Haptic Feedback Systems for Disabled Computer Users

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Abstract

Haptics is a fundamental communication channel between a human and their environment. Without the sense of touch it would be difficult if not impossible to perform simple tasks such as walking, grasping, pulling, pushing etc. Developments in computing architecture have enabled haptic technology to be incorporated into human-computer interaction. Haptic technology and computer graphics have enabled realistic, three-dimensional, virtual environments to be created that the user can physically interact with.

Many disabled computer users often find it difficult to use traditional input devices due to the fact that they are almost always designed for able-bodied users. As the key feature of most graphical user interfaces is to point and click with a cursor this can make a computer inaccessible for many people. This thesis focuses on haptic rendering algorithms to make a computer more accessible for motion impaired users. These have been achieved using the Phantom Omni.

The range of disability can vary significantly for people with cerebral palsy. As a result a certain haptic calibration may assist a certain user or disability but could equally hamper a different user. This thesis aims to produce a system to calibrate traditional haptic techniques to suit the needs of the individual. A number of new non-calibrating haptic techniques are introduced that are designed to be less constricting on the operator. A comparison has been made between the techniques to determine if one performs better than its competitors.

The results of the study have enabled a system to be produced that has significantly improved computer access for many people with cerebral palsy. Each haptic technique has been developed in a way that it can be automated into an existing interface. Full haptic automation has been achieved for Microsoft Office applications

and the Windows On-Screen Keyboard to allow greater access to commonly used software.

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Firstly, I would like to thank my Supervisor Dr. Stephen Laycock for his support and guidance throughout the course of the project. His advice, enthusiasm and academic experience, have been invaluable to me.

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Finally, I would like to acknowledge my family and my girlfriend for supporting and encouraging me throughout my life and in my studies.

Glossary

0.1 Assisted Systems

Assisted systems provide information to help a person to interact with computer software. Within this thesis the assistance that will be provided is in the form of haptic feedback.

0.2 Boxplot

A boxplot is used to provide a visual summary of many important aspects of a distribution. Within the boxplot are five data summaries: the smallest observation (minimum whisker), lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation (maximum whisker). Often the mean will be included in the boxplot and is depicted by a cross. An example of a boxplot is given in Figure 1.

0.3 Calibrated Systems

A calibrated system uses a method to tune important variables to maximise the performance of an objective. Within haptic assistance the calibrated system will aim to improve interaction rates either through faster completion times or a reduction in error rates.

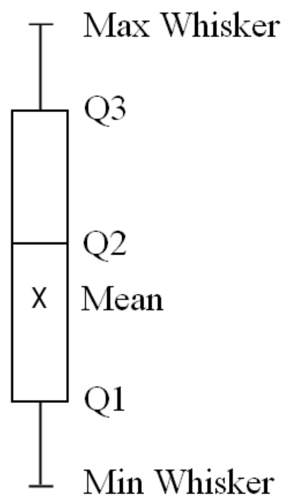

Figure 1: A boxplot example showing the smallest observation (minimum whisker), lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation (maximum whisker). The mean is depicted by the cross.

0.4 Degrees of Freedom (DOF)

The degrees of freedom of a haptic device describes the range of movement a device has in terms of its translations and rotations. For example, a traditional mouse can move in the x-y plane and so has two degrees of freedom. Devices that have a three-dimensional workspace allow translations along the x-axis, y-axis and z-axis, and are classed as three DOF. Devices that allow these translations and are also able to rotate about all three axes have six DOF.

0.5 Force Feedback

Force feedback is used to describe the interaction between the user and the interface by applying forces via a haptic feedback device. It conveys real-time information on an object's stiffness, weight and inertia. It will resist the user's contact motion and can stop motion. For example, colliding with a virtual wall.

0.6 God-Object (Proxy)

The God-object algorithm was originally designed to overcome the problem of object push-through. The God-object algorithm tracks a history of contact with a surface. The position of the God-object (proxy) is then chosen to be the point which locally minimizes the distance to the HIP along a surface. A restoring spring force is calculated between the HIP and the proxy using Hooke's Law. An example of this is shown in Figure 2.

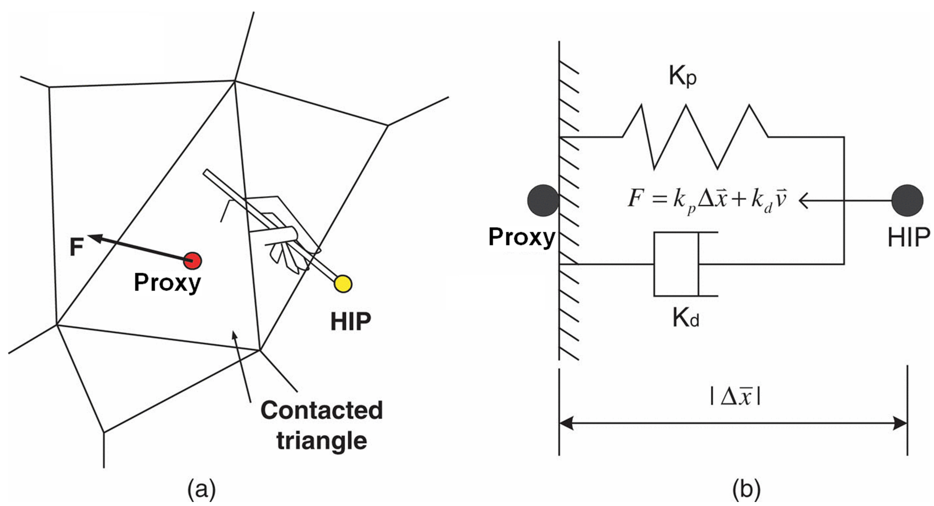

Figure 2: The haptic rendering of a surface (adapted from Peng et al. [PL04])

0.7 Graphical User Interface (GUI)

A graphical user interface is a visual type of user interface that allows interaction with computer software.

0.8 Haptic Feedback

The term haptic feedback is used to include both tactile and force feedback.

0.9 Haptic Interface Point (HIP)

When exploring virtual environments, the user will interact with objects through the end point of the probe, known as the haptic interface point. This point represents the virtual representation of the haptic device end effector, as shown in Figure 3.

Figure 3: The HIP position on the Phantom Omni (adapted from Openhaptics Toolkit Programmer's Guide. [Teca])

0.10 Haptic Probe

A haptic probe is the virtual tool that is controlled by the haptic feedback device in the virtual environment. The probe can represent a single point or the virtual representation of the tool in use. It is positioned in terms of the device translations and oriented in terms of the device rotations.

0.11 Haptic Rendering

The term haptic rendering was introduced to designate an algorithm for generating force feedback during interaction with virtual objects.

0.12 Intrusive Systems

An intrusive system is a system that the operator is forced to use and does not have a choice of ignoring. This can disrupt interaction and have a negative bearing on the overall performance of the system.

0.13 Object Push-Through

Object push-through occurs when the HIP undesirably passes through a thin mesh. An example of this occuring is given in Figure 4.

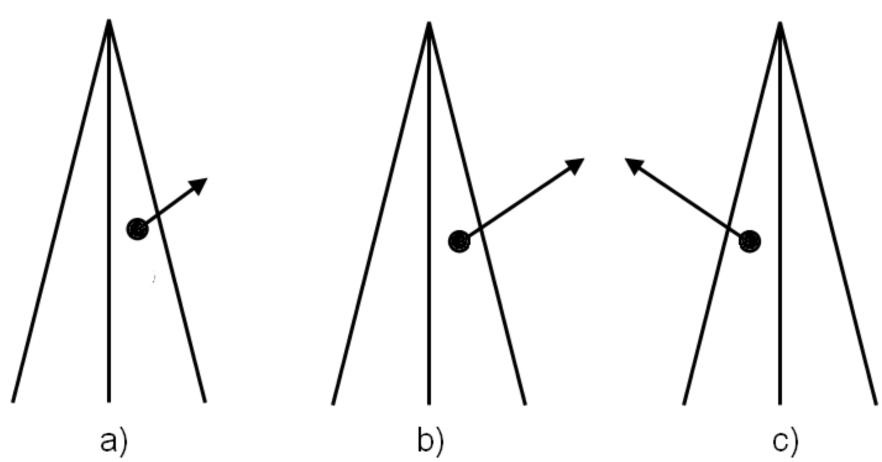

Figure 4: a) user touches surface and feels small force, b) as he pushes harder he penetrates deeper into the object, until c) he passes more than halfway through the object where the force vector changes direction and shoots him out the other side (adapted from Zilles et al. [ZS95])

0.14 Tactile Feedback

Tactile feedback conveys real-time information on the contact surface of an object, which includes heat, pressure and vibration. Feeling a surface texture is one example of tactile feedback.

0.15 Target Acquisition

Target acquisition is the process of using a pointing device to position the cursor within a desired target and selecting it by click-and-releasing the device switch.

0.16 Target Homing

Target homing is the process of navigating the cursor towards the desired target using a pointing device.

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Chapter 1

Introduction

1.1 Background

The word haptic is of Greek origin from the word haptesthai meaning to touch. The second edition of the Oxford English Dictionary [Kan] defines the word haptic as "of, pertaining to, or relating to the sense of touch or tactile sensations". The study of haptics covers the science and physiology of the sense of touch. Haptic technology was first introduced in computing, to a certain extent, in the 1960's. Early work on haptic interfaces began in the 1960's [Sut65][CJ68][JT66] but it was not until the early 1990's that processing power was great enough to incorporate both graphics and haptics to any great extent. Advances in computer hardware and software techniques now allow, realistic, high quality, virtual environments to be produced.

With the introduction of haptic techniques it is now possible to physically interact with these environments. In the most successful virtual environments, a user will feel that they are present in the simulated world. For this to be the case the experience in the virtual world must match that of the experience in the environment being simulated. This sensation is often referred to as immersion. To create this effect a haptic device can provide two types of feedback and these are tactile and kinaesthesic. Tactile feedback is often defined as the sense of touch e.g. heat, pressure, texture etc. Kinaesthesic feedback is defined as force sensations e.g. weight, resistance etc.

There are many haptic feedback devices on the market [LD03b] that have varying degrees of freedom (DOF) which describes the range of movement a device has. The device most widely used for force feedback exploration of 3D data, assessment and rehabilitation of manual dexterity is the Phantom haptic stylus [CS07] produced by SensAble Technologies [Tecd]. The aim of this thesis is to explore ways to make a computer more accessible for disabled users through haptic feedback using the Phantom Omni [Tecd]. This will be achieved by developing new techniques to analyse a person's ability to operate a device and then applying haptic assistive techniques to meet the needs of the individual.

This thesis focuses on the design of new algorithms that incorporate haptic techniques in a virtual environment to improve computer accessibility for disabled computer users. By analysing a person's ability to use the device it will be possible to identify areas of weakness. The results of the analysis will be used to select an appropriate type of assistance and calibrate it to benefit that individual. These techniques are formally known as haptic assistance and are discussed in detail, with existing algorithms, in Chapter 3. The project has been undertaken with the Norfolk & Norwich Scope Association (NANSA), which is a local voluntary organisation, formed in 1954 to offer support for Norfolk people with cerebral palsy and associated disabilities. As a result this thesis will concentrate on this area of disability. However, there are many techniques presented that may benefit other disabled computer users or indeed able bodied users.

1.2 Challenges

One of the main challenges of this work is to create a system that will accommodate a wide range of disability. The effects of cerebral palsy affect each individual in different ways and so the system needs to be flexible enough to meet the needs of that person.

The challenge will be to improve interaction rates in terms of faster completion times or a reduction in error rates. This will be addressed by designing new haptic techniques that do not require tuning or by calibrating traditional haptic assistance to the needs of the individual. The traditional techniques will be dynamically calibrated to ensure that the system reacts accordingly to a person's short term needs such as fatigue or long term needs such as a progression in impairment.

For the system to benefit an individual it needs to be applied to software that they will use. Another challenge that has not yet been addressed by current research is to integrate haptic assistance into existing graphical user interfaces (GUI's). Manually designing and mapping an interface for haptic assistance would be too time consuming due to the fact that many interfaces have tens if not hundreds of buttons. In addition to this the toolbars may be moved or resized which will result in the mapping becoming inaccurate. Full automation of the Windows on-screen keyboard and Microsoft Word has been achieved in Appendix A.

1.3 Motivations and Research Objectives

The motivation for undertaking this project is to improve computer access for motion impaired operators. The functionality of a computer could have many benefits for disabled users either in work, education or leisure. Simple resources such as the Internet, Word-processing, Computer Aided Design (CAD) etc. could be a great asset in these areas but without a suitable interface these cannot be easily fulfilled. Access to a computer could significantly improve a disabled person's quality of life. One major difficulty encountered with haptic assistance, at its current stage, is that there is very little knowledge or expertise on which feedback is most appropriate to the task or the individual. The main research objectives are to determine which haptic techniques are most successful in improving target homing and target acquisition.

Cursor analysis measures will be used to evaluate the effect of various forms of haptic assistance.

1.4 Opportunities

The advances in processing power and haptic technology mean that there is now an opportunity to incorporate touch into human-computer-interaction (HCI). The introduction of multi-core processors has meant that consumer level hardware is now affordable. Efficient haptic rendering and collision detection techniques have also been influential in making this possible. Most commercially available haptic feedback devices operate based on the principle of point interaction. This means that contact between the user and the virtual environment occurs only at an arbitrary single point, typically the tip of a stylus or thimble [WH01]. This single point method links in well with the concept of using a pointing device to operate the cursor in a GUI.

1.5 Thesis Outline

Chapter 1 briefly discusses the background of haptic assistance. The motivations and research objectives of the thesis are presented. The chapter provides a relevant understanding that is important to any developer when designing haptic feedback systems for disabled computer users.

In Chapter 2 the history and uses of haptic feedback systems are discussed. The chapter identifies the problems faced by disabled computer users when using traditional pointing devices. It covers the early uses of haptic devices and discusses areas in which they have been beneficial to disabled computer users. Justification of using the Phantom Omni is provided within the chapter.

Haptic assistance is designed to improve interaction by reducing the error rate or the time to target. Two methods of universal design are taken into consideration to produce a haptic system to benefit the widest range of disability. The first considers producing haptic assistance that does not require force calibration and so does not require tuning to optimise interaction. The second considers tuning force levels of traditional haptic techniques to benefit the needs of the individual. A number of studies have been identified that have attempted to calibrate traditional input devices to meet the needs of the operator.

Finally the chapter considers a number of safety issues and the need for stable force interaction when working with motion impaired users.

The implementation of new and traditional haptic assistive techniques is described in Chapter 3 using an open source API named CHAI3D. The implementation of four target acquisition techniques are presented, which includes gravity wells, high-friction targets, haptic cones and haptic walls. Two target homing techniques have been implemented which are haptic damping and haptic tunnels. The calibration variables are identified for each traditional technique.

Chapter 4 discusses the key measures often used in cursor analysis and describes what they attempt to capture. These include traditional cursor techniques such as Fitts' Law and measures proposed by Mackenzie et al. [MKS01]. A series of new measures are suggested at the end of the chapter that are designed to provide greater insight into a person's clicking characteristics.

In Chapter 5 a series of experiments have been taken in attempt to capture what effects the type and level of assistance has on interaction. These are captured using the cursor analysis techniques discussed in Chapter 4. A detailed analysis of both target homing and target acquisition techniques are presented.

Chapter 6 identifies the key cursor measures that are important to the appropriate selection and calibration of haptic assistive techniques that are designed to aid target acquisition. The concept of dynamically calibrating haptic assistance is presented.

Dynamic calibration ensures that the force levels of the assistance are appropriate for the long and short term needs of the operator. The experiments within the chapter are used to evaluate the effectiveness of the dynamic calibration of gravity well spring stiffness and the dynamic friction level of high-friction targets. The results are useful for comparing the performance of calibrated haptic assistance and the new techniques that do not require force calibration. The chapter identifies which techniques perform better in certain areas than others. A comparison is also made between each haptic technique and an able bodied operator to give a measure of its effectiveness.

The final conclusions are made in Chapter 7. The chapter identifies areas in which further work could be continued. In Appendix A the process of automating existing software packages with haptic assistance is discussed. The mapping of a Microsoft Word interface and the Windows On-Screen Keyboard has been achieved to provide greater computer access to motion impaired operators at the NANSA centre.

Chapter 2

Background

2.1 Introduction

Given the wide functionality of haptic devices, what benefits can they give to a disabled computer user? To answer this question a basic knowledge of how the brain operates is required. There is a large section of the brain called the primary sensory cortex that is responsible for processing information from mechanoreceptors all over the body [Corb]. It are these receptors that allow haptic interaction such as touch, heat, pressure etc. Most user interfaces only make use of graphical and audio interaction. As touch is such an important sense it is surprising that it has not been used to greater effect in human computer interfacing. The reason why it could be so important to a disabled computer user is because according to Keates et al. [KLCR00] motion-impaired users often exhibit decreased motor control and muscle strength, but not necessarily a decreased haptