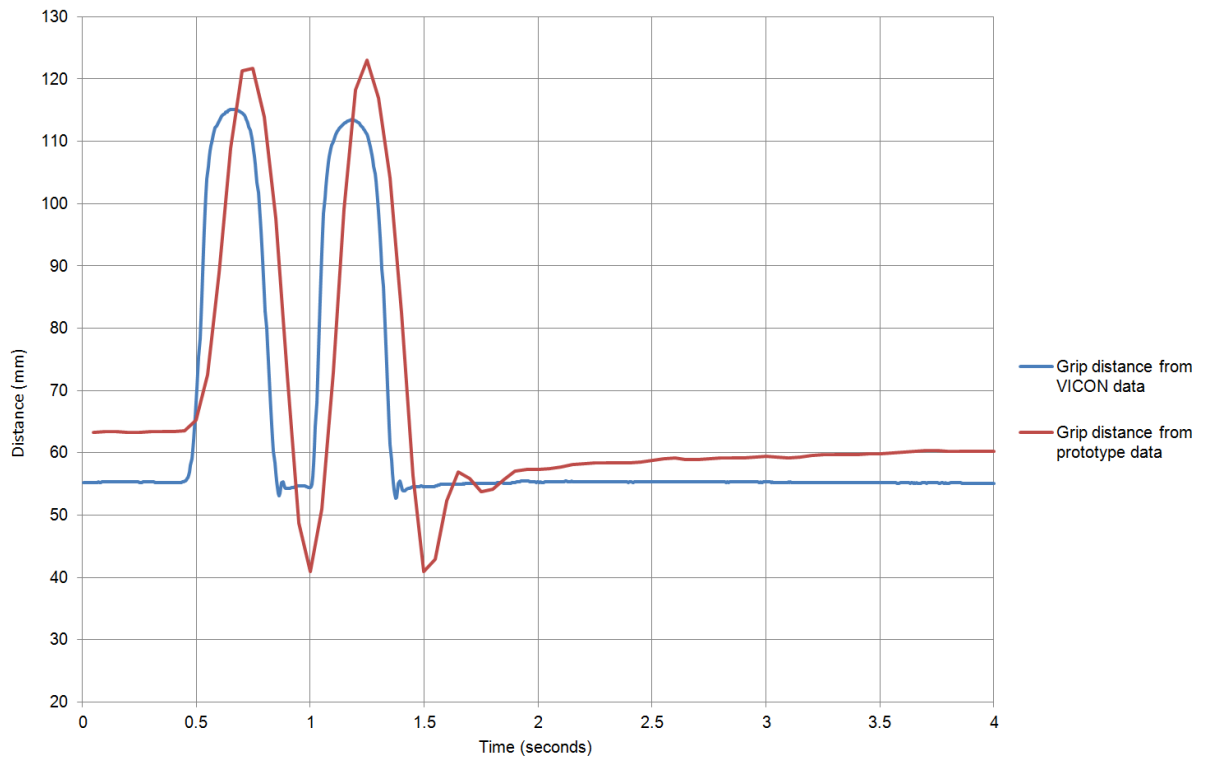
Figure 4.4.5b. Open hand to closed hand at high velocity
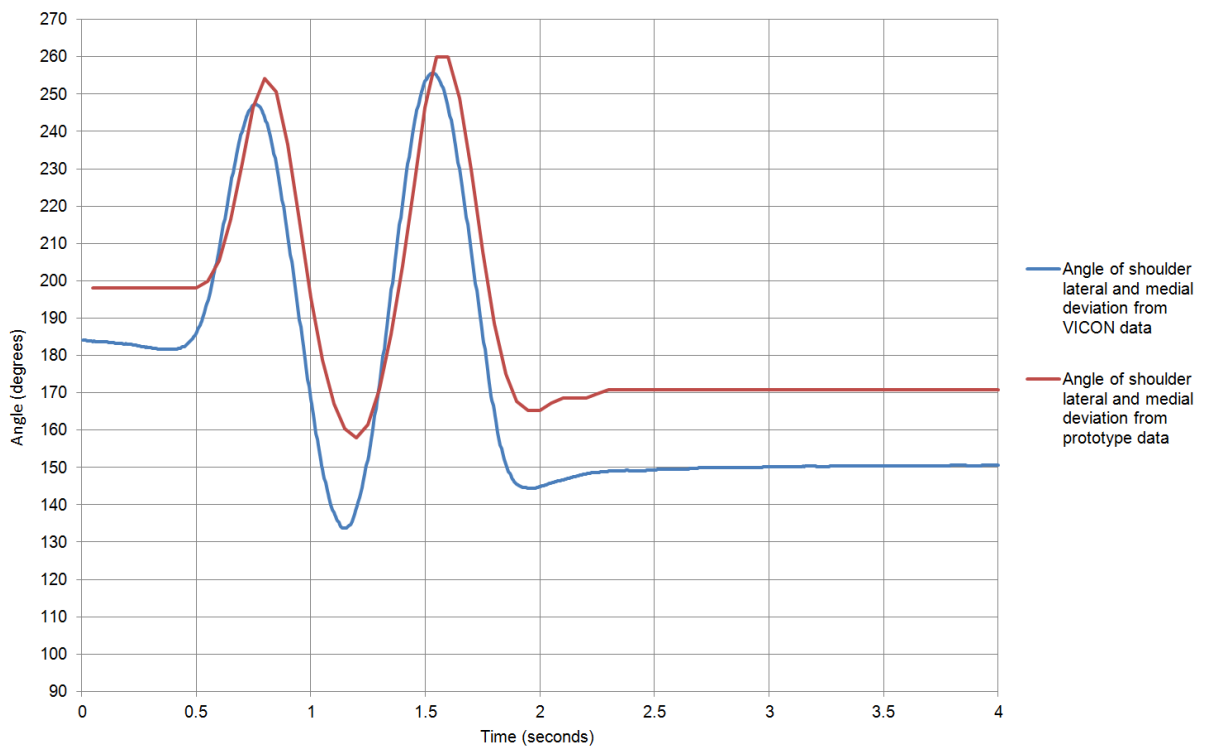
Figure 4.4.5c. Shoulder medial rotation to lateral rotation at high velocity
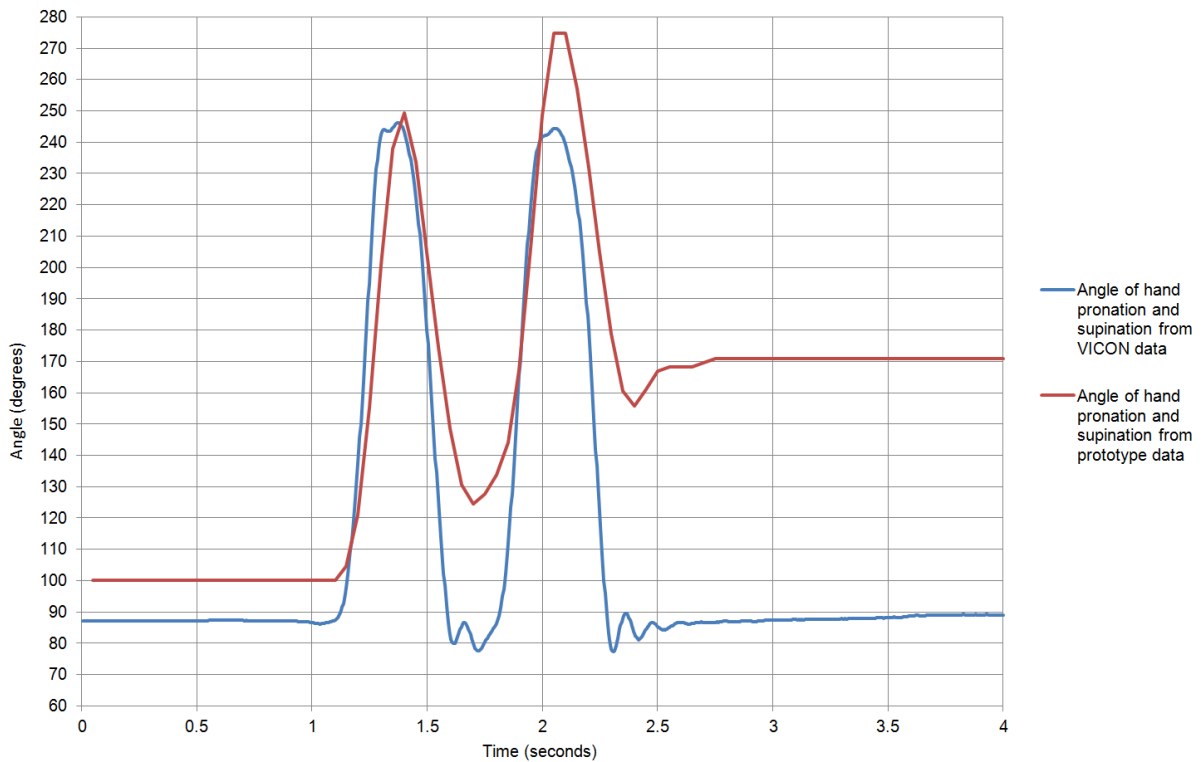
Figure 4.4.5d. Hand pronation to supination at high velocity

Figures 4.4.5b to 4.4.5d show that the differences between data from the prototype hardware and from VICON were again greater when performing high velocity movements than when performing the ADL movements. This may be due to sensors moving relative to the skin due to inertia. Also, it can again be seen that differences between data from the prototype hardware and from VICON are more apparent towards the end of the movement, more so as the second repetition of the movement was performed. This may be due to errors from two repetitions accumulating during the integration calculation. In all movements, correlation between data from the prototype hardware and VICON can be seen.

Table 4.4.5. Maximum velocities during movements performed at high velocity

Elbow extension to flexion (degrees/second)	Open hand to closed hand (mm/second)	Shoulder medial rotation to lateral rotation (degrees/second)	Hand pronation to supination (degrees/second)
577	825	477	1290

Table 4.4. shows that the maximum angular velocity occurred at the hand in pronation to supination at 1290 degrees per second or approximately 215 RPM. The angular velocity of 1290 degrees per second exceeds the rating of the gyro sensor of maximum input of 300 degrees per second. However no cut-off characteristics were observed. It was thought that perhaps the manufacturers of the gyro sensor recommend a maximum of 300 degrees per second because the response would become less linear at angular velocities higher than this.

4.4.6. Minimum velocities and displacements detectable

This section investigates the behaviour of the prototype hardware when the DOFs were moved at velocities progressively reducing to zero.
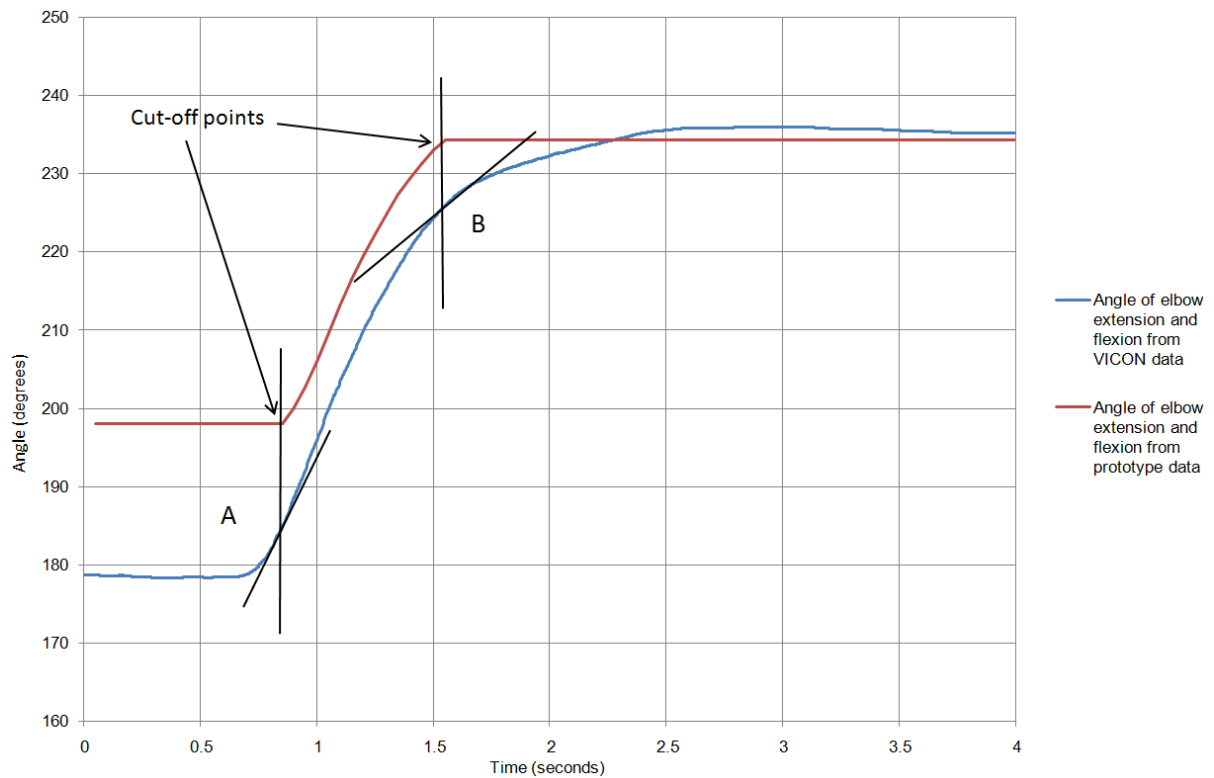
Figure 4.4.6a. Elbow moved through extension with progressively reduced velocity

Cut-off points can be seen in Figure 4.4.6a in the data from the prototype system where recording of movement stopped. These are due to the velocity thresholds built into the program as described in section 3.6.4. The velocity was identified from the data from VICON at the times of cut-off. The velocities at A and B were then read, where 'A' was the velocity at the start of the movement and 'B' at the end (see Figure 4.4.6a). This gave 'A' and 'B' as 32.06 and 26.78 degrees per second respectively (from the VICON data). The same was done for the other movements.
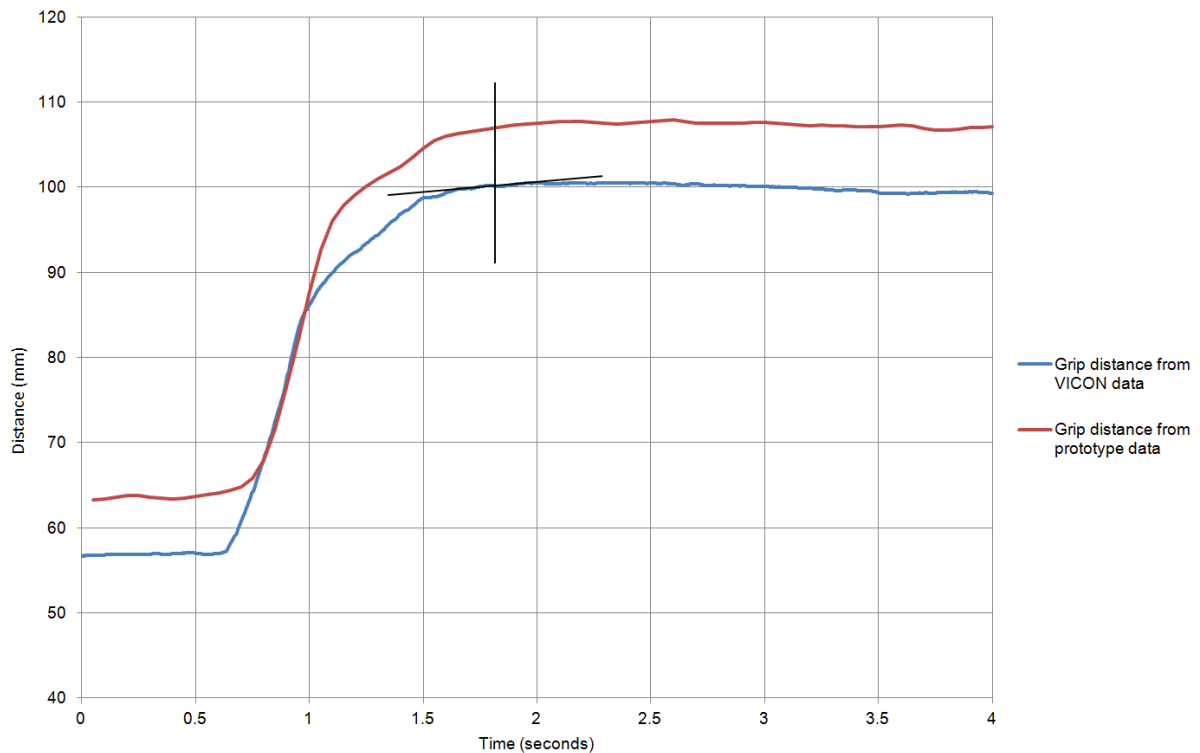
Figure 4.4.6b. Hand opened with progressively reduced velocity

As the hand opening and closing was measured using a flex sensor, no velocity threshold was applied to the signal meaning that no distinct cut-off points exist (shown in Figure 4.4.6b). The approximate velocity where the data from the prototype hardware reduced to zero gradient was therefore identified visually and the corresponding velocity was identified as 6.19 mm per second. This was only done at the end of the movement because the data from the prototype hardware appeared to be slightly delayed. This could have been caused by slight flex in the sensor mounting. Figures 4.4.6c and 4.4.6.d show the responses from shoulder lateral deviation and hand supination with angular velocities progressively reducing to zero:
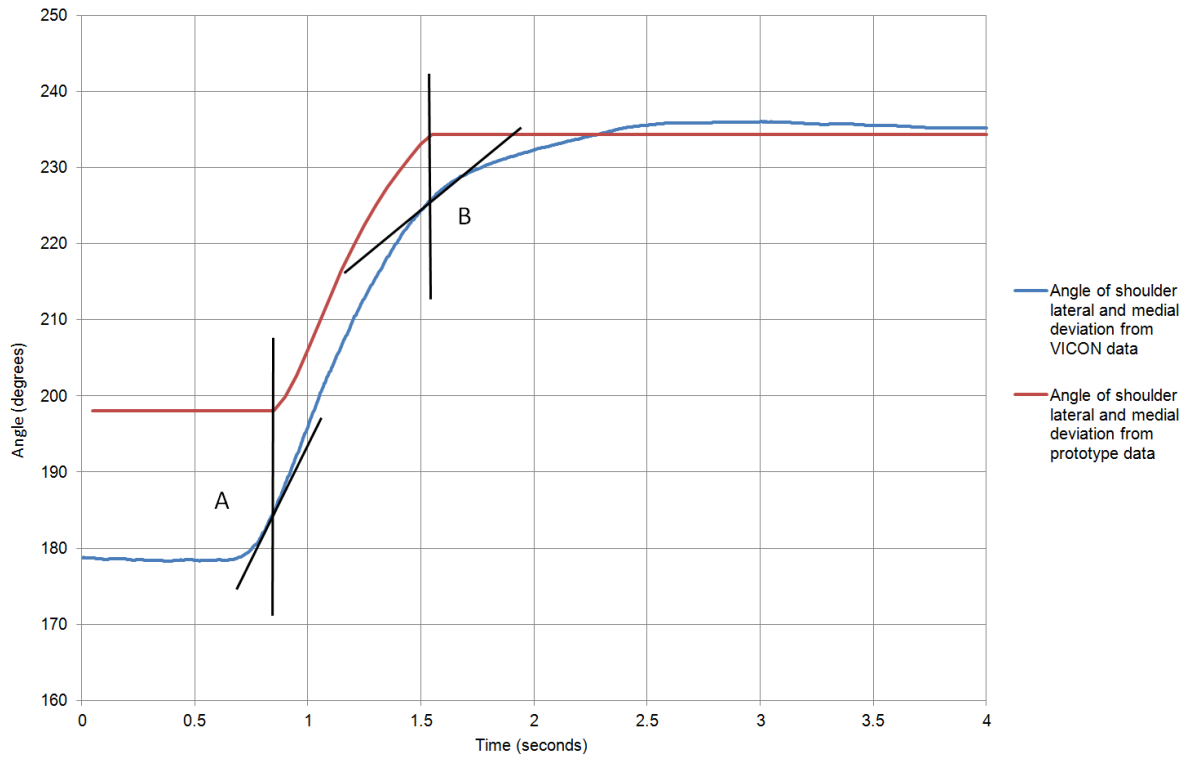
Figure 4.4.6c. Shoulder moved through lateral deviation with progressively reduced velocity
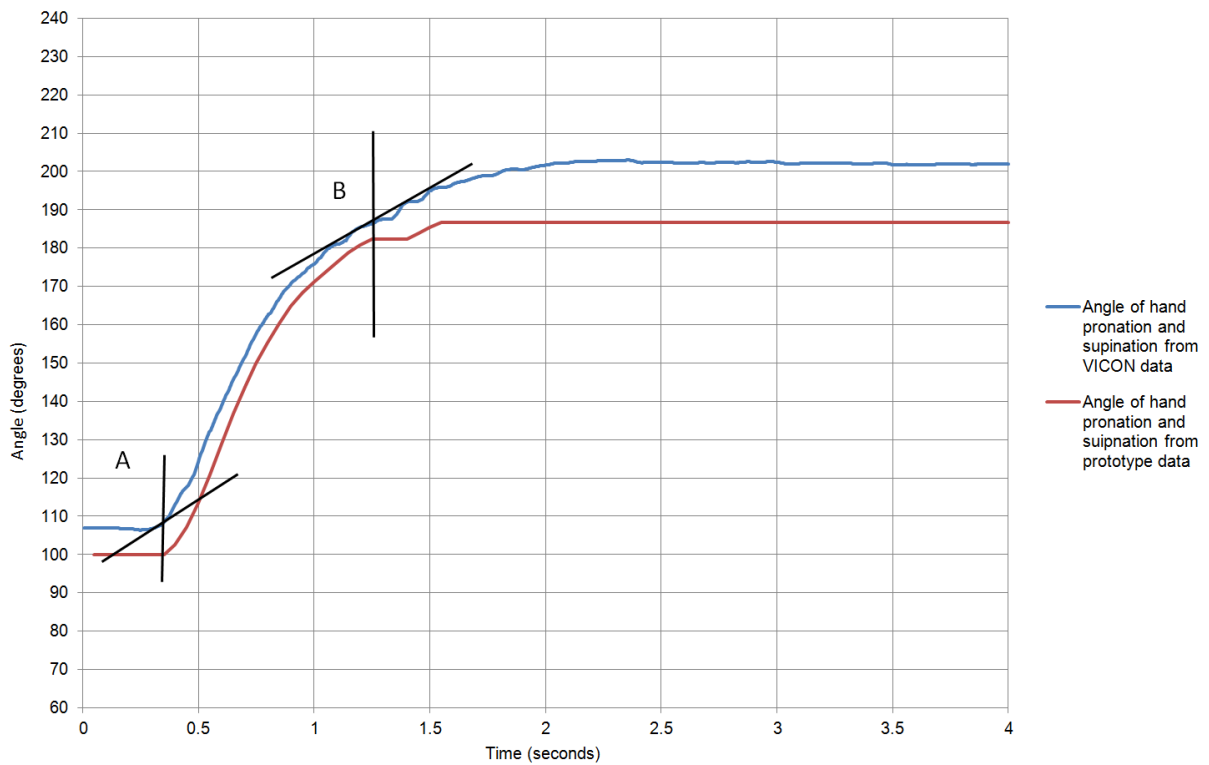
Figure 4.4.6d. Hand moved through supination with progressively reduced velocity

Table 4.4.6a. Minimum readable velocities by the prototype hardware

	Elbow moved through extension with progressively reduced velocity (degrees/second)	Hand opened with progressively reduced velocity (mm/second)	Shoulder moved through lateral deviation with progressively reduced velocity (degrees/second)	Hand moved through supination with progressively reduced velocity (degrees/second)
Start of movement (A)	32.06	Not available	38.71	32.81
End of movement (B)	26.78	6.19	34.91	17.96

From the data in Table 4.4.6a, the mean minimum angular velocity (from elbow extension, shoulder lateral deviation and hand supination) was calculated as 30.54 degrees per second. The minimum displacements readable by the prototype hardware are functions of the minimum readable velocities and the sample rate of the prototype hardware. The sample interval at a sample rate of 20 Hz is 0.05 seconds. This was multiplied by the mean minimum angular velocity (30.54 degrees per second) and the minimum linear velocity (from hand opening, 6.19 mm per second) to obtain estimates for the minimum displacements detectable by the prototype hardware, as shown in Table 4.4.6b:

Table 4.4.6b. Estimated minimum detectable displacements by the prototype hardware

	Linear displacements (mm)	Angular displacements (degrees)
Minimum detectable displacements	0.31	1.53

Conclusions from these results are drawn in section 4.5.

4.4.7. Intra-variability of the prototype hardware

Intra-variability was calculated as variation in differences between data from the prototype hardware and VICON during repetitions of the ADL movements. This was chosen as a method of investigating intra-variability, because as stated, VICON is known to be accurate and repeatable in measuring human movement. For each repetition of each of the ADL movements, differences were calculated at three points. This was done as opposed to

calculating a mean difference over the entire movement, because the exact start and end points of movements would be difficult to locate. Also, a mean difference would in many cases be a poor representation of the differences, because positive and negative differences at different parts of the movement can have a cancelling effect. The difference at the peak of the movement was therefore calculated as well as at plus and minus 0.25 of a second from the peak (see Figure 4.4.7).
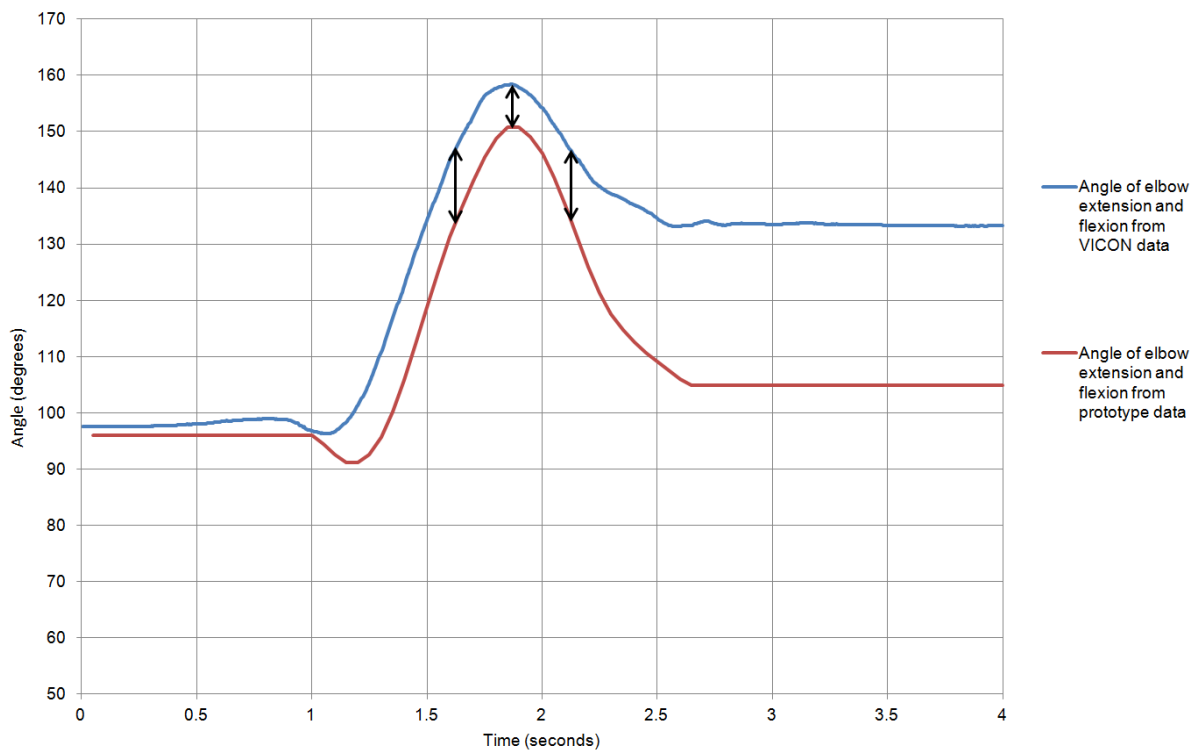
Figure 4.4.7. The locations of calculations of difference between the prototype hardware and VICON during an example ADL movement examining elbow extension and flexion

Initially, these three differences were calculated for each of the 10 repetitions of the ADL movement examining elbow extension and flexion performed by the participant one.

Table 4.4.7a. Differences for repetitions of the ADL movement examining elbow extension and flexion by participant one

Repetition number	Values from the prototype hardware (degrees)	Values from VICON (degrees)	Differences between values from the prototype hardware and values from VICON (degrees)
1	131.22	144.87	13.65
1	136.60	149.14	12.54
1	141.33	152.73	11.41
2	134.49	138.14	3.65
2	142.04	143.56	1.52
2	148.45	149.13	0.69
3	139.35	140.43	1.08
3	145.37	145.13	-0.23
3	151.11	149.32	-1.78
4	135.80	142.26	6.46
4	141.85	147.74	5.89
4	147.52	150.87	3.34
5	133.23	144.86	11.63
5	141.77	151.68	9.92
5	149.72	155.70	5.98
6	131.70	138.75	7.06
6	138.91	144.72	5.81
6	146.27	150.12	3.86
7	128.66	140.11	11.45
7	137.49	147.08	9.60
7	145.80	153.79	7.99
8	128.09	133.16	5.08
8	135.30	139.32	4.02
8	142.16	145.30	3.14
9	129.20	141.63	12.42
9	136.41	147.76	11.35
9	143.41	153.24	9.83
10	130.44	138.83	8.39
10	138.38	144.77	6.40
10	145.73	150.53	4.80

The variability of the differences shown in Table 4.4.7a was investigated by calculating the standard deviation. This was done manually to allow a fuller understanding to be gained. The standard deviation was calculated by taking the square root of the sample variance. Sample variance was calculated using Equation 4.4.7a (Heiman 2006):

$$S_X^2 = \frac{\sum X^2 - \frac{(\sum X)^2}{N}}{N} \quad \text{Equation 4.4.7a}$$

In Equation 4.4.7a, X is the difference between value from the prototype hardware and value from VICON and N is the number of differences (see Table 4.4.7a for values of differences).

$$S_X^2 = \frac{1802.84 - \frac{196.95}{30}}{30} = 17.00 \; degrees^2 \quad \text{Equation 4.4.7a}$$

Standard deviation was calculated using Equation 4.4.7b (Heiman 2006):

$$S_X = \sqrt{\frac{\sum X^2 - \frac{(\sum X)^2}{N}}{N}} \quad \text{Equation 4.4.7b}$$

Therefore:

$$S_X = \sqrt{17.00} = 4.12 \; \text{degrees} \quad \text{Equation 4.4.7b}$$

The same was then done for the differences calculated from the repetitions of the elbow extension and flexion movement performed by participant two, giving a standard deviation of 3.64 degrees. The mean (or pooled) standard deviation (s_p) for the elbow extension and flexion movements performed by both participants was then calculated using Equation 4.4.7c (Utts, Heckard 2005):

$$S_p = \sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2}} \quad \text{Equation 4.4.7c}$$

In Equation 4.4.7c, s_1^2 is the variance of participant one, s_2^2 is the variance of participant two and n is the sample size.

$$S_p = \sqrt{\frac{(30-1)17.00 + (30-1)13.25}{30+30-2}} = 3.88 \; \text{degrees} \quad \text{Equation 4.4.7c}$$

Standard deviations were calculated separately for each participant, prior to calculating the pooled standard deviation, to avoid influence from any differences in the way the participants moved. The same was then done for the other movements and the results are shown in Table 4.4.7b:

Table 4.4.7b. Intra-variability during repetitions of the ADL movements performed

	Elbow extension and flexion (degrees)	Hand opening and closing (mm)	Shoulder lateral and medial deviation (degrees)	Hand pronation and supination (degrees)
Mean standard deviation	3.88	2.32	4.56	5.53

The values in Table 4.4.7b describe the intra-variability of the data recorded by the prototype hardware during the ADL movements. The mean standard deviation from the gyro sensors (angular displacement data) was then calculated as 4.66 degrees. The mean standard deviations in Table 4.4.7b were then calculated as percentages of the ranges of displacements (Table 4.4.7d) during repetitions of the ADL movements to give a more useful perspective. In order to do this, first the ranges of displacement were calculated by identifying the maximum and minimum displacements from the data from VICON for repetitions of the elbow extension and flexion movement as shown in Table 4.4.7c:

Table 4.4.7c. Ranges of displacement during repetitions of the elbow extension and flexion movement

Maxima (degrees)	Minima (degrees)	Range (degrees)
Participant one		
158.37	96.33	62.04
156.44	86.06	70.38
154.78	88.67	66.11
153.84	88.47	65.36
159.41	87.54	71.87
157.72	87.37	70.35
161.89	88.62	73.26
152.97	84.32	68.65
160.99	86.17	74.82
157.59	85.87	71.73
Participant two		
139.48	67.30	72.19
139.02	71.15	67.87
140.85	72.73	68.12
146.19	72.48	73.71
141.68	70.98	70.70
142.66	73.92	68.74
147.26	74.17	73.09
138.97	75.76	63.21
141.20	72.34	68.86
142.07	78.10	63.97

The mean range of displacement was then calculated as 69.25 degrees. Standard deviation as a percentage of the range of displacement was calculated as 5.60 % at the elbow (extension and flexion). This was done for the other ADL movements also as shown in Table 4.4.7d:

Table 4.4.7d. Intra-variability as percentages of the ranges of displacement

	Elbow extension and flexion (%)	Hand opening and closing (%)	Shoulder lateral and medial deviation (%)	Hand pronation and supination (%)
Mean standard deviation as percentages of the ranges of displacement	5.61	4.92	8.08	5.41

Again, the values in Table 4.4.7d describe the intra-variability of the data recorded by the prototype hardware during the ADL movements. The mean standard deviation from the

gyro sensors (elbow extension and flexion, shoulder lateral and medial deviation, hand pronation and supination) as a percentage of the ranges of displacement was calculated as 6.36 %.

4.4.8. Inter-variability of the prototype hardware

The variability between the participants (inter-variability) was estimated using Equation 4.4.8:

$$\text{Inter-variability} = \bar{X}_1 - \bar{X}_2 \qquad \text{Equation 4.4.8}$$

In Equation 4.4.8, $\bar{X}_1$ is the mean difference (between data from the prototype hardware and VICON) during repetitions of the ADL movements for participant one (see Table 4.4.7a for values). $\bar{X}_2$ is the mean difference (between data from the prototype hardware and VICON) during repetitions of the ADL movements for participant two. Prior to calculating the mean differences per participant, differences were squared and square rooted to convert negative values to positive. The mean difference between VICON and the prototype hardware during the elbow extension and flexion movements for participant one ($\bar{X}_1$) was 6.70 degrees. The same mean difference for participant two ($\bar{X}_2$) was 3.56 degrees. Therefore:

$$\text{Inter-variability} = 6.70 \text{ - } 3.56 = 3.34 \text{ degrees} \qquad \text{Equation 4.4.8}$$

This was then calculated as a percentage of the mean range of movement (see Table 4.4.7c for values) during the elbow extension and flexion movements giving 4.83 %. The same was then done for the other movements and DOFs as shown in Table 4.4.8:

Table 4.4.8. Inter-variability of the prototype hardware

	Elbow extension and flexion	Hand opening and closing	Shoulder lateral and medial deviation	Hand pronation and supination
Inter-variability	3.34 degrees	9.07 mm	0.16 degrees	1.84 degrees
Inter-variability as a percentage of the respective mean range of movement (%)	4.83	19.25	0.28	1.80

The mean angular inter-variability (elbow extension and flexion, shoulder lateral and medial deviation, hand pronation and supination) between participants was then calculated as 1.80 degrees. The mean inter-variability as a percentage of the respective mean range of movement was calculated as 2.30 %. Conclusions from these results are drawn in section 4.5.

4.4.9. Limitations of tests

- There will have been slight spatiotemporal variation between movements. However, from observations it was thought that participants had moved in a largely consistent manner. It was also thought that participants had moved mainly within the planes aimed to move within because the estimated error as a percentage of the range of movement was 2.65 %. The spatiotemporal variation between movements will mean that a worst case description of variability is given. However, the effect of this will have been minimised by the fact that relative comparisons were made between the data from the prototype hardware with that from VICON for each movement.

- The accuracy of the prototype hardware was not calculated because to do so would require the prototype hardware to be calibrated. This would require a third measure to allow scale and offset values to be established for the data from the prototype hardware. This was beyond the scope of this research because the investigation of variability was considered most important.

- Some aspects such as the sample relative to the movement for the calculation of difference, and the evaluation of performance at high velocity, were identified through observation of the graphical data. This required qualitative assessment which will have increased the variability of results.

- The small number of movements and of participants limited the statistical power of the tests, particularly the inter-variability of the prototype hardware. Also, although the participants were of similar anthropometric dimensions, some differences were inevitably present.

- The re-sampling of the data from VICON will have led to an increase in variability of results. This is because the sample rate of the data recorded from the prototype hardware was not divisible by the sample rate of the data recorded by VICON, which meant that interpolation was required.

- Some movement between the markers and the skin will have inevitably occurred during tests, although from visual observation it appeared to be minimal.

4.5. Conclusions to chapter

- It was established in the design specification that the prototype hardware should be as low variability as possible. The mean intra-variability value of 6.36 % of the range of movement suggests that the variability of results from the system may be high. This means that reliability of the data from the prototype system is lower, particularly when calculating single values or mean values when fewer movements are performed in sessions.

- Inter-variability from the gyro sensors was lower than from the flex sensors, with a mean value of 2.30 % of the mean range of angular displacement. The value from the flex sensor was 19.25 % of the range of linear displacement. This may have been caused by slight differences in the mounting positions of the flex sensor. This suggests that care should be taken when mounting the sensors.

- In some cases, a slight delay occurred in the response from the prototype hardware, and differences between the data from the prototype hardware and VICON, in some cases, became greater towards the end of the movement.

- The effects of noise can be minimised using low pass filters in the software programs for the prototype system. Also, the variability of the data recorded by VICON was small relative to the distances moved through by the participants, and the movements were mainly within the specified planes. This supports the validity of the tests performed in chapters 5 and 6.

- When movements are performed through large displacements or at high velocity, the difference between the values from the prototype hardware and the values from VICON become greater. This may be due to there being more displacement moved through and thus a greater chance of errors occurring as well as sensors moving relative to the skin due to inertia. The prototype hardware was observed reading angular velocities of 1290 degrees/second which exceeds the performance requirement in the design specification of reading velocities of up to 112 degrees/second. Similarly the linear velocities of 825 mm/second were read which exceeds the requirement of 76 mm/second.

- The resulting minimum readable displacement of 1.53 degrees is marginally greater than the estimated requirement in the design specification of a sensitivity of 1.4 degrees. However, because the system was only to be tested on healthy participants (described further in Chapter 6), for the purpose of this research it was not considered to be a limiting factor.

- The performance of the prototype hardware was considered suitable to allow the tests in chapters 5 and 6 to be performed satisfactorily.

The findings from this chapter formed the basis for discussion of the results in relation to the hypothesis and research questions in Chapter 7.

CHAPTER 5. TESTS OF THE EFFICACY OF THE PROTOTYPE SYSTEM IN DETECTING MOVEMENT SYNERGISM

5.1. Introduction to chapter

This chapter describes the tests performed to investigate the efficacy of the prototype system in detecting movement synergism. The synergism recording program described in section 3.6.4 is used, where movement synergism is defined as the extent of simultaneous movement of one or more DOFs as conceptualised in section 3.6.4. In this chapter, VICON is again used, and movements are performed synergistically and then sequentially. The movements are assessed from the data recorded by VICON. The variability of the prototype system in detecting movement synergism is then investigated by comparing the data from the prototype system with that from VICON. The same switch mechanism and marker locations described in section 4.3.6 are used. Also, the same calculated ranges of movement of the DOFs from the coordinate data from VICON are used. Since the inter-variability of the data recorded by the prototype hardware had been investigated, a single participant performed all movements during these tests. Also, due to the limited availability of VICON, the efficacy in detecting movement synergism was investigated rather than trying to measure movement synergism itself at different levels of synergy of movements. This is because an ability to detect movement synergism is a prerequisite for ability to measure movement synergism at different levels.

In this chapter, the objectives of the tests are established with respect to system objectives, design specification, the prototype system itself, hypothesis, research questions and findings from the information review. The movements performed, data recorded and test schedule are then described. The processes of converting the data collected using VICON and synchronising count data are also described. The levels of movement synergism present during the movements performed are then investigated along with the variability of the prototype system in detecting movement synergism. Finally, the limitations of the tests are discussed and conclusions are drawn on the level of the system objectives and the design

specification. This formed the basis for discussion of the results in relation to the hypothesis and research questions in Chapter 7.

5.2. Objectives of the tests

The main objective was to investigate the efficacy of the prototype system in detecting movement synergism, which as described in section 3.2.5, was a specific objective of the system. This was to be done by investigating the variability of the prototype system in detecting movement synergism. To help this, the levels of movement synergism present during the movements performed were also to be investigated.

5.3. Test methodology

5.3.1. Movements performed

As established in section 3.6.2, the functional movements to perform consisted of movement of certain DOFs. Performance in measuring movement synergism at these DOFs was therefore investigated. To allow this, the DOFs were moved both synergistically and then sequentially as follows:

Synergistic reach and grasp movement

This movement consisted of simultaneous extension of the shoulder and elbow and closing of the hand (the hand was open at the start of the movement). The duration of the synergistic movements was approximately 1 second.

Synergistic turn door handle movement

This movement was similar to the synergistic reach and grasp movement but instead of closing the hand, pronation was performed.

Sequential reach and grasp movement

This movement consisted of sequential extension of the shoulder followed immediately by extension of the elbow and then closing of the hand. Each DOF was therefore moved in sequence. The duration of the sequential movements was approximately three seconds.

Sequential turn door handle movement

This movement was again similar to the sequential reach and grasp movement but instead of closing the hand, pronation was performed.

Each of the above movements was performed 21 times to allow an understanding of performance during a session to be gained. During synergistic movements, a deliberate attempt was made to ensure that no DOFs moved individually. Guidance markings as shown in Figure 3.6.1b were again used.

5.3.2. Data recorded

During all movements, voltage samples were recorded from the prototype system from all sensors at a sample rate of 20 Hz. As described in section 3.6.4, the synergism recording program then calculates and records movement synergism in the categories of positive-positive, negative-negative, positive-negative, negative-positive and general movement synergism for each DOF combination. This was taken in the form of the number of program iterations that occurred whilst velocity thresholds were being exceeded. This data is referred to here as movement synergism 'counts'. Also summed positive-positive, summed negative-negative and summed general movement synergism for all DOFs were recorded. Movement synergism in all of the above categories was then saved in a CSV output file. It is summed general movement synergism that is examined during these tests. This is to allow a preliminary understanding of the efficacy in detecting movement synergism to be gained.

The recording sequence of VICON was set to six seconds to allow sufficient time to perform the movements whilst avoiding generating overly large output files. The sequence of the program for recording from the prototype system was set to a longer duration of eight seconds to ensure that all data from VICON could be compared. The theoretical maximum counts would be obtained if all measured DOFs were moving simultaneously during a movement. At a sample rate of 20 Hz, the movement synergism counts would be six seconds multiplied by 20 Hz which gives 120. The sum of the three movement synergism counts would therefore be three times as much as this, that is 360. Coordinate samples were recorded from VICON at a sample rate of 250 Hz; a nominal rate recommended for

most recording situations. As 84 movements were performed, 84 output files were generated from VICON. However, because each movement described above was performed in an individual session, 4 output files in CSV format containing the movement synergism counts were generated by the prototype system, each containing the movement synergism counts from both the synergistic and respective sequential movements.

5.3.3. Test schedule

This section describes the activities performed in the laboratory during performance of the tests. Since VICON was again used, some of the activities performed are the same as those described in section 4.3.6:

1. Align the table and guidance sheets with the VICON axes.
2. Boot up the VICON computer system and load the Nexus software program
3. Ensure no shiny objects are causing interference with VICON and remove them if present
4. Calibrate VICON using the T shaped bar with markers at specific positions known by VICON
5. Ensure the camera error values for each of the cameras are equal to or less than '0.25'
6. Set the sample rate of VICON and set the "start recording sequence" method to "switch"
7. Specify file names and locations for the outputs files from both the prototype system and VICON
8. Plug the switch mechanism into the VICON computer system and test that it operates correctly
9. Mount the prototype hardware to the participant
10. Mount the markers to the participant
11. Perform the movements. Assess the extent of movement synergism or how sequential the movement was, by examining the graphical outputs from the synergism recording program, and re-record if necessary

5.4. Data analysis

5.4.1. Conversion of data

Conversion of VICON data

The data from VICON was converted to displacements of the DOFs as described in section 4.4.1. The displacements were then converted to velocities by differentiation. In order to obtain the equivalent of the count data from the VICON data, Function 5.4.1a was constructed:

```
If (V > VT) Then
        V = 1
Else
        V = 0     Function 5.4.1a
```

In Function 5.4.1a, V is the velocity of a DOF at a given sample and VT is a velocity threshold. Therefore if the velocity at a given sample is greater than the threshold velocity, a number 1 was generated, and if not a number 0. The total of these counts were then summed per DOF. Combinations of exceeded velocity thresholds were then examined to identify general movement synergism. This gave an equivalent to the data recorded by the prototype system from the data from VICON. For simplicity, hand opening and closing is referred to as 'hand', elbow extension and flexion as 'elbow' and shoulder extension and flexion as 'shoulder'. The following logic function was used to define hand and elbow movement synergism (Function 5.4.1b):

```
If (Hand > 0) Then
        If (Elbow > 0) Then
                V = 1
        Else
                V = 0
Else
        V = 0           Function 5.4.1b
```

Therefore if the hand velocity threshold has been exceeded, and the elbow velocity has been exceeded also, a number 1 was generated at that given sample, and if not then a 0. This was done with all measured DOFs giving counts for hand and elbow, hand and

shoulder, and elbow and shoulder per movement. The sum of these was then calculated per movement.

Synchronisation of count data

As was the case with the synergism recording program, single velocity thresholds to be applied to data from all movements were established for the data recorded by VICON. To do this, a velocity threshold shared by the elbow and shoulder was established empirically, which resulted in elbow and shoulder counts per movement that matched those from the synergism recording program. This was done for each synergistic reach and grasp movement. From the velocity thresholds identified per individual movement, a mean velocity threshold was calculated. Velocity thresholds were then established empirically for the hand. This resulted in hand and elbow and hand and shoulder counts per movement that matched those from the synergism recording program. This was also done for each synergistic turn door handle movement. This meant that a mean velocity threshold had been established which was shared between the elbow and shoulder. Also, a second mean velocity threshold had been established for the hand, either in opening and closing or through hand pronation and supination. These mean velocity thresholds were then applied to the data recorded by VICON for all movements. The values are not listed because, for simplicity, the time period of the differentiation calculation was not considered. The minimum readable velocities of the prototype hardware were investigated in section 4.4.6.

5.4.2. Levels of synergism in the movements performed

As described in section 5.3.1, the aim was to perform movements completely synergistically then completely sequentially. This section aims to assess the extent that this was achieved. To do this, first the data recorded by VICON was examined.

Table 5.4.2a. Synergism counts from the data recorded by VICON for repetitions of the synergistic reach and grasp movement

Hand and elbow synergism counts	Hand and shoulder synergism counts	Elbow and shoulder synergism counts
15	15	18
14	16	18
15	16	18
15	17	18
13	16	17
14	15	18
17	18	22
16	18	21
16	16	21
14	16	20
12	14	21
16	17	20
15	15	20
16	17	21
15	16	20
14	16	18
13	15	20
15	16	17
12	12	16
10	14	15
12	14	15

From the values shown in Table 5.4.2a, and from the values recorded by VICON for the synergistic turn door handle movement, the means and standard deviations were calculated.

Table 5.4.2b. Means and standard deviations of the counts from the data recorded by VICON for the synergistic movements

	Hand and elbow synergism	Hand and shoulder synergism	Elbow and shoulder synergism	Means
Mean synergism counts from the synergistic reach and grasp movements	14.24	15.67	18.76	16.22
Mean synergism counts from the synergistic turn door handle movements	18.52	18.71	18.43	18.56
Standard deviation of counts from the synergistic reach and grasp movements	1.69	1.39	2.00	1.69
Standard deviation of counts from the synergistic turn door handle movements	1.76	1.69	1.33	1.60

Although the count values were integers, the values shown in Table 5.4.2b were to decimal places because standard deviations and means had been calculated. The same was then done for the sequential movements performed (shown in Table 5.4.2c):

Table 5.4.2c. Means and standard deviations of the counts from the data recorded by VICON for the sequential movements

	Hand and elbow synergism	Hand and shoulder synergism	Elbow and shoulder synergism	Means
Mean synergism counts from the sequential reach and grasp movements	0.00	0.00	0.05	0.02
Mean synergism counts from the sequential turn door handle movements	1.33	0.33	0.00	0.56
Standard deviation of counts from the sequential reach and grasp movements	0.00	0.00	0.21	0.07
Standard deviation of counts from the sequential turn door handle movements	1.13	0.64	0.00	0.59

In order to make the standard deviations of the counts (shown in Tables 5.4.2b and 5.4.2c) more meaningful, they were calculated as percentages of the respective mean movement synergism counts from the synergistic movements recorded by VICON (shown in Table 5.4.2b). The synergism counts from the synergistic movements were chosen to calculate percentages from because they had higher counts than those from the sequential movements. Percentages were calculated to allow making relative comparisons more easy. The results are shown in Table 5.4.2d.

Table 5.4.2d. Standard deviation of counts from the data recorded by VICON as percentages of the mean synergism counts from the synergistic movements

	Hand and elbow (%)	Hand and shoulder (%)	Elbow and shoulder (%)	Means (%)
Standard deviation of counts from the synergistic reach and grasp movements	11.85	8.88	10.65	10.46
Standard deviation of counts from the synergistic turn door handle movements	9.52	9.05	7.22	8.60
Standard deviation of counts from the sequential reach and grasp movements	0.00	0.00	1.14	0.38
Standard deviation of counts from the sequential turn door handle movements	6.08	3.43	0.00	3.17

The data in tables 5.4.2b to 5.4.2d indicate that the movements performed were largely synergistic and then sequential. To help assess the levels of movement synergism present, graphical displays of the times when the DOFs exceeded the velocity thresholds were generated. This was done for both an example synergistic movement and example sequential one from the data recorded by VICON.
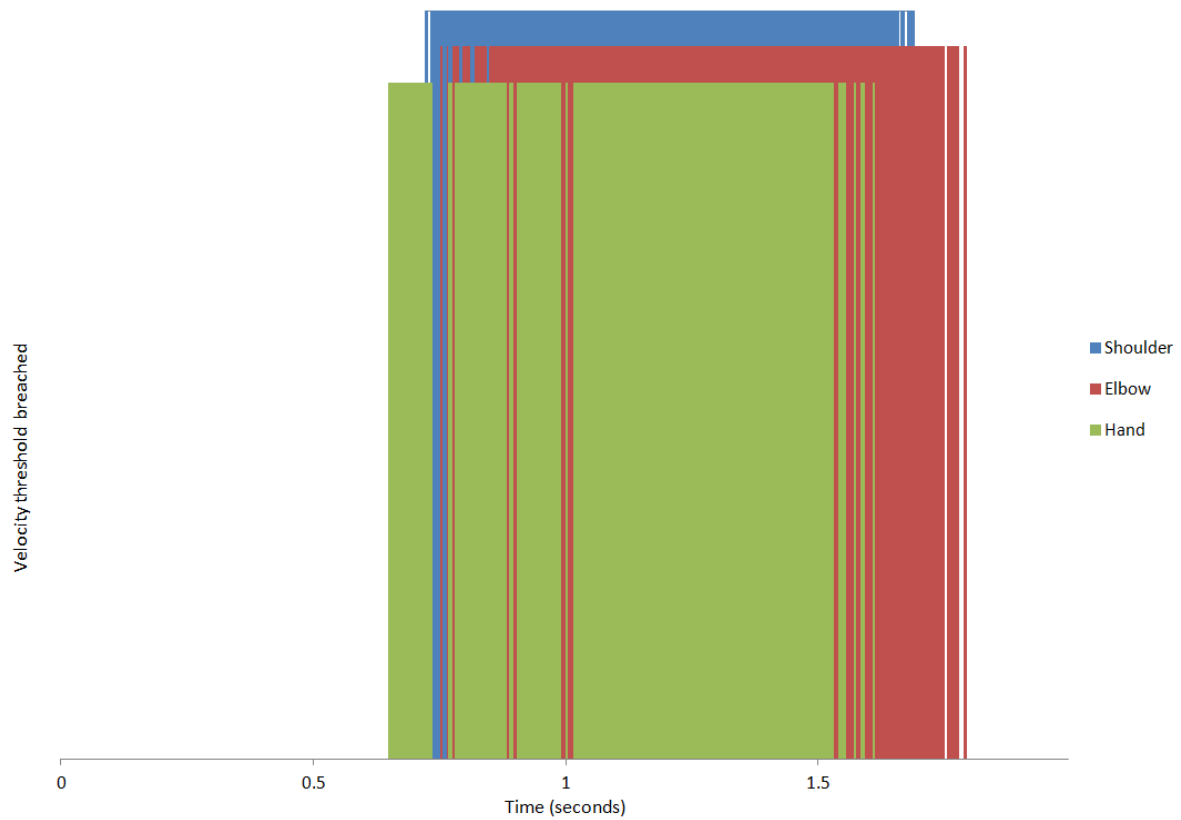
Figure 5.4.2a. Graphical display of the times when the velocity thresholds were exceeded during an example synergistic reach and grasp movement
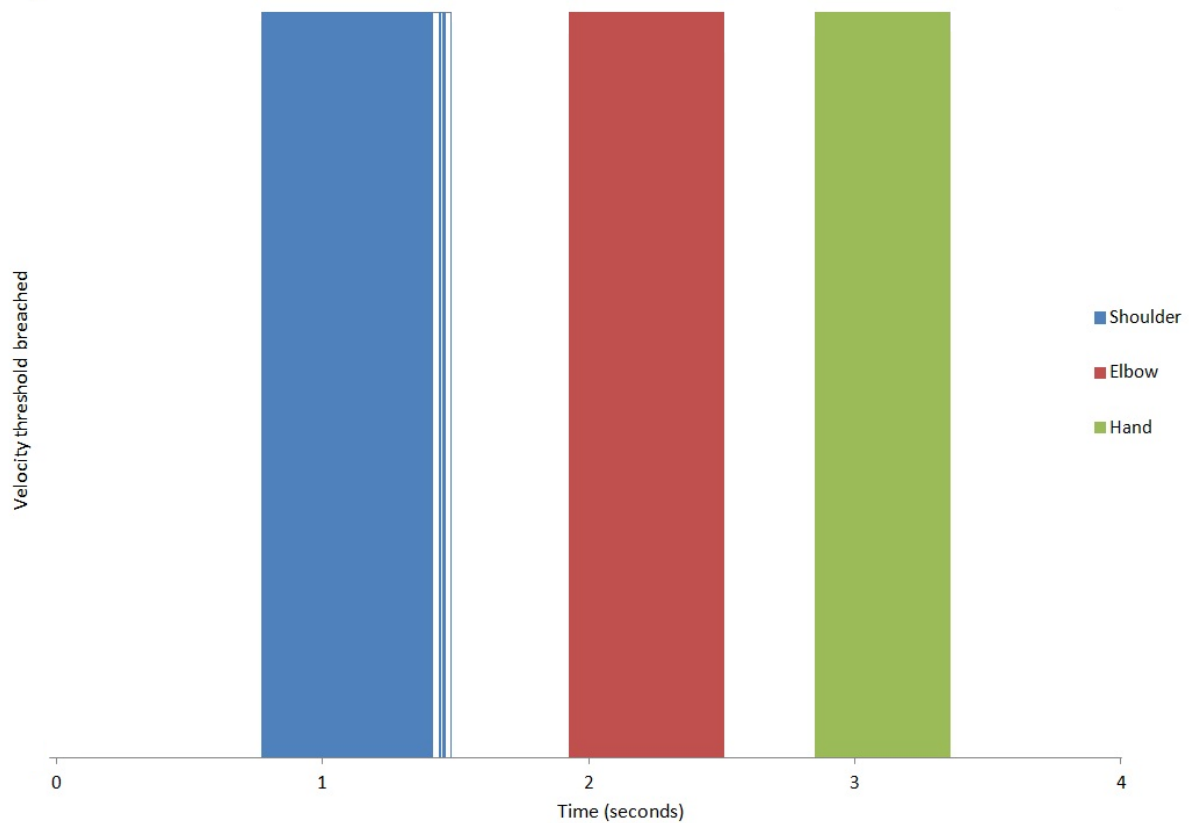
Figure 5.4.2b. Graphical display of the times when the velocity thresholds were exceeded during an example sequential reach and grasp movement

Figures 5.4.2a and 5.4.2b indicate that the movements performed were largely synergistic (where the bars overlap) and then sequential (where the bars are separate), where movement synergism is defined as the extent of simultaneous movement between the shoulder, elbow and hand. Although only single examples are shown of a synergistic movement and a sequential movement, other respective movements were found to be similar.

5.4.3. Variability in detecting movement synergism

In this section, variability of the prototype system in detecting movement synergism is estimated by comparing the movement synergism counts from the prototype system with those from VICON. The movement synergism counts per movement repetition from the prototype system were noted (shown in Table 5.4.3a):

Table 5.4.3a. Synergism counts recorded by the prototype system for repetitions of the synergistic reach and grasp movement

Hand and elbow synergism counts	Hand and shoulder synergism counts	Elbow and shoulder synergism counts
13	16	20
11	15	17
14	17	18
10	16	17
13	18	17
14	17	17
12	16	20
15	19	21
14	14	21
13	18	19
11	18	20
12	15	22
14	15	21
12	16	17
14	18	20
12	16	22
15	20	20
17	20	17
12	17	11
7	24	11
15	22	17

The differences between movement synergism counts from the prototype system and those from VICON were then calculated (see Table 5.4.3b):

Table 5.4.3b. Differences between synergism counts from the prototype system and those from VICON for the synergistic reach and grasp movements

Hand and elbow synergism count differences	Hand and shoulder synergism count differences	Elbow and shoulder synergism count differences
-2	1	2
-3	-1	-1
-1	1	0
-5	-1	-1
0	2	0
0	2	-1
-5	-2	-2
-1	1	0
-2	-2	0
-1	2	-1
-1	4	-1
-4	-2	2
-1	0	1
-4	-1	-4
-1	2	0
-2	0	4
2	5	0
2	4	0
0	5	-5
-3	10	-4
3	8	2

From the differences shown in Table 5.4.3b, and from the differences recorded for the synergistic turn door handle movement, standard deviations were calculated (as shown in Table 5.4.3c). Note that the mean count differences are not given as it would only give an indication of the accuracy of the established velocity thresholds applied to the data from VICON.

Table 5.4.3c. Standard deviations of the differences between the synergism counts from the prototype system and those from VICON during synergistic movements

	Hand and elbow	Hand and shoulder	Elbow and shoulder	Mean
Standard deviation of the count differences from the synergistic reach and grasp movements	2.13	3.17	2.08	2.46
Standard deviation of the count differences from the synergistic turn door handle movements	1.51	1.90	2.01	1.81

The same was then done for the sequential movements performed (as shown in Table 5.4.3d).

Table 5.4.3d. Standard deviations of the differences between the synergism counts from the prototype system and those from VICON during sequential movements

	Hand and elbow	Hand and shoulder	Elbow and shoulder	Mean
Standard deviation of the count differences from the sequential reach and grasp movements	0.84	0.00	3.05	1.30
Standard deviation of the count differences from the sequential turn door handle movements	2.01	0.89	2.15	1.68

The standard deviations in tables 5.4.3c and 5.4.3d were then calculated as percentages of the respective mean movement synergism counts from the synergistic movements recorded by VICON, shown in Table 5.4.3b. The results are presented in Table 5.4.3e.

Table 5.4.3e. Standard deviations of the count differences as percentages of the mean counts from the respective synergistic movements recorded by VICON

	Hand and elbow (%)	Hand and shoulder (%)	Elbow and shoulder (%)	Mean (%)
Synergistic reach and grasp movements	14.93	20.24	11.10	15.43
Synergistic turn door handle movements	8.15	10.15	10.91	9.74
Sequential reach and grasp movements	5.93	0.00	16.25	7.39
Sequential turn door handle movements	10.88	4.75	11.68	9.10

Again, the values in Table 5.4.3e describe the variability of the prototype system in detecting movement synergism. Conclusions from these results are drawn in section 5.5.

5.4.4. Limitations of tests

- The counts from VICON and the synergism recording program were not synchronised per individual movement synergism count because the output from the synergism recording program contained movement synergism counts from shared DOFs. For example, both hand elbow and hand shoulder contain the hand DOF. This made it difficult to establish suitable velocity thresholds applied to the data from VICON. The synergism recording program was not altered for the tests because it was considered preferable to test the output from the prototype system as it would be during physiotherapy.

- The accuracy of the prototype system in measuring movement synergism was not calculated because to do so would require the prototype hardware to be calibrated. This would require a third measure to allow scale and offset values to be established for the data from the prototype hardware. This would allow investigation of the efficacy of the prototype system in measuring movement synergism at different levels. This was beyond the scope of this research because as stated, ability to detect synergism is a prerequisite for ability to measure movement synergism at different levels.

- As described in section 3.6.4, a threshold system was incorporated into the programs of the prototype system to allow velocity data over a certain value from the gyro sensors to be considered. This was done to overcome instabilities in resting values. This meant that the corresponding velocity thresholds established during processing of data from VICON had to be high also. Consequently, if one or more of the DOFs are moving at low velocities, this may cause the prototype system to miss movement synergism.

5.5. Conclusions to chapter

The estimated mean variability in measurements of movement synergism during synergistic reach and grasp and the turn door handle movements were 15.43 % and 9.74 % respectively. These results suggest that the prototype system is capable of detecting

movement synergism in a session, but is less suited to measuring movement synergism in a single movement, because the reliability of the result would be low. However, the specific objective of including an ability to detect movement synergism had been achieved. The prototype system had also met the requirement in the design specification of providing information for clinicians and researchers in a specific kinematic parameter.

The findings from this chapter formed the basis for discussion of the results in relation to the hypothesis and research questions in Chapter 7.

CHAPTER 6. TESTS OF THE EFFICACY OF THE COMPLETE PROTOTYPE SYSTEM

6.1. Introduction to chapter

This chapter describes the tests performed to investigate the efficacy of the prototype system as a whole. To do this, participants were recruited to participate in tests to investigate the efficacy of the prototype system in guiding movements. As established in Chapter 3, the first general objective of the system was to be capable of enabling regular guided and monitored therapeutic exercises in the home to provide a means for stroke patients to achieve a higher level of physical rehabilitation. These tests were therefore performed to investigate the efficacy of the prototype system with respect to this objective. A controlled test was performed where two groups of participants, a 'feedback group' and a 'control group', were introduced to the two target movements established in section 3.6.2. The 'feedback group' performed a physiotherapy session for the movements whilst receiving feedback from the prototype system. The control group performed the same physiotherapy session without feedback. Comparisons between the two groups in terms of conformance to the target movements were then made. Although the system was designed to help stroke patients, testing with stroke patients was beyond the scope of this research due to the time and resources it would require. Healthy participants were therefore employed, where efforts were made to simulate the situation and characteristics of stroke patient motor learning. The worded bandwidth element of the feedback was disabled during the tests. This is because, as discussed in section 3.6.4, in order provide a benefit to patients, it was thought that a physiotherapist's assistance would be required to define thresholds for the worded feedback. However, due to the scope of this research, this was not carried out.

In this chapter, the objectives of the tests are established with respect to the system objectives, design specification, the prototype system itself, hypothesis, research questions and findings from the information review. The safety and ethical issues are then considered, and a research application constructed for the Ethical Advisory Committee (EAC) is outlined. The methodology to allow simulation of stroke patients is described along with the

statistical power analysis used to estimate the required sample size, the sampling methods and recruitment techniques. The target movements are then described in more detail along with the data recorded during the tests. The instructions given to participants, the interaction carried out during tests and the laboratory setup are described. Relevant characteristics, such as the age and handedness, of the recruited participants are then described. The feedback and comments given by the participants during tests are presented. Comparisons of conformances to target movements by the feedback group with those of the control group are then made. This includes comparisons per movement and per DOF. An independent samples t-test performed in the statistical software package SPSS is described. The variability across participants in each group (inter-variability), per movement and DOF, is investigated and statistical tests are performed to investigate improvements in conformance of the feedback group. Finally, the limitations of the tests are discussed and conclusions are drawn on the level of the system objectives and the design specification. This formed the basis for discussion of the results in relation to the hypothesis and research questions in Chapter 7.

6.2. Objectives of the tests

The first general objective of the system was to be capable of enabling regular guided and monitored therapeutic exercises in the home to provide a means for stroke patients to achieve a higher level of physical rehabilitation. As concluded from the information review, Since the aim of regular physiotherapy is to improve, the aim could also be considered as to allow target movements to be conformed to more closely than if physiotherapy was performed by the patient on their own. In this way independence, the overall aim of stroke physiotherapy, is improved by improving performance during physiotherapy, as a result of conforming more closely to target movements. This is achieved by guidance provided by the physiotherapist which enhances motor learning. It is by these principles that the prototype system aims to function. It is therefore considered that improving conformance to the target movements will help allow a higher level of physical rehabilitation to be achieved, and it is improvement in conformance to target movements which is investigated in this chapter.

It was also concluded from the information review that no existing systems investigate the effects of feedback on DOFs other than the DOF for which feedback is given. As described in section 3.6.4, an aim of the prototype system was for the effects of guidance to also occur at other DOFs which also move significantly during the target movements. Investigation of this phenomenon is therefore also an objective of this chapter. The DOF for which guidance is given is hand, opening and closing during the reach and grasp movement, or in pronation and supination during the turn door handle movement. The other DOF at which conformance to target movements is investigated is elbow extension and flexion. Although the shoulder also moves through large displacements during the target movements, because healthy participants were recruited to test the prototype system, the conformances at the shoulder were not investigated. This is because, as noted from literature and from observation of movements, shoulder extension and flexion is largely proportional to elbow extension and flexion during reaching movements in healthy people. It was therefore considered that conformance of the elbow would be representative of conformance of the shoulder.

The objectives of the tests were therefore to investigate the following:

- The effect of feedback on conformance to target movements of the hand and of the elbow
- The inter-variability across participants in each group with respect conformances to target movements of the hand and of the elbow
- Whether or not differences between the feedback and control groups in conformances to target movements of the hand and of the elbow are statistically significant

6.3. Test methodology:

6.3.1. Safety and ethical approval

Since testing of the prototype system involved participants, approval by the Loughborough University Ethical Advisory Committee (EAC) was required. As the tests involved new

equipment, a research application was required by the EAC. This included the description of the DAQ and safety precautions to be taken shown in Table 6.3.1:

Table 6.3.1. Description of the DAQ and safety precautions to be taken as submitted to the EAC

Model: NI USB-6009. Power supply: standard USB at 5 V (maximum), 0.5 A (maximum) and at approximately 2.125 W (maximum). Conforms to the following safety standards:

- IEC 61010-1, EN 61010-1
- UL 61010-1, CSA 61010-1

Also meets the essential requirements of applicable European Directives, as amended for CE marking as follows:

- 2006/95/EC; Low-Voltage Directive (safety)
- 2004/108/EC; Electromagnetic Compatibility Directive (EMC)

All safety instructions of the DAQ have been read. The DAQ will be used as described in the user guide with all filler panels installed during operation. The following measures will also be taken to ensure safety of the new equipment:

- Only the USB power supply will be used to power the equipment
- No wire cores will be exposed
- The laptop and power cable have been PAT tested
- Participants will be informed that they can adjust or remove the small straps which mount the sensors at any time in case of adverse effects such as discomfort
- The participants will also be informed that they can withdraw from the test at any time if desire for any reason

The application also included details about the participants, including the number involved, ages, sampling method, recruitment technique and the time required from the participants for tests to be performed. The application also described the method of allocation to groups, chaperoning, health and safety issues, information to be provided to the participants, and written consent forms to be signed by participants. Finally, the application

included the data to be recorded, the steps taken to ensure the anonymity of participants and the steps taken to ensure conformance with the Data Protection Act 1998. The research application was subsequently accepted by the EAC, allowing the participant tests to go ahead.

6.3.2. Stroke patient simulation

Although the system was designed to help stroke patients, testing with stroke patients was beyond the scope of this research due to the time and resources it would require. Since healthy participants were employed, efforts were made to simulate the situation and characteristics of stroke patient motor learning. This was to allow the value of the prototype system in relation to its objectives to be understood as fully as possible. Employment of healthy participants was considered satisfactory given the scope of this research, particularly because it has been found that, although stroke patients are less accurate and more variable when executing skills, the capacity to learn in a similar way to healthy people is generally present (Winstein, Merians & Sullivan 1998). The characteristics of relearning a movement by stroke patients were considered in relation to the characteristics of learning a novel movement by healthy participants (shown in Table 6.3.2).

Table 6.3.2. Comparison of relearning a movement by stroke patients to learning a novel movement by healthy participants

	Characteristics of relearning a movement by stroke patients	Characteristics of learning a novel exercise movement by healthy participants
Absence of ability	Neural data that previously allowed the movement to be skilfully performed has been lost	No neural data that allows the movement to be skilfully performed
Goal	The goal will be known, for example picking up a cup to drink water to quench thirst	There may be no practical benefit to the movement other than the learning itself
Intrinsic feedback	Proprioceptive and exteroceptive	[Same as by stroke patients]
Knowledge of the movement	Performance of the movement with the healthy limb, memory of how the movement should look and feel from before the stroke	Instruction of the target movement, for example by watching someone perform it either live or on video, reading about the movement or listening to a verbal explanation
Implicit learning	Improvements made that learners are unaware of or unaware how they were made	[Same as by stroke patients]

Since healthy participants would already be capable of performing the exercise movements that are performed by stroke patients during physiotherapy such as reaching for and grasping objects, exercise movements novel to healthy participants were established. To ensure novelty of target movements to healthy participants, the spatiotemporal parameters of the movements were varied, which is described further in section 6.3.4. Other ways of creating novelty of movements to healthy participants were initially investigated. Attempts to reproduce a target movement whilst viewing the arm only in an inverted webcam view were made by the researcher. In this case, a series of dots on paper were moved between. However, it was found that movements in an inverted view were learnt after just one or two attempts. Similarly, movements were attempted with the non-preferred limb, but again learning took place very quickly. Movements with varied spatiotemporal parameters were found to be more challenging and to allow suitable scope for learning, and so were considered to be most suitable for simulating the situation of stroke patient learning.

Although stroke patients will know the goals of movements practiced in physiotherapy and will receive extrinsic feedback, physiotherapists provide useful additional information to that available to stroke patients practising alone. It is this additional information which allows for a greater extent of recovery. Similarly, the prototype system provides additional information as guidance with the aim of resulting in greater conformance to target movements. As well as attempting to simulate stroke physiotherapy, the following issues were also considered:

- Avoiding leaving the control group participants 'blind' in comparison to the feedback group participants
- Avoiding designing target movements in a way that would specifically ensure superior conformance to target movements as a result of the feedback

In order to avoid leaving the control group participants blind, or at a disadvantage other than through lack of feedback, efforts were made to ensure the conditions of the control group were the same as for the feedback group, with the only difference being the absence of feedback. Both groups were therefore provided with the same description of the target movements. This included video descriptions and guidance markings as described in section

3.6. The aim of this was to make the characteristics and appearance of the target movements as well known to all the participants as possible. Although no feedback was given to the participants in the control group, notification was given of when a movement was in progress. This was given in the form of a green light on the screen which lit up during movements, shown in Figure 6.3.2. This was to prevent participants from returning to the start position prior to the end of the recording sequence, which would prevent data from being recorded. To enable this, the main feedback program was simplified and saved as a separate program. This allowed participants in both groups to fully understand how to perform the target movements and to know when a movement was being recorded.
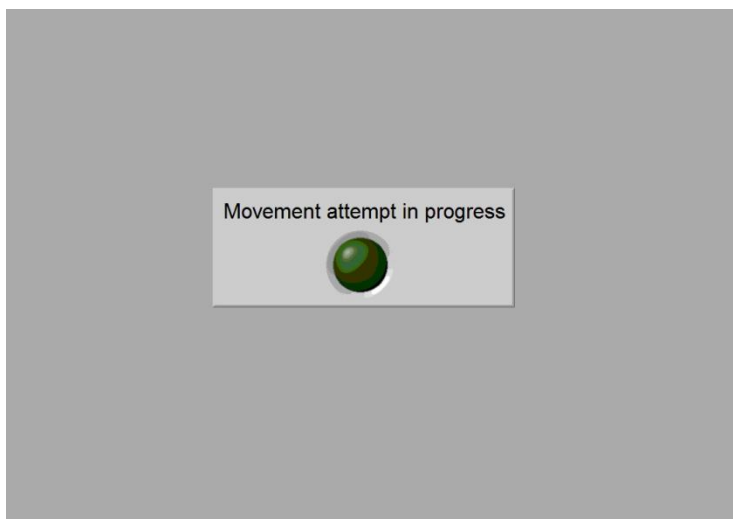
Figure 6.3.2. Notification of movements in progress given to participants in the control group

It may be that conformance would be increased due to feedback more with some movements than with others. For example, simple extension and flexion movements may be easiest to follow. The target movements were not designed with the aim of ensuring superior conformance when receiving feedback. Instead, target movements that simulate movements made whilst performing the BI ADLs (Mahoney, Barthel 1965) were established. As described in section 3.6.2, this allowed simulation of the types of movements commonly practised during stroke physiotherapy.

Although it may be considered that additional guidance information would probably result in superior conformance to target movements in general, this may not be the case. This is because additional visual and cognitive focus was required on the feedback which may

distract from the implicit learning processes. Even if it was considered probable that the feedback would result in superior conformance, because the prototype system had not previously been tested, investigation of the extent to which, as well as how, the conformance is superior to the control group would still be useful.

6.3.3. Participant sampling

Before participant recruitment commenced, an investigation was made into the number of participants appropriate for the chosen statistical tests to be carried out. To do this, power and level of significance were considered, where power is defined as the probability of not making a type 2 error, and level of significance is the probability of a type 1 error (Heiman 2006). A type 2 error is defined as retaining the null hypothesis when the null hypothesis is false, whilst a type 1 error is defined as rejecting the null hypothesis when the null hypothesis is true (Heiman 2006). The effect size was also considered (Cohen 1988). In order to estimate the required number of participants values for power, level of significance and effect size were established. As the phenomenon being tested was new but was to be tested under laboratory conditions, a medium effect size of 0.5 was selected (Cohen 1988). Moreover, for statistical tests under such conditions it is advised that values for power and level of significance be 0.8 and 0.05, respectively (Cohen 1988). Based on these values, from tabulated data, a sample size of 50 participants was suggested (Cohen 1988). This number was aimed for when recruiting participants.

As stated, the situation and characteristics of stroke patient motor learning were aimed for. Convenience sampling, which is sampling of units (participants in this case) which are conveniently available (Frankfort-Nachmias, Nachmias 1996), was used. Convenience sampling was used because, although it was thought it would lead to a mean participant age being less than the typical age at which strokes occur, it allowed for a larger sample size which increased the power of the tests. Potential participants were contacted via email and in person as well as through networking. An information sheet was always given or made available prior to the participants committing to participation.

As established, two target movements were performed by both a feedback group and a control group. Since two target movements were performed, the order of performance was alternated per participant. This was done to avoid the effect of practising one movement first and then better understanding the prototype system when performing the second movement. The assignment to either control group or feedback group was also alternated. This was done to avoid the effect of any varying conditions throughout the test, for example the researcher becoming more practiced in giving instructions to participants due to experience towards the end of the tests. This also meant that the allocation of participants to the feedback and control groups was completely random. The order of test schedules performed by participants shown in Table 6.3.3 was therefore repeated throughout the tests. The specific test schedule performed by an individual participant was therefore defined randomly by their time of availability.

Table 6.3.3. Repeated order of test schedules by participants

Participant number (order of participation)	Test schedule
1	Feedback group, reach and grasp movement performed first
2	Control group, reach and grasp movement performed first
3	Feedback group, turn door handle movement performed first
4	Control group, turn door handle movement performed first

Participants were not told which group they would be assigned to prior to the tests or which they were assigned to during the tests. This was to avoid control group participants trying to influence the tests results for example by deliberately performing badly. However, for ethical reasons, the participants were told which group they had been assigned to after the tests and were offered to be shown the alternative test conditions if they desired.

6.3.4. Target movements

The reach and grasp movement and turn door handle movement introduced in section 3.6 were both performed with reference to the guidance markings shown in Figure 3.6.1b.

Reach and grasp target movement

As described in section 3.6.1, the start position is with the hand at the edge of the table at the start mark. This is a comfortable and natural position with the angle of elbow extension from the forearm to the upper arm at approximately 90 degrees. The numbered positions shown are then moved between and the start position is then returned to. The movement consisted of reaching forward from the start position to location 1 (see Figure 3.6.1b) with the hand closed and then continuing to reach to 2 whilst opening the hand to approximately 100 mm between the end of the forefinger and thumb. The hand was then withdrawn to 3 (the same position as 1) whilst closing the hand. Location 4 was then reached to whilst opening the hand to approximately 50 mm, and then the hand was withdrawn to 'finish' whilst closing the hand. After remaining at the finish mark for a period to ensure the target movement had finished being read by the program, the start position was returned to, ready to perform the next movement attempt. The maximum extension displacement was such that the angle of elbow extension from the forearm to the upper arm was 160 degrees. Guidance markings were therefore scaled to accommodate participants of different anthropometric dimensions, which is described further in section 6.3.6. During the movement, the hand remained approximately 10 mm above the guidance markings. To allow novelty for healthy participants, the spatiotemporal parameters of the movement were varied as shown in Table 6.3.4. The duration of the target movements was approximately three seconds, which meant the movements were likely performed with closed-loop control.

As stated, the videos showed the target movements being performed relative to the guidance markings. The videos were made of the target movements being recorded by the target recording program described in section 3.6.4, directly above the movement for clarity, using a webcam. A screenshot of the video is shown in Figure 6.3.4a.
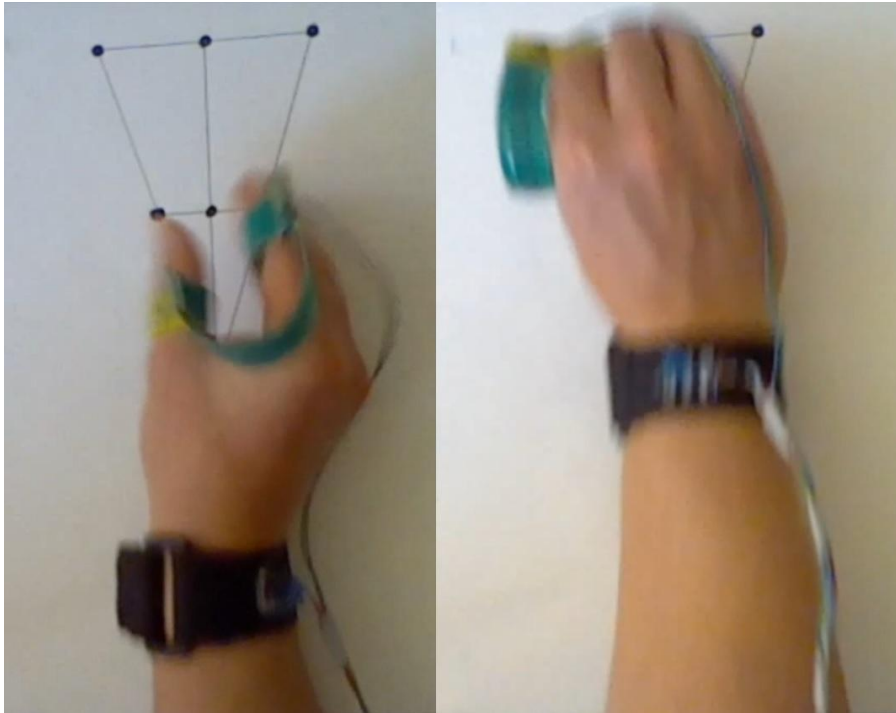
Figure 6.3.4a. A screenshot of the videos of the reach and grasp target movement at position 4 (left) and the turn door handle movement at position 2 (right)

Table 6.3.4. Variation of spatiotemporal parameters during the reach and grasp target movement

Spatiotemporal parameter	Variation of parameter
Velocity	The velocity was higher between locations 3 to 4 to finish than between locations start to 1 to 2 to 3
Direction	The direction between locations start and 2 to between 3 to 4 was opposite to the direction between locations 2 to 3 and between 4 to finish
Displacement	The displacement between locations 1 to 2 was greater than between locations 3 to 4. Also, the hand opening distance at location 2 was greater than at location 4.

Turn door handle target movement

This movement was largely identical to the reach and grasp target movement, but instead of opening and closing the hand, the hand was rotated through pronation and supination. The hand was at zero degrees pronation from the start position to position 1. To position 2, the hand was rotated to approximately 90 degrees pronation, and then from position 3 to position 4, to approximately 45 degrees pronation. The spatiotemporal parameters were therefore varied in the same manner as for the reach and grasp movement.

Also, as described in section 3.6.2, to help minimise movements of the trunk, the participants were provided with a back support. To aid the process of aligning the participants with the apparatus to achieve the starting position, an office chair was used. In this way, small adjustments could be made to the positions of participants where necessary due to the chair wheels. However, office chairs can also rotate, which in this case was an unwanted movement. The rotation mechanism was therefore locked by inserting two straps from the wheeled base to the back rest.

6.3.5. Data recorded

Recording of target movements

As described in section 3.6.4, the output files from the target recording program are in CSV format and contain samples of the signals from each measured DOF in separate columns. The duration of the recording sequence was set to four seconds, to allow sufficient time whilst avoiding overly large output files. The sample rate was set to 20 Hz, meaning a set of 80 scaled voltage samples were recorded for each DOF. This was done for both the reach and grasp and turn door handle target movements. After recording of the target movements, the data recorded by the target recording program was analysed to ensure the required variation of spatiotemporal parameters had been achieved. This was done by performing graphical analysis on the output files.
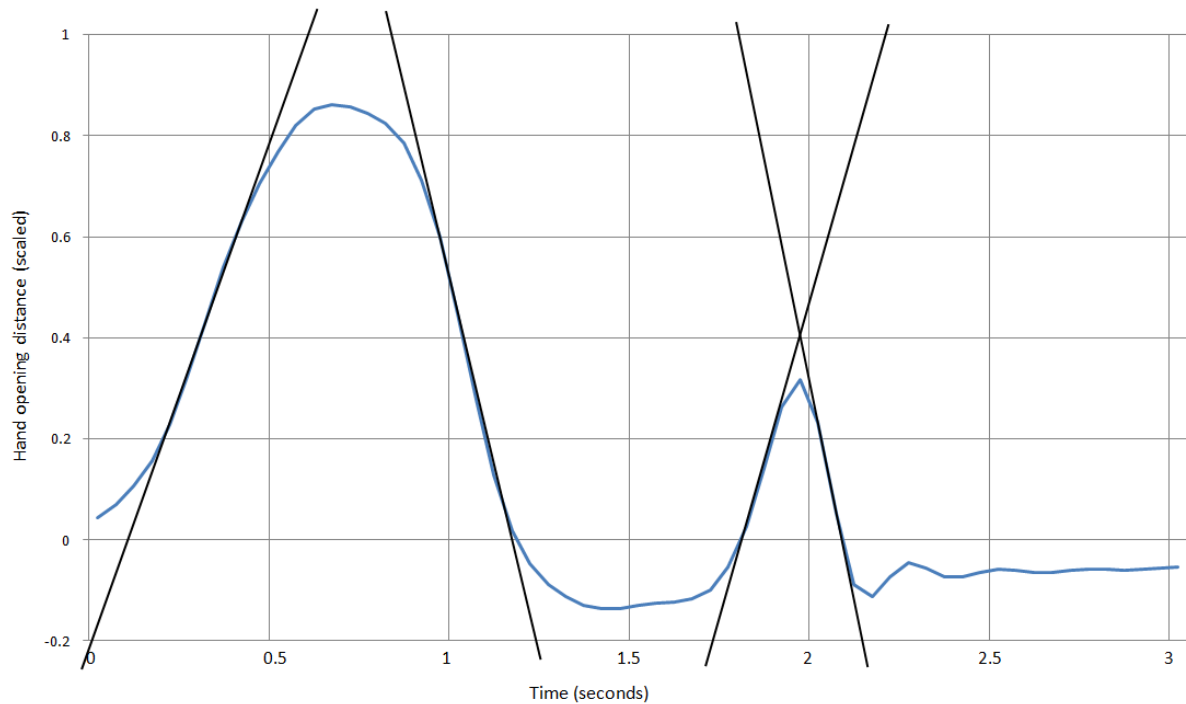
Figure 6.3.5. Graph of the reach and grasp target movement with positive and negative gradients of the two peaks highlighted

The required spatiotemporal characteristics were achieved empirically. It can be seen in Figure 6.3.5 that two velocities, two directions and two displacements are present, which indicates that the desired variation of spatiotemporal parameters had been achieved for the reach and grasp movement. The same was then done for the turn door handle target movement to ensure that the desired variation of spatiotemporal parameters were achieved.

Summed deviation values

As described in section 3.6.4, the output files from the feedback program are in CSV format and contain summed deviation values which correlate to conformance to the target movement of the hand and elbow per movement attempt. During a session, after attempting to reproduce the target movement an initial time for future comparisons, participants were asked to attempt to reproduce the target movement a further 35 times. This number was established after a pilot test was performed, which is described in section 6.3.6. As two target movements were performed per participant, two output files were generated.

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Participant information

As required by the EAC, each participant was required to sign an informed consent sheet, which was filed for future reference. The participants' age, gender and handedness were also recorded.

6.3.6. Instructions and test schedule

The main interaction activities performed with each participant are listed below:

1. Thank the participant for their participation and offer them refreshments
2. Establish which test schedule and participant number are to be assigned to the participant
3. Ensure the participant has read the appropriate information sheet; either for the feedback or control group
4. Ensure the participant has signed the informed consent sheet
5. Ask the participant's age and handedness, and record gender
6. Measure participant's reach distance at 160 degrees elbow extension and place appropriate guidance markings
7. Verbally explain the feedback mechanisms and play a feedback instruction video (described below) to participant (feedback group) or explain the notification of movements in progress (control group)
8. Verbally describe the first target movement and play the video of it. Play the video again during the session as requested by the participant
9. Mount the prototype hardware to the participant
10. Describe the start position to the participant with the aid of a diagram
11. Load the program for the first movement and specify names and locations of the output files according to the current participant
12. Have a practice session: explain the feedback (feedback group) or notification of movements (control group), end position of the movement and the trigger mechanism to distinguish one movement attempt from the next
13. When the participant feels ready, perform the session of the first movement, independently without assistance from the researcher

14. Verbally describe the second target movement and play the video of it. Play the video again during the session as requested by the participant

15. Load program for the second movement and specify names and locations of the output files according to the current participant

16. Have a practice session

17. When the participant feels ready, perform the session of the second movement, independently without assistance from the researcher

18. Thank participant and ask if they have any questions and show them the alternative test conditions if they would like. Allow the participant to keep the information sheet

A private office was temporarily used to perform the tests within. This was to allow for adequate space and to ensure noise levels were low. Also, to allow the test conditions to be maintained across all tests.

Figure 6.3.6a. Room arrangement and equipment setup used to perform the participant tests

The equipment setup included the following items as shown in Figure 6.3.6a:

- Main computer to run the feedback programs and save the output files
- A laptop to play videos of the target movements to the participants, to play the feedback instruction video (feedback group) and to display the diagram of start position
- An office chair with locked rotation mechanism
- Guidance marking sheets
- Goniometer and tape measure to measure participants' reach distance at 160 degrees elbow extension
- The prototype hardware
- A logbook in which to make notes including comments and feedback given by the participants
- A sheet listing the interaction activities (for the researcher's reference), multiple copies of the information sheets and informed consent forms

As mentioned, a pilot test was performed prior to embarking on the main participant tests. The pilot test involved carrying out the tests with two pilot study participants; one simulating the feedback condition and the other simulating the control condition. This was done to allow the participant interaction procedure to be practised and also to help identify any problems prior to contacting multiple potential participants and scheduling times for their participation. It was found that the time taken to perform 50 repetitions of each target movement exceeded the time of approximately 30 minutes specified within the application to the EAC. Due to this and because 50 repetitions in one session fatigued the participants, the number of repetitions was reduced to 35. Practice sessions were performed by each participant prior to recording full sessions. This allowed the participants to familiarise themselves with the feedback mechanisms. It also allowed small adjustments to be made as necessary, for example to the positions of the sensors. During the pilot test it was found that it was necessary to allow the participant to choose how long to practise for before feeling comfortable and ready to begin the tests for recording. Although this inevitably led to some variations in the test conditions between participants, it allowed them to

understand the prototype system as necessary. This was important because some participants were more confident and experienced in reading graphs than others.

As stated in section 3.6.2, guidance markings of different scales were required for participants of different anthropometric dimensions. This allowed the dimensions of the target movement to be scaled. Since the participants were of varying segmental dimensions, the target movement was adapted for each individual accordingly. To do this, the participants were asked to assume the start position and extend their elbow to 160 degrees with their hand approximately 10 mm above the table. The reach distance from the start position was then measured and the movement guidance markings (see Figure 3.6.1b) were scaled in the sagittal axis accordingly. This ensured that the elbows and shoulders of participants of different dimensions extended and flexed through the same angles during reproduction of the target movements. To aid the adaptation of the target movement, a series of guidance markings with different levels of scaling in the sagittal axis were drawn. These ranged from a minimum of 200 mm reach distance to a maximum of 340 mm, with increments of 20 mm. This allowed the test apparatus to be adjusted quickly as necessary for each participant. The guidance markings were not scaled in the transverse axis because this would result in erroneous reading of target deviations. Instead, all participants were asked to attempt to reproduce the hand distances of 100 mm and then 50 mm shown in Figure 3.6.1b during the reach and grasp movement, and 0 and then 90 degrees pronation during the turn door handle movement. Theoretically, these positions should be achievable by the participants without limitations due to anthropometric dimensions.

As discussed in section 3.6.4, because of the technical nature of the graphical area of the feedback, instruction to patients may be required to allow an understanding to be gained. The feedback mechanisms were explained to participants verbally and an instruction video was also played to the participants in the feedback group. The video was constructed by recording a simple movement with the target recording program for the purpose of demonstration. The movement was a simple opening and closing of the hand (see Figure 6.3.6b), which was loaded into the feedback program. The video was made by recording the graphical part of the feedback with a webcam whilst reproducing the movement in different

ways relative to the peak in grip distance for demonstration. The feedback explanation video was then edited to include the following elements:

- Axes: time and hand displacement
- Target movement profile and the participant's movement trace
- An example of what a well performed movement would look like
- Examples of what poorly performed movements would look like including too fast, too slow, too early, too late, too far and not far enough
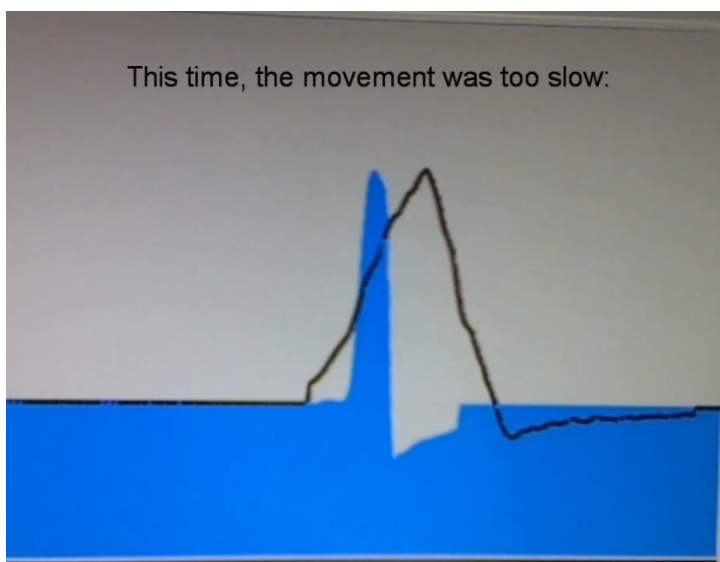
Figure 6.3.6b. A screenshot from the feedback explanation video showing a movement performed too slowly relative to the target movement

6.4. Data analysis

6.4.1. Details about the participants

40 participants participated in the tests; 20 in the feedback group and 20 in the control group. Their ages and other details are shown in tables 6.4.1a and 6.4.1b.

Table 6.4.1a. Ages of participants

Ages (years) in order of participation in feedback group	Ages (years) in chronological order in feedback group	Ages (years) in order of participation in control group	Ages (years) in chronological order in control group
28	23	28	21
29	24	24	22
27	25	22	23
26	25	53	24
36	25	21	24
25	25	24	24
30	25	26	25
35	26	24	26
24	27	30	26
62	28	60	26
32	29	25	27
25	30	23	28
33	31	29	28
23	31	33	29
25	32	31	30
32	32	30	30
31	33	27	31
25	35	28	33
31	36	26	53
25	62	26	60

Table 6.4.1b. Details about the participants

	Feedback group	Control group
Mean age (years)	30.2	29.5
Males	12	12
Females	8	8
Right handed	17	17
Ambidextrous	0	1
Left handed	2	0
Left handed but trained to use right	1	2

The groups were well matched in terms of age, gender and handedness. One participant from the feedback group and one from the control group were unable to perform the turn door handle movement. Although they were able to attempt the movement they were unable to prevent excessive shoulder abduction. This resulted in the shoulder trigger mechanism either disabling during the movement or not enabling at all. This meant that data was not recorded for these movements. Consideration of missing data and only managing recruiting 40 participants instead of the suggested number of 50 is described in section 6.4.4.

6.4.2. Feedback from participants

The following comments and feedback were given by the participants during the sessions:

- *"Slightly confusing that opening the hand sideways* [in the transverse axis] *makes the line go upwards on the screen"*
- *"It would be useful to have a graph of performance generated at the end of the session"*
- *"I feel I am trying less towards the end of the session because I know it's nearly over"*
- *"It's like playing a game in the sense of motivation"*
- *"It's somewhat stressful because I want to do my best"*
- *"The elbow strap* [strap supporting the gyro sensor to measure lateral and medial rotation] *was catching slightly on my body"*
- *"The wrist strap* [strap supporting the gyro sensor to measure pronation and supination] *was catching slightly on the table"*
- *"The sensor straps were comfortable to wear"*
- *"An actual game instead of simply following a profile might be more fun"*
- *"It was good fun to use"*

This feedback is discussed in Chapter 7 and forms the basis for some recommendations for future research in Chapter 8.

6.4.3. Comparison of mean conformances

As described in section 3.6.4, the output from a session is a series of summed deviation values per movement attempt, where lower values indicate higher conformances to target movements per movement attempt. No units are given for the summed deviation values, because as stated in section 3.6.4, the signal multiplication factors were established to allow similar amplitude responses from the DOFs which move during movements.

Table 6.4.3a. Example output data from the feedback program from a participant's session performing the reach and grasp target movement with feedback

Movement repetition number	Summed deviation values from the hand	Summed deviation values from the elbow
1	12.70	24.38
2	11.90	28.65
3	11.84	31.65
4	9.64	25.02
5	7.65	25.65
6	12.59	23.86
7	7.69	22.44
8	10.71	32.11
9	9.70	23.20
10	7.68	33.31
11	5.67	24.30
12	9.69	27.91
13	6.63	35.79
14	7.49	29.32
15	6.14	30.14
16	9.61	33.04
17	8.17	32.70
18	7.91	28.46
19	6.45	36.86
20	8.16	34.70
21	6.03	30.77
22	8.41	29.75
23	8.74	30.35
24	6.11	32.22
25	5.08	23.08
26	10.59	30.26
27	10.02	34.07
28	9.91	30.13
29	11.59	25.54
30	9.78	28.60
31	7.56	24.18
32	10.32	30.53
33	9.85	28.52
34	9.95	35.55
35	12.70	24.38

From the data shown in Table 6.4.3a, the mean summed deviation values from the hand and elbow were calculated as 8.96 and 29.58 respectively. This was done for each participant performing the reach and grasp target movement with feedback.

Table 6.4.3b. Mean hand and elbow summed deviation values from participants performing the reach and grasp target movement with feedback

Mean summed deviation values per session from the hand	Mean summed deviation values per session from the elbow
8.96	29.58
11.95	11.83
11.40	21.88
18.95	22.54
16.91	31.18
15.71	45.90
15.79	61.26
15.01	28.03
13.39	12.87
13.64	17.56
20.32	21.85
12.60	20.55
10.64	14.48
7.56	41.10
11.54	15.71
12.46	26.54
13.15	14.04
13.58	13.91
10.34	28.40
17.09	11.45

From the data shown in Table 6.4.3b, the means from the hand and elbow were calculated as 13.55 and 24.53 respectively. This was done for each target movement and for both the feedback and control groups.

Table 6.4.3c. Mean summed deviation values per DOF, target movement and group

		Feedback group	Control group
Reach and grasp movement	Hand	13.55	16.50
	Elbow	24.53	29.52
Turn door handle movement	Hand	14.98	21.04
	Elbow	36.22	44.10

Table 6.4.3c shows that the summed deviation values from the feedback group are lower than those from the control group, suggesting superior conformances. To help clarify this, the difference in conformance between the feedback group and the control group at the hand during the reach and grasp movement was calculated as a percentage as follows:

$$\left(\frac{(16.5 - 13.55)}{16.5}\right) \times 100\% = 17.90\%$$

This was done for both target movements and at both DOFs (shown in Table 6.4.3d).

Table 6.4.3d. Percentage positive differences of the feedback group over the control group in mean summed deviation values per target movement and per DOF

Reach and grasp movement	Hand (%)	17.90
	Elbow (%)	16.88
Turn door handle movement	Hand (%)	28.80
	Elbow (%)	17.87

The mean percentage positive difference at the hand and elbow were then calculated as 23.35 % and 17.37 % respectively. The mean overall percentage improvement was also calculated as 20.36 %. Conclusions from these results are drawn in section 6.5.

6.4.4. Inter-variability and statistical significance

Having identified positive differences in mean conformance of the feedback group compared to the control group, the variability across participants in each group (inter-variability), per movement and DOF, was investigated and statistical tests were performed to investigate improvements in conformance of the feedback group. This was done to give an indication of consistencies in conformances of both the feedback group and control group for comparison purposes. The calculation of statistical significance allowed factors such as sample size and the missing data to be taken into consideration. To do this, an independent samples t-test was performed in the statistical analysis software SPSS. As mentioned in section 6.3.5, initially the mean summed deviation values were calculated per DOF and per movement. This gave a mean hand and a mean elbow summed deviation value per reach and grasp movement and per turn door handle movement per participant. This meant that 4 mean summed deviation values were obtained per participant. These values were entered into SPSS and the missing data described in section 6.4.1 were specified. An independent samples t-test was then performed.

Table 6.4.4. Results from SPSS for the independent samples t-test

Movement (and DOF)	Mean, mean summed deviation value (feedback)	Standard deviation (feedback)	Mean, mean summed deviation value (control)	Standard deviation (control)	df	N	t-value	Significance value (significant if less than 0.05)
Reach and grasp (hand)	13.549	3.243	16.504	4.467	38	20	-2.39	0.022
Reach and grasp (elbow)	24.533	12.844	29.516	16.053	38	20	-1.08	0.285
Turn door handle (hand)	14.983	4.081	21.043	7.194	36	19	-3.19	0.003
Turn door handle (elbow)	36.220	16.338	44.098	12.989	36	19	-1.65	0.109

In Table 6.4.4, df is a correction factor and is used to avoid underestimating variability when calculating the significance value. The t-value is a value calculated using standard formulae for independent samples t-tests. If the independent samples t-test had been performed manually, a critical t-value would have been looked up in a table of data based on the df and the level of significance that was specified. The calculated t-value would then be compared with the critical t-value and a significant difference would exist if the calculate t-value was beyond the critical t-value (Cohen 1988).

As shown in Table 6.4.4, there was less inter-variability (given by standard deviation) in the feedback group in all movements and DOFs except during the turn door handle movement at the elbow. This indicates that the prototype system consistently guided participants. It can also be seen that the improvement in conformance between the feedback and control groups is statistically significant for the hand for both the reach and grasp movement and the turn door handle movement. The differences in conformance between the feedback and control groups were not significant for the elbow. This could be due to the higher inter-variability, the missing data, or the fact that fewer than the suggested 50 participants were recruited. The latter could have resulted in the tests having less statistical power. Conclusions from these results are drawn in section 6.5.

6.4.5. Limitations of tests

- Two participants were unable to perform the turn door handle movement, and only 40 participants were recruited despite the calculated recommendation being 50. However, the missing data were specified in SPSS, and the calculations performed took the number of participants into consideration for statistical significance. The lower number of participants made it more difficult to achieve a statistically significant difference between groups. However, the superior performance of the feedback group was statistically significant for the hand in both the reach and grasp movement and the turn door handle movement.

- Only the performance of the prototype system in a single session (as opposed to across multiple sessions) was tested, as was the aim of the tests. This only allowed the efficacy of the system in guiding movements to be investigated. Also, it was considered that too little time was spent using the system during the sessions for learning to occur. Consequently, enhancements to motor learning and the extent of dependency on feedback were not investigated. This was considered appropriate given the scope of this research and because guiding movements was considered a prerequisite for enhancements to motor learning.

- During the pilot test it was found that it was necessary to allow the participant to choose how long to practise for before feeling comfortable and ready to begin the tests for recording. Although this inevitably led to some variations in the test conditions between participants, it allowed them to understand the prototype system as necessary. This was important because some participants were more confident and experienced in reading graphs than others.

- Two of the participants from the feedback group were left handed but no participants from the control group were left handed. Although this led to variation between groups, it gave a worst case for the performance of the feedback group because the hardware of the prototype system accommodated the right arm.

- The mean ages of the participants in both groups were lower than the mean age of people who suffer a stroke. Also, the participants were recruited from within the university meaning that most of them were from an academic environment with more experience in reading graphs and working with computers than perhaps a typical stroke patient would be. However, this approach allowed for a larger sample size which was necessary in order to perform the statistical tests required to test the prototype system.

- As pointed out by a participant, it can be confusing that opening the transverse axis causes the line in the feedback graph to move upwards on the screen. Also as pointed out by some of the participants, the straps at the elbow (supporting the gyro sensor to measure lateral and medial rotation) and the wrist (supporting the gyro sensor to measure pronation and supination) caught slightly on the body and table during movements.

- It was assumed that the ratio of upper arm length to lower arm length remained constant for all participants. Although this will not have been entirely the case, from visual observations, it was thought that variation in ratio had been minimal.

6.5. Conclusions to chapter

- Feedback resulted in improvements in conformance to target movements over the control group at the hand during the reach and grasp movement and turn door handle movement of 17.90 % and 28.80 % respectively. This gave a mean improvement of 23.35 %, which suggested that the feedback resulted in superior performance at the DOF for which feedback was given.

- Feedback resulted in improvements in conformance to target movements over the control group at the elbow during the reach and grasp movement and turn door handle movement of 16.88 % and 17.87 % respectively. This gave a mean improvement of 17.37 %, which suggested that the feedback resulted in superior performance at the DOFs which also move but for which no feedback was given.

- The variability across participants in the feedback group was lower at the hand for both target movements. This indicates that the prototype system consistently guided participants at the DOF for which feedback was given.

- The variability across participants in the feedback group was lower at the elbow for reach and grasp movement but not for the turn door handle movement. Therefore no support was found for the prototype system guiding participants consistently at the DOFs which also move but for which no feedback was given.

- The improvement in conformance between the feedback and control groups was statistically significant for the hand in both the reach and grasp movement and the turn door handle movement. This strongly suggests the prototype system guided target movements effectively at the DOF for which feedback was given.

- Although the feedback resulted in improvements in conformance between the feedback and control groups at the elbow, they were not statistically significant. It could therefore not be concluded that the prototype system guided target movements at the DOFs which also move but for which no feedback was given.

- Most of the participants found use of the prototype system interesting and entertaining. This suggested motivation during use.

- Once participants had been appropriately instructed, they were able to use the prototype system independently without assistance from the researcher.

- The prototype hardware was found to be easy to put on and take off, and it was thought that carers could do so unassisted. However, it was thought that instructions would need to be provided to carers to ensure fitting of the sensors in the correct locations.

The findings from this chapter formed the basis for discussion of the results in relation to the hypothesis and research questions in the following chapter.

CHAPTER 7. DISCUSSION

7.1. Introduction to chapter

In this chapter, the prototype system, test results, addressing of the research questions and supporting of hypothesis are discussed. This was to allow the implications of findings from this research to be considered. First, the shortcomings of the prototype system with respect to the design specification are reviewed along with achievement of the system objectives. Next, test results are discussed in relation to the research questions and hypothesis. Subsequently, the novelty of this research is described in greater detail than was done in section 1.6. Finally, the addressing of the research questions and supporting of hypothesis are discussed. All of this formed the basis for drawing conclusions from this research and recommendations for future research in Chapter 8.

7.2. Discussion of the prototype system

Shortcomings with respect to the design specification

Radial and ulnar deviation and extension and flexion at the wrist were not measured. This is because after observing movements, and considering the BI ADLs (Mahoney, Barthel 1965) reviewed in section 2.6.3, these DOFs appeared to be used less compared with the other major DOFs. However, some movements do involve movement of these DOFs. Movement at these DOFs could therefore be measured in future by adding gyro sensors or flex sensors at the wrist and hand. This would allow a larger range of exercise movements to be performed.

The estimated required sample rate was 80 Hz, but the sample rate of the prototype system was 20 Hz. As described 3.6.4, this was to allow detail about the movement to be obtained whilst avoiding delays in the graphical feedback on slower computer systems. The lower sample rate, for the purpose of performing tests involving healthy people, did not cause negative effects. However, the sample rate could be increased in future if tests involving stroke patients were to be performed. This would allow more details about slower movements to be obtained, and also allow details about faster movements such as spasticity to be obtained. To avoid delays in graphical feedback, the feedback program could

be modified in future to allow graphics to be generated from re-sampled data. Alternatively, a more powerful computer system could be used, which is a realistic option given the performance of modern computer systems.

The prototype system was required to be flexible to allow movement to be performed naturally and comfortably. However, as pointed out by some of the participants, the straps at the elbow (supporting the gyro sensor to measure lateral and medial rotation) and the wrist (supporting the gyro sensor to measure pronation and supination) caught slightly on the body and table during movements. This could be overcome in future by moving the locations of the Velcro fastenings towards the distal area of the arm.

The prototype system was intended to be simple, subtle and non-invasive in appearance. However as stated, in terms of the scope of this research, the aim of the prototype system was to allow tests to be performed. This meant that the generation of suitable data was considered important, and refinement and aesthetics were considered less important, and as such, wires were routed externally and the sensors were left in view. This could be overcome in future by implementing wireless technology, and placing covers over the sensors to increase the simplicity of the appearance.

Achievement of the prototype objective

The prototype objective was to allow tests to be carried out and investigation to be performed to allow the hypothesis and research questions to be addressed. This objective has been achieved, despite the shortcomings identified above and the limitations to the tests in chapters 4 to 6. The prototype system allowed the tests in chapters 4 to 6 be performed satisfactorily.

Achievement of the general objectives

1. Be capable of enabling regular guided and monitored therapeutic exercises in the home to provide a means for stroke patients to achieve a higher level of physical rehabilitation.

As described in section 3.6.1, the prototype system aimed to achieve this objective by providing guidance which allows target movements to be conformed to more closely, as is done during regular physiotherapy. This enhances motor performance during

physiotherapy, which increases the motor learning by stroke patients. The findings and results presented in Chapter 6 indicate that this objective has been achieved, particularly as the mean improvement compared to the control group of the DOF for which feedback was given was 23.35 %. This improvement was found to be statistically significant (reach and grasp movement: $t = -2.39$, $\rho = 0.022$; turn door handle movement: $t = -3.19$, $\rho = 0.003$). Other aspects regarding the achievement of this objective are discussed in the following sections of this chapter.

2. Focus on rehabilitation of the upper limb.

This objective has been achieved.

3. Be low enough cost to be affordable for private purchase (less than £500).

This objective has been achieved because readily available materials, sensors and connectivity methods were used and the total cost, as described in section 3.6.1, was approximately £291. The price of a commercial equivalent of the prototype system would likely cost less to produce than the prototype, where product specific DAQ and software programs would probably be used. However, the cost to the end user would likely be similar.

4. Be useable within the home (compact, easy to set up and safe).

This objective was considered to have been achieved because, as described in section 3.6.3, the prototype hardware occupied a space similar to that required for a desk and computer, and when not in use, can be folded for storage, for example in a drawer. Also, as concluded in section 6.5, the prototype hardware was found to be easy to put on and take off, and it was thought that carers could do so unassisted if provided with instructions to ensure fitting of the sensors in the correct locations. The prototype hardware was also safe to use, where, as identified in section 6.3.1, the DAQ conformed to relevant safety standards and a standard USB power system is used.

5. Be useable independently by patients and carers.

This objective was considered to have been partially achieved. As described in section 6.3.6, an instruction video which described the graphical part of the feedback to participants,

videos of the target movements, a graphical description of the starting position and verbal instruction of the procedure were given to participants. Also, the amount of information provided to participants and its complexity was kept to a minimum and layman's terms were used. Once participants had been appropriately instructed, they were able to use the prototype system independently without assistance from the researcher. However, as described above, it was thought that instructions would need to be provided to carers to ensure fitting of the sensors in the correct locations. Also, the verbal instruction of the procedure given to participants would have to be converted into an automated form. The test apparatus, as described in section 6.3.6 consisted of multiple elements, which would require combining for use by stroke patients and carers. This is discussed further in section 7.3.3.

6. Be capable of informing clinicians and researchers of performance of specific kinematic parameters.

This objective has been achieved because, as tested in Chapter 5, the prototype system processed the data recorded to allow movement synergism to be detected. This is discussed further in section 7.3.2.

7. Be capable of remotely informing clinicians and researchers of patient performance.

Integration with tele-rehabilitation platforms was beyond the scope of this research, where instead, more fundamental elements were focused on. However, the objective was considered to have been partially achieved because data was converted to a digital from which was held on a standard computer system connected to the internet. This supports integration with tele-rehabilitation platforms which could be implemented in future research.

Achievement of the specific objectives given in section 3.2.5 is discussed in the following sections. The prototype system was considered to meet the design specification and have achieved the system objectives satisfactorily given the scope of this research.

7.3. Discussion of the test results

7.3.1. Validation of the prototype hardware using VICON

This section discusses the tests performed to validate the performance of the prototype hardware against VICON. Also, the tests performed to investigate the behaviour and capabilities of the prototype hardware when movements were performed in multiple planes and whilst varying spatiotemporal parameters. These tests were performed to assess the suitability of the prototype hardware for performing further tests in chapters 5 and 6, and also to allow the results from the further tests to be better understood.

As stated in section 4.4.9, there will have been slight spatiotemporal variation between the movements performed during the tests. To overcome this, testing using a robotic arm was contemplated, to perform movements with minimal spatiotemporal variability. However, it was decided to test on the human arm because as identified in section 3.2.4, there are characteristics of measuring human movement which make it unique. These include the centres of rotation of DOFs being difficult to locate and ability of the skin to move relative to the bone. This would make use of a robotic arm a poor simulation of measuring human movement.

It was established in the design specification that the response from the prototype hardware should be as linear as possible. Although some characteristics of non-linearity were seen, they were not considered to be a limiting factor on the performance of the prototype system. Linearity of response is important for the graphical area of the feedback to be effective. This is to allow the response of the system to behave in a way as would be expected during use. For example if the hand was opened at a constant velocity, the user would expect the height of the line to increase at a constant velocity also. This would allow the target profile to be followed more easily. If the response was non-linear, some additional learning would be necessary to use the system which could be time consuming and detract from the process of learning the skill.

In future, the accuracy of the prototype hardware could be quantitatively calculated, by using a third measure of movement to calibrate the prototype hardware, such as an

electrogoniometer, to allow scale and offset values to be established for the data from the prototype hardware. This way, accuracy as a displacement could be calculated using VICON, which would allow a further understanding of the performance of the prototype hardware to be gained.

It was established in the design specification that the data recorded by the prototype hardware should be as low in variability as possible. The mean intra-variability value of 6.36 % of the range of movement could be a limiting factor on the performance of the prototype system. It was thought that this intra-variability was caused mainly by the instabilities in the resting voltages from the gyro sensors. As described in section 3.6.4, these instabilities occurred immediately after exercise movements. This caused the data recorded by the prototype hardware to appear as though slow movements of small displacements occurred after movements were performed, when in fact the limb was held stationary. This was discovered whilst performing practice movements using the system when developing the feedback program. To minimise the effects of these instabilities, the velocity threshold system introduced in section 3.6.4 was implemented to allow only velocity data over or under a certain value from the gyro sensors to be considered. However, as identified in section 4.4.6, this caused distinct minimum velocities and hence displacements which could be read. It was also thought that reading the displacements at the start and end of movements, where velocities were low, may have been when the majority of the high intra-variability in results was caused. This is because any variation in relation to movement would have a magnified effect because it could result in movement being falsely considered or overlooked. This would have a pronounced effect on recorded displacements because as stated, any errors will accumulate due to the integration calculations. The high intra-variability at the hand opening and closing could have been caused by the sensor moving slightly during movements. This means that reliability of the data from the prototype system was lower, particularly when calculating single values or mean values when fewer movements are performed in sessions.

As concluded in section 4.5, the minimum readable displacements were marginally greater than the estimated requirements in the design specification. For the purpose of this research it was not considered to be a limiting factor because the system was only tested on

healthy participants. As identified in section 3.2.2, the velocities moved through by healthy people were greater than the minimal readable velocities by the prototype hardware as investigated in section 4.6.6. However, it was thought that this would be detrimental for use of the system to aid stroke patients, because they are likely to move at low velocities and through small displacements compared to healthy people. This may result in some movements, particularly by severely impaired patients, being overlooked by the prototype hardware. This would negatively affect the efficacy of the system in aiding stroke patients.

In order for the prototype system to be useful for stroke patients, the intra-variability would need to be reduced and the minimum readable velocities and displacements would need to be decreased. This could perhaps be achieved in future by investing in gyro sensors with signals that remain more stable after movements. For example the L3G4200D gyro sensor costs £38 but has a higher linearity rating than the gyro sensors used in the prototype system (Proto-Pic 2013). This could also be achieved by attaching the flex sensor at the hand more securely by using neoprene straps. This would allow more detail about slower movements to be obtained, and also allow details about faster movements such as spasticity to be obtained.

As concluded in section 4.5, the inter-variability from the gyro sensors was lower than from the flex sensors, with a mean value of 2.30 % of the mean range of angular displacement. The value from the flex sensor at the hand was higher than this, at 19.25 % of the range of linear displacement. This may have been caused by slight differences in the mounting positions of the flex sensor. This suggests that care should be taken to mount the sensors in the same positions in all sessions. As mentioned in section 4.4.9, the small number of participants limited the power of the tests and although the participants were of similar anthropometric dimensions, some differences were inevitably present. The participants could have also been aligned slightly differently to one another relative to the axes defined by VICON during tests. This high inter-variability would have a negative effect because different results could be obtained from one session to another, which would make it more difficult to track performance consistently and to identify improvements. This high inter-variability could be overcome to an extent in future by providing instructions to ensure fitting of the sensors in the correct locations.

7.3.2. Tests of the efficacy of the prototype system in detecting movement synergism

As discussed in section 3.4.3, once data corresponding to movement has been acquired, a virtually unlimited number of possibilities exist regarding processing, calculations and parameters to asses. Including an ability to detect movement synergism was established as a specific objective of the prototype because restoring movement coordination through repetitive practice is performed during regular stroke physiotherapy. Detecting movement coordination during physiotherapy may therefore be useful to monitor patient performance and optimise physiotherapy programs. Also, as concluded in section 2.8, with existing systems, little emphasis has been placed on the detection of coordination of movements during physiotherapy, and there appears to be no widely agreed method of defining movement coordination or movement synergism.

The variability of the prototype system in detecting movement synergism was investigated by comparing the data from the prototype system with that from VICON whilst movements were performed both synergistically and then sequentially. The prototype system considers the extent of movement synergism, as proposed in section 2.8, as the extent that two or more DOFs are moving simultaneously. This definition seems to be the simplest method of defining movement synergism in the way in which it relates to movement coordination.

The estimated mean variability in measurements (between the prototype system and VICON) of movement synergism during reach and grasp and the turn door handle movements were calculated as 15.43 % and 9.74 % respectively. These were percentages of the mean counts obtained during the synergistic movements as described in section 5.4.2. As described in section 3.6.4, the counts were of program iterations which occurred whilst movement synergism was present in the categories established in section 3.4.3. These results suggest that the prototype system is capable of detecting movement synergism in a session, but is less suited to measuring movement synergism in a single movement, because the reliability of the result would be low. It was therefore considered that the specific objective of including an ability to detect movement synergism had been partially achieved. It was thought that this variability was caused mainly by the instabilities in the resting

voltages from the gyro sensors. The variability could perhaps be reduced in future, as described in section 7.3.1, by investing in gyro sensors with signals that remain more stable after movements.

As stated, in future, the accuracy of the prototype hardware could be quantitatively calculated, by using a third measure of movement to calibrate the prototype hardware, such as an electrogoniometer. This would allow investigation of the efficacy of the prototype system in measuring movement synergism at different levels. This would allow a fuller understanding to be gained, of the efficacy of the prototype system in measuring movement synergism. This was beyond the scope of this research because as stated, ability to detect movement synergism is a prerequisite for ability to measure movement synergism at different levels.

As described in section 3.6.4, the synergism recording program defines movement synergism in the categories of positive-positive, negative-negative, positive-negative, negative-positive and general movement synergism for each DOF combination. Also summed positive-positive, summed negative-negative and summed general movement synergism for all DOFs. These categories therefore give single counts per movement attempt. To aid the process of comparing performance during movements, these counts could be divided by the duration of the respective movements. Also, in future the series of movements during a session could be displayed in a graph to allow the performance over a session to be understood more easily by clinicians and researchers. Alternatively, average feedback could be generated describing the movement synergism performance in a session using a single figure.

KP in specific categories may also be of use to the patients themselves. The worded bandwidth feedback mechanism of the prototype system gave KP based on deviation of movements exceeding predefined thresholds. Alerting a patient when they move in a particularly sequential manner may also be useful. They may then be able to give cognitive focus to moving DOFs of the arm in a synergistic manner. After several movement attempts in this way, through practice, the process of moving synergistically may become automatic. This could enhance the process of motor learning.

7.3.3. Tests of the efficacy of the whole prototype system

This section discusses the tests performed to investigate the efficacy of the prototype system as a whole. As established in Chapter 3, the first general objective of the system was to be capable of enabling regular guided and monitored therapeutic exercises in the home to provide a means for stroke patients to achieve a higher level of physical rehabilitation. These tests were performed to investigate the efficacy of the prototype system with respect to this objective and therefore the hypothesis of this research. Results were in support of the hypothesis, in particular, the mean improvement of the feedback group compared to the control group for the DOF for which feedback was given was 23.35 %. This improvement was found to be statistically significant (reach and grasp movement: $t = -2.39$, $\rho = 0.022$; turn door handle movement: $t = -3.19$, $\rho = 0.003$). This shows that the specific objective of allowing target movements to be conformed to more closely has been achieved. Also, positive comments were made by participants during use of the prototype including *"it was good fun to use"*, and *"it's like playing a game in the sense of motivation"*. Moreover, as discussed in section 7.2, the prototype system was low enough cost to be affordable for private purchase (less than £500), and was useable within the home (compact, easy to set up and safe).

The specific objective of allowing movements to be performed in a similar way to how they would be during a regular physiotherapy session has also been achieved, where pausing between movements and continuing when ready is possible. Similarly, the specific objective of providing quantitative information to patients of their personal improvements during physiotherapy, combined with graphical feedback of their movements and the target movements has been achieved.

As a result of the efficacy of the prototype system concluded in section 6.5, the mechanism to allow movements to be performed in a similar way to how they would be during a regular physiotherapy session appeared to be effective. The results suggest that the feedback system including the combination of quantitative information to patients of their personal improvements during physiotherapy for motivation, and graphical feedback of the patient's movements and target movements, had also been successful.

As concluded in section 6.5, the improvement seen at DOFs which also move but for which no feedback was given, was not statistically significant. Also, no support was found for the prototype system guiding participants consistently at these DOFs. Performance of the prototype system in these categories could perhaps be improved in future by enabling the worded bandwidth feedback. The lack of statistical significance could also have been due to some variation in measurement of reach distance of participants for selection of table marking scaling.

As stated in section 6.1, healthy participants were employed for these tests, where efforts were made to simulate the situation and characteristics of stroke patient motor learning. The use of healthy participants somewhat limits the value of the results because the aim of the system was to aid stroke patients. Employing stroke patients was beyond the scope of this research due to the time and resources it would require. Instead the potential value of this type of system for stroke patients was investigated by considering fundamental elements of the system, such as variability of the prototype hardware. This allowed the system as a whole to be better understood.

In further support of the hypothesis, the benefit to stroke patients of regular stroke physiotherapy has been well documented. For example the randomised controlled trial mentioned in section 2.5.4 (Cirstea, Ptito & Levin 2006) investigated the effects of feedback to stroke patients practicing a reaching task. It was found that feedback resulted in superior performance. The prototype system simulates regular stroke physiotherapy as described in section 3.6.4, through a combination of quantitative information to patients of their personal improvements during physiotherapy for motivation, and graphical feedback of the patient's movements and target movements. Also in support of the prototype system being effective for stroke patients, efforts were made to simulate the situation and characteristics of stroke patient motor learning. As stated in section 6.3.2, this included varying the spatiotemporal parameters of the movements in a way that allowed novelty in a similar way to that in stroke patient motor learning. It has been found that, although stroke patients are less accurate and more variable when executing skills, the capacity to learn in a similar way to healthy people is generally present (Winstein, Merians & Sullivan 1998). Also, existing systems similar to the prototype system have been shown to be effective in aiding stroke

patients. For example, stroke patients improved as measured by the Wolf Motor Function Test after playing therapeutic games using Nintendo Wii technology (Saposnik et al. 2010) as reviewed in section 2.6.6. Also, the Therapy-WREX (T-WREX) (Sanchez et al. 2006) was shown to allow stroke patients to improve their performance in reaching and drawing movements and improvements were found using the Fugl-Mayer scale during unassisted movements.

It may be possible that too much information was provided to the participants in a form which was too complicated, making it difficult for stroke patients to understand. However, the information provided in the feedback was chosen because it was considered to be the most beneficial for stoke patients, and as described in section 3.6.4, aimed to allow a simulation of the guidance provided by physiotherapists to be implemented. Therefore, instead of ruling out this type of feedback, as described in section 6.3.6, a defined instructions procedure was developed and was provided to participants prior to their use of the system. The instructions were designed to be understandable by those with limited academic ability and they appeared to be effective. However, the participants were mainly from academic backgrounds, meaning they may have been more experienced in reading graphs than the layman. Future research could involve optimisation of the instructions through tests involving stroke patients. As listed in section 6.4.2, one participant commented that it was confusing that opening the hand in the transverse axis moved the line upwards on the screen. Instructions in future could provide a more detailed explanation of the patient's interaction with movements.

It may also be considered that, because information is provided during movements as well as after each movement, dependency on the feedback provided may occur. As described in section 6.1, the objective of the tests involving participants was to investigate the efficacy of the prototype system in guiding movements. This was done prior to any investigation of the efficacy in enhancing motor learning or increasing independence. This was done because guidance is considered to be the fundamental function of the system, and a prerequisite for enhancing motor learning. Therefore, if the efficacy in enhancing motor learning or increasing independence had been tested first, and if the system was found to be ineffective, the cause of the failure would have been more difficult to identify. As described

in section 6.3.6, each participant only performed one session per target movement. This was considered optimal given that the efficacy of guidance was being tested as it allowed time for a greater number of participants to be involved. This meant that, because participants only performed one session per target movement, in all cases, participants were at an early stage of motor learning. Consequently, it was more appropriate to provide feedback during movements and after every attempt to reproduce the target movement (Schmidt, Wrisberg 2008). If future studies were to involve more than one session per participant, the timing and frequency of the feedback provided could be altered. For example, summary feedback or faded feedback could be given.

As explained in section 6.3.4, the target movements performed by participants were complicated to allow novelty. It is thought that complicated movements are more likely to involve closed-loop control. Movements performed by stroke patients may be simpler and may therefore be more likely to involve open-loop control (Wrisberg 2007). Closed-loop control requires more cognitive function, where more use of the LTM occurs. Since dependency is partly caused by distraction from use of the LTM, closed-loop controlled movements may be more susceptible to the development of dependency on feedback. Therefore the movements performed by stroke patients may be less susceptible to dependency.

It is thought that the feedback would still be effective if the target movements to be guided were simpler. For example, if a single reaching forward movement was the target, it could still be shown in the graphical area, and how the participant is performing, how they could improve and their improvements could still be fed back. Also, as stated in section 3.6.4, even if the patients are severely impaired, it is thought that the feedback would still operate correctly. This is because even small movements will show in the graphical area, and any improvements in the participant's performance will still be fed back. However, as the prototype system distinguishes one movement attempt from another based on a reach distance threshold, participants would need to be able to perform this movement. To overcome this in future, a more external mechanism could be used to distinguish one movement from another, for example a trigger activated by the ipsilesional limb.

As described in section 3.6.4, the feedback to patients consists of multiple elements. This makes the elements responsible for any benefits impossible to identify individually. However, this approach was taken, as opposed to implementing elements of the feedback individually for testing, to allow the prototype system to be developed in a way that provides as much benefit to patients as possible. This allowed the guidance by physiotherapists to be simulated.

As described in section 3.6.4, the prototype system consisted of multiple software programs. The test apparatus described in section 6.3.6 also consisted of two different computers and separate instructions which were provided graphically and through verbal explanation by the researcher. In future, these separate elements could be combined into a more consolidated arrangement. This could be achieved by combining the separate software programs. Also, instructions could be provided in the form of a wizard, with separate steps and clear instructions, which could be run on a single computer system. This could include the following elements:

- The locations and mounting methods of the prototype hardware and sensors
- The start position of the target movements in relation to the guidance markings
- Introduction to the feedback system including detailed video instructions of the graphical area
- Videos of the target movements being performed

As concluded in section 6.5, once participants had been appropriately instructed, they were able to use the prototype system independently without assistance from the researcher. It was therefore thought that if the above elements could be provided by a single computer system, the prototype system would be useable by patients and carers independently. This supports the hypothesis of this research.

There may also be potential for the prototype system beyond allowing further rehabilitation for stroke patients. The prototype system may also have potential in treating other conditions where motor learning, or simply continued exercise is important, for example

cerebral palsy and multiple sclerosis. The system may also have potential in training for sports such as tennis or snooker. In such sports, repeated practice to maintain and improve specific motor skills is clearly beneficial. Specific target movements would of course be required, which could be recorded by coaches or athletes who already possess the required motor skills. Another potential use for the prototype system, in addition to enabling further stroke physiotherapy after discharge from care, is use whilst the patient is still in care in addition to regular physiotherapy to increase intensity. This may allow for faster rehabilitation. Adaptation of the prototype system to cater for other areas of the body could also be implemented and tested, for example the left arm or the lower limb.

As identified in section 2.6.1, the Wii Fit system is analogous to the hypothesis of this research in that monitored exercise in the home can improve one's condition. Such systems are highly popular and commercially successful. Use of technology is becoming more widespread, where the cost of complicated electronic systems is reducing and the performance of such systems is increasing. This allows more information about people's details and behaviour to be digitised, processed and communicated. For example, applications are now available for smart phones which record the number of steps taken in a day. This allows one to monitor their exercise. Similarly, wearable systems are available that monitor hart rates and other biometrics. Systems such as smart-phones and smart-watches allow technology to be deeply integrated with our lives. Such systems have internet connectivity that allows for transmission, processing and sharing of data. With technology improving, its use becoming more widespread and internet connectivity increasing, widespread adoption and use of systems such as that outlined by the hypothesis of this research, is considered very realistic.

7.4. Description of novelty

This section expands on the summary of the novelty of this research given in section 1.6 by providing more detailed descriptions.

1. A prototype system for testing was designed and built which measured movement using a novel combination of gyro sensors and flex sensors. The prototype system was useable within the home being low cost, compact, easy to set up and safe. The estimated cost of the prototype hardware of £291 was lower than the cost of existing systems which measure movement in individual DOFs such as the therapy-WREX gravity reducing feedback robot which costs approximately 4000 USD (Sanchez et al. 2006). The prototype hardware was also more compact than existing systems which measure movement at individual DOFs such as the adaptive mixed reality feedback system (Lehrer et al. 2011). The performance of the prototype hardware was tested thoroughly against a system known to be accurate and repeatable in measuring human movement.

2. A novel mechanism was developed which allowed movements to be performed in a similar way as they would be during a regular physiotherapy session, whilst receiving automated feedback. Then, as patients move, their movement is drawn onto a graph of displacement with time against target movements for comparison. Patients can also pause for as long as they wish between movements to give them time to contemplate and remember feedback.

3. The feedback mechanism was a unique combination of two main separate elements. This consisted of quantitative information to patients of their personal improvements during physiotherapy for motivation, combined with graphical feedback of their movements and target movements. Existing systems have given graphical feedback such as the Feedback Training System (FTS) (Kohler, Schmitz-Rode & Disselhorst-Klug 2010). Existing systems have also combined graphical feedback with numeric feedback (Winstein, Merians & Sullivan 1998). However, no systems have combined graphical feedback with numeric information of patient improvement. This combination of feedback elements was thought would be advantageous because it would allow for positive reinforcement which is similar to a reward (Schmidt, Wrisberg 2008) that increases motivation. The efficacy of this feedback was investigated.

4. The effects of guidance of movements at one DOF on improvements in performance at other DOFs was investigated, which has not been done previously. For example, the FTS gives feedback of a single end point, the hand, which moves during physiotherapy (Kohler, Schmitz-Rode & Disselhorst-Klug 2010). It may be that only the DOF for which feedback is given is affected by the feedback. The effect on other DOFs, which also move but for which no feedback was given, was therefore investigated. This was done by testing mean improvement, variability and statistical significance for the feedback group compared to the control group and comparing conformance to the DOF for which feedback was given.

5. A novel categorisation of movement synergism was established and a novel method for detecting movement synergism (a form of movement coordination) was developed and tested. Movement synergism has been considered in terms of peak velocities and accelerations and decelerations of DOFs (Alazmani et al. 2008). Also amongst pairs of DOFs (van Vliet et al. 2012) including shoulder extension and elbow extension, forearm rotation and shoulder flexion, and forearm rotation and elbow extension (Lehrer et al. 2011). It was proposed during this research that movement synergism could also be defined as the extent that two or more DOFs were moving simultaneously. Categorisation of movement synergism was established in terms of combinations of directions of DOFs, described in section 3.6.4. The efficacy of the prototype system in detecting movement synergism was investigated.

7.5. Addressing of the research questions

1. How do stroke physiotherapists usually assist rehabilitation with respect to the patient's symptoms?

An understanding of the necessary fields has been gained through the information review, which included stroke, human anatomy and mechanisms, motor performance, feedback during motor learning, and existing systems and technology. The morbidity of stroke and the physical deficits caused were reviewed along with the resulting rehabilitation guidelines and procedures. From the reviewing of literature and interviews with stroke physiotherapists, an understanding of how physiotherapists usually assist rehabilitation with respect to the

patient's symptoms was gained. The findings with regards to research question 1 can be found in Chapter 2, particularly in sections 2.2 and 2.7.

2. What systems exist that provide a means for stroke patients to further rehabilitate?

Having gained an understanding of how a physiotherapist rehabilitates with respect to the deficits caused by stroke, research question 2 was addressed. An understanding has been gained of existing systems that provide a means for stroke patients to further rehabilitate. Eleven systems were reviewed in detail, which measured movement in ways ranging from movement of handles to optical systems and game console technology. Feedback systems ranged from virtual reality to graphical guidance of functional movements to the playing of games. The aims and mechanisms of these systems as well as their performance in tests were reviewed. The findings with regards to research question 2 can be found in Chapter 2, particularly in sections 2.6.6 and 2.8.

3. What are the requirements for a system to provide a means for stroke patients to further rehabilitate?

The points mentioned above for addressing research question 2, along with the rest of the information review including interviews with stroke physiotherapists, allowed an understanding of the requirements for systems to provide a means for stroke patients to further rehabilitate to be gained. These requirements are listed in section 3.2.5 (System objectives), and in section 3.3 (Design specification).

4. What are the limitations of any existing systems to provide a means to further rehabilitate?

Having gained an understanding of the requirements for a system to provide a means for stroke patients to further rehabilitate, the limitations of the existing systems were evaluated and an understanding of these was gained. As concluded in section 2.8, these include the fact that little was specified in terms of the method of interaction with the system and no system explores the combination of quantitative feedback of improvements combined with graphical feedback. Also, no existing systems investigated the effects of guidance of movements at one DOF on improvements in performance at other DOFs. Finally, little had been investigated regarding the detection of coordination of movements during a session.

5. Can a system be designed that overcomes the limitations of existing systems to provide a means for stroke patients to further rehabilitate?

The prototype system largely achieved the system objectives and conformed to the design specification satisfactorily given the scope of this research. In doing so, the prototype system overcame the identified limitations. As described in section 3.6, the prototype system included a trigger mechanism which allowed patients to pause for as long as they wish between movements, allowing time to contemplate and remember feedback. A combination of quantitative feedback of improvements combined with graphical feedback was also included. The effects of guidance of movements at one joint on improvements in performance at other joints was investigated in detail in Chapter 6. Finally, a method of defining movement synergism was proposed and a method of detecting movement synergism was developed and tested.

6. What is the efficacy of the designed system in providing a means to further rehabilitate?

The results from the tests of the prototype system were positive overall. The main shortcoming in terms performance was high intra-variability of results from the prototype hardware. Healthy participants were employed to test the efficacy of the prototype system, where efforts were made to simulate the situation and characteristics of stroke patient motor learning. Overall, the results were considered to support the efficacy in providing a means to further rehabilitate. As stated, the mean improvement of the feedback group compared to the control group for the DOF for which feedback was given was 23.35 %. This improvement was found to be statistically significant (reach and grasp movement: $t = -2.39$, $\rho = 0.022$; turn door handle movement: $t = -3.19$, $\rho = 0.003$). Also, positive comments from the participants during use of the prototype system included *"it was good fun to use"*, and *"it's like playing a game in the sense of motivation"*. Also, as discussed in section 7.2, the prototype system was low enough cost to be affordable for private purchase (less than £500), and was useable within the home (compact, easy to set up and safe).

7.6. Supporting of the hypothesis

As stated in section 1.3, the hypothesis was as follows:

A system that enables regular guided and monitored therapeutic exercises in the home can provide a means for stroke patients to achieve a higher level of physical rehabilitation.

From the findings from this research and from discussion in this chapter, particularly in sections 7.3.3 and 7.5, the hypothesis has been supported overall.

The discussion in this chapter formed the basis for drawing conclusions from this research and recommendations for future research given in the following chapter.

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

8.1. Introduction to chapter

In this chapter, overall conclusions from this research are drawn. Recommendations for future research are then made based on the findings from this research.

8.2. Overall conclusions

1. An understanding of the requirements for systems to provide a means for stroke patients to further rehabilitate has been gained. A prototype system was developed that met these requirements satisfactorily.

2. Test results suggested that the novel mechanism developed to allow movements to be performed in a similar way to how they would be during regular physiotherapy was effective.

3. Test results suggested that the unique combination of quantitative information provided to patients of their personal improvements during physiotherapy for motivation, and graphical feedback of their movements and target movements, was effective.

4. The prototype system was capable of detecting movement synergism in a session using the proposed categorisation and detection method. However, the prototype system is less suited to measuring movement synergism in a single movement, because the reliability of the result would be low.

5. Use of the prototype system resulted in superior performance at multiple DOFs which moved in multiple planes during multiple target movements. Improvement was found to be statistically significant at the DOF for which feedback was given (reach and grasp movement: $t = -2.39$, $\rho = 0.022$; turn door handle movement: $t = -3.19$, $\rho = 0.003$), but not at DOFs which also moved but for which no feedback was given.

6. The most significant limitations of this research are considered to be the high variability in the data recorded by the prototype hardware, and that healthy participants were employed to test the prototype system rather than stroke patients.

7. The research questions were answered and the hypothesis (A system that enables regular guided and monitored therapeutic exercises in the home can provide a means for stroke patients to achieve a higher level of physical rehabilitation) has been supported overall.

8.3. Recommendations for future research

1. Variability of the data recorded by the prototype hardware could be reduced by investing in gyro sensors with signals that remain more stable after movements. For example the L3G4200D gyro sensor costs £38 but has a higher linearity rating than the gyro sensors used in the prototype system (Proto-Pic 2013).

2. Having gained positive initial results from tests involving healthy participants, further tests could be performed involving stroke patients. This would increase the understanding of the efficacy of the system.

3. Having performed tests to investigate the efficacy of the prototype system in guiding movements, the extent to which the system enhances motor learning and the extent of dependency on feedback could be investigated. This could be achieved by performing tests involving participants as was done in this research, but over multiple sessions.

4. Optimisation of target movements could be worked towards with the assistance of stroke physiotherapists. This would help allow movements which were most beneficial to stroke patients to be practised.

5. Optimisation of feedback, feedback frequency, schedule and instructions could be worked towards empirically. This could be done by varying these parameters and recording which configurations are most beneficial to patients.

6. The accuracy of the prototype hardware could be quantitatively calculated, by using a third measure of movement to calibrate the prototype hardware, such as an electrogoniometer. This way, accuracy as a displacement could be calculated using VICON, which would allow a further understanding of the performance of the

prototype system to be gained. It would also allow investigation of the efficacy of the prototype system in measuring movement synergism at different levels.

7. The efficacy of individual elements of the feedback of the prototype system could be investigated, for example by testing the graphical area of the feedback in isolation. This may help with the process of optimising the feedback.

8. Feedback of other kinematic parameters for clinicians and researchers, as conceptualised in section 3.4.3, could be developed and investigated. These could include range of movement, velocities, times taken and spasticity.

9. The thresholds for the worded bandwidth feedback could be defined with the assistance of stroke physiotherapists. This would allow it to be enabled during physiotherapy sessions.

10. To allow detail about slower movements and faster movements, such as spasticity, to be obtained, the sample rate of the prototype system could be increased. This could be achieved by generating graphics from re-sampled data, or using a more powerful computer system.

11. The separate elements of the prototype system could be combined into a more consolidated user-friendly arrangement. This could be achieved by combining the separate software programs and providing all instructions, including fitting instructions and instructions of how to use the feedback system, via a wizard. This would allow a single computer system to be used.

12. The prototype system could also be made more user-friendly by moving the Velcro straps to the distal area of the arm. This would avoid the slight movement restrictions seen when testing the prototype system. The appearance of the prototype system could also be improved by implementing wireless technology and placing covers over the sensors to increase the simplicity of the appearance.

13. The prototype system could be modified to accommodate additional DOFs, such as those of the wrist. This would allow a larger range of exercise movements to be performed.

14. Integration of the prototype system with tele-rehabilitation systems could be investigated. For example, programs could be developed to allow sharing of all recorded data over the internet amongst the patient and physiotherapists. The system could also allow feedback to be given to patients based on their performance, remotely by physiotherapists, and allow exercises or changes to physiotherapy programs to be prescribed as necessary. This could reduce the resources required and allow the efficacy of rehabilitation to be increased.

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VI. Appendices

Appendix 1. Block diagram of the target recording program
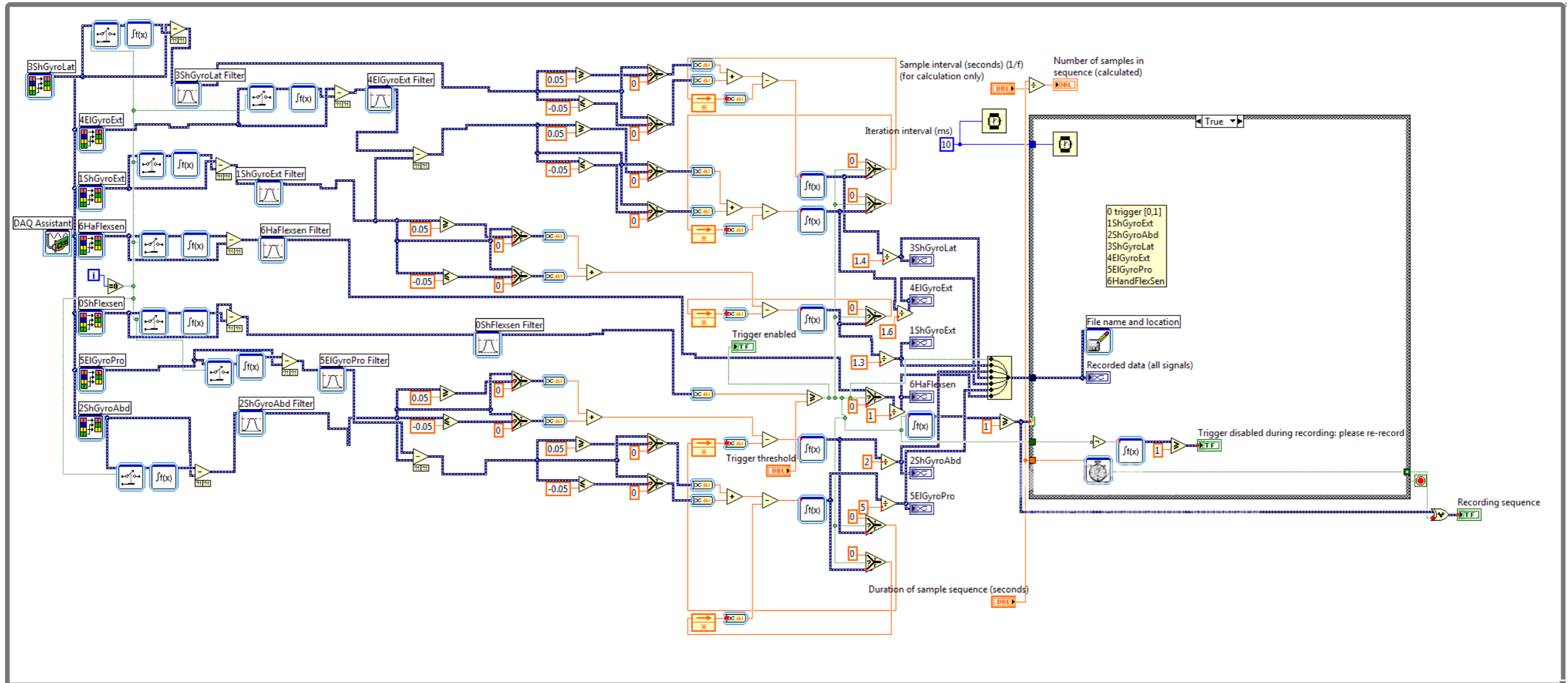

Figure Appendix 1. Block diagram of the target recording program

Appendix 2. Block diagram of the feedback program
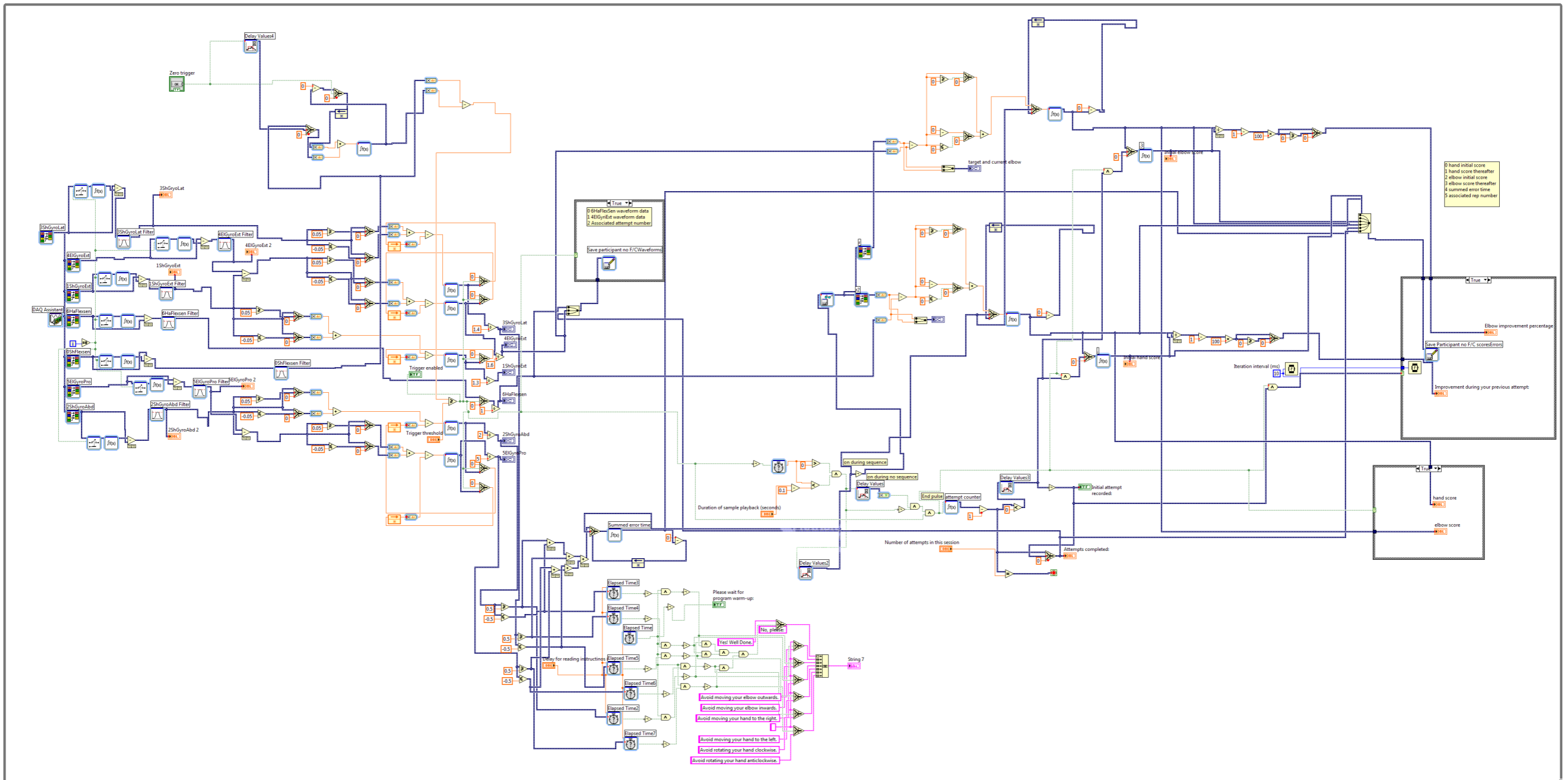

Figure Appendix 2. Block diagram of the feedback program

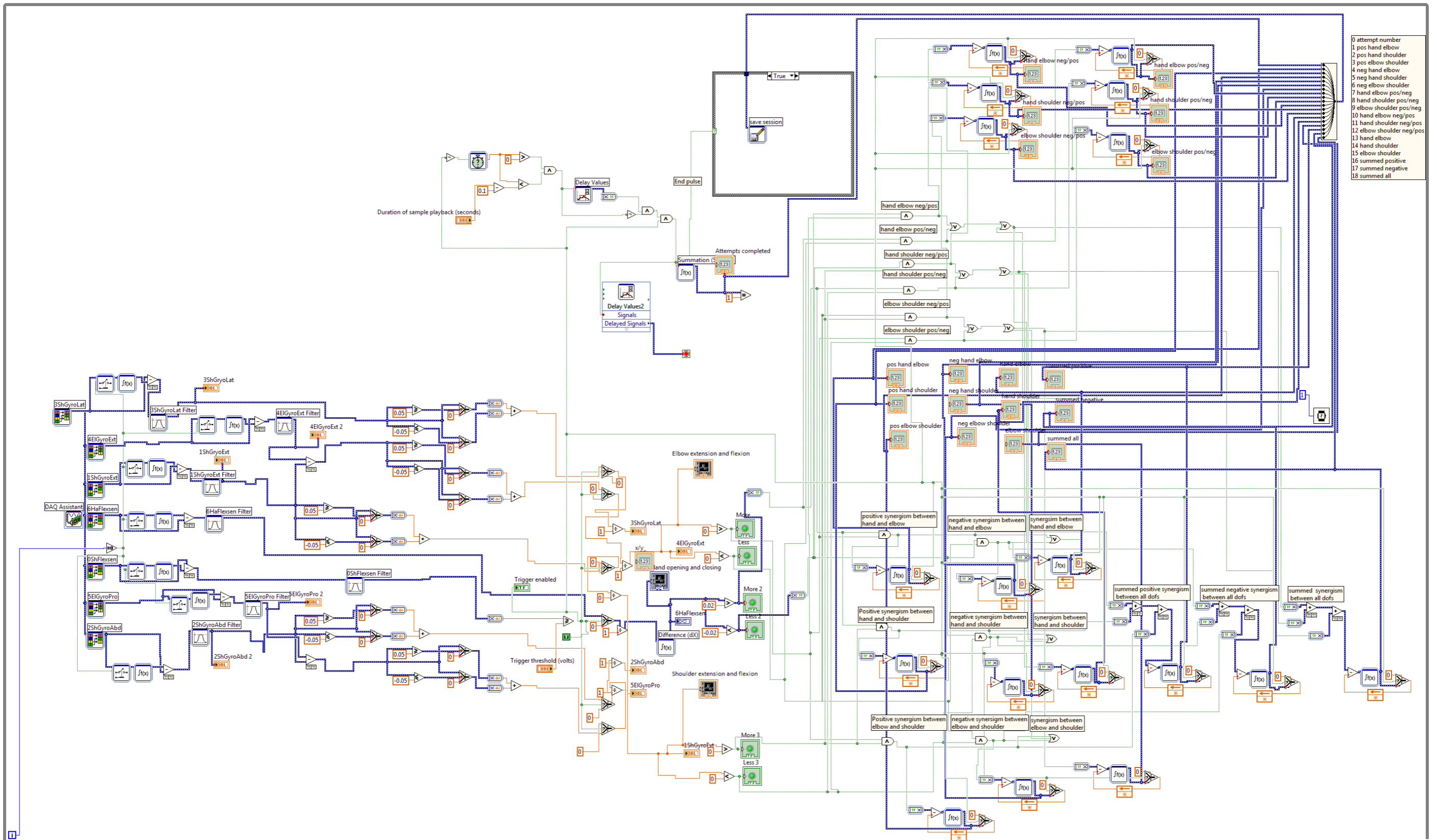# Appendix 3. Block diagram of the synergism recording program

Figure Appendix 3. Block diagram of the synergism recording program

Appendix 4. Trigonometry calculations for investigation of the effect of out-of-plane movements
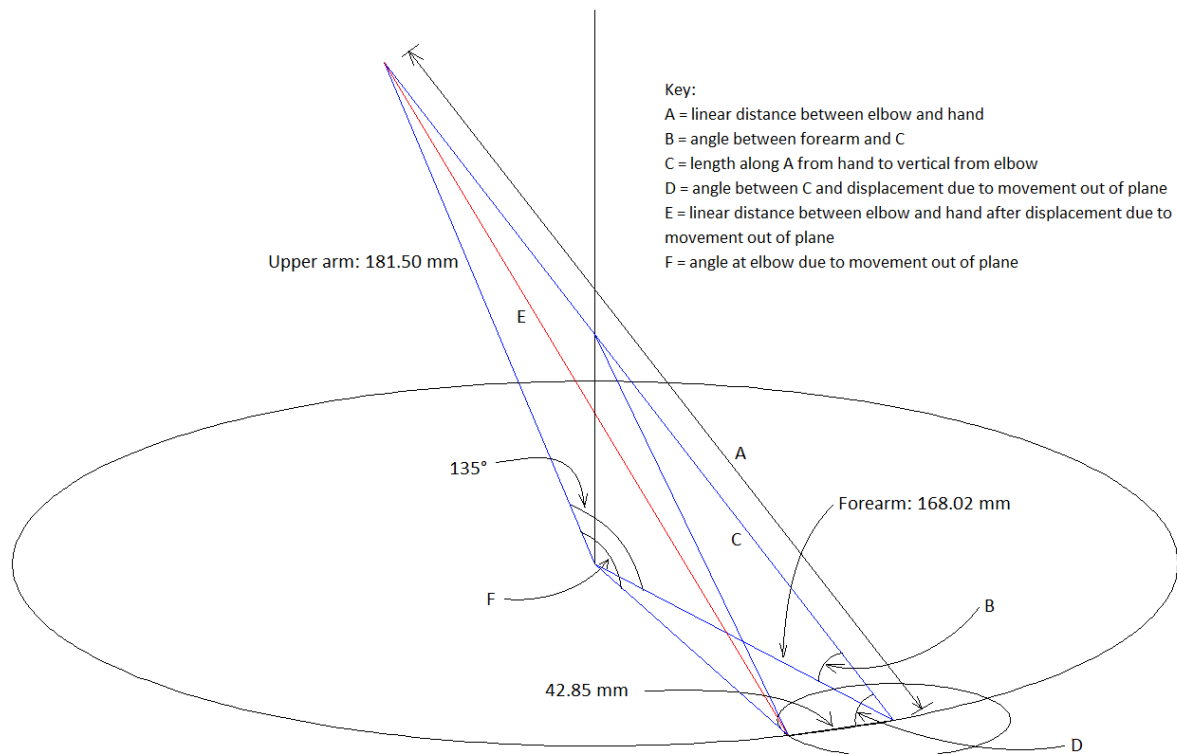

Figure Appendix 4. Dimensions of the nominal position of the upper arm and forearm with the out-of-plane movement shown

A in Figure Appendix 4 was calculated using the Cosine rule:

$$A = \sqrt{181.50^2 + 168.02^2 - 2 \times 181.50 \times 168.02 \times Cos135}$$

Therefore A = 322.96 mm. The cosine rule was again used to calculate B:

$$B = Cos^{-1}\left(\frac{181.05^2 - 168.02^2 - 322.96^2}{-2 \times 168.02 \times 322.96}\right)$$

Therefore B = 23.41 degrees. The mean range of differences previously calculated can be considered as a displacement to cause lateral deviation at the shoulder. This would create an angle of lateral deviation at the forearm. A vertical was considered to exist from the elbow forming the length C. C was calculated:

$$C = \frac{168.02}{Cos\ 23.14}$$

Therefore C = 183.10 mm. D was then calculated:

$$D = Cos^{-1}\left(\frac{183.10^2 - 42.85^2 - 183.10^2}{-2 \times 42.85 \times 183.10}\right)$$

Therefore D = 83.281 degrees. E was then calculated:

$$E = \sqrt{42.85^2 + 322.96^2 - 2 \times 42.85 \times 322.96 \times Cos\ 83.281}$$

Therefore E = 320.78 mm. F was then calculated:

$$F = Cos^{-1}\left(\frac{320.78^2 - 168.02^2 - 181.50^2}{-2 \times 168.02 \times 181.50}\right)$$

Therefore F = 133.17 degrees.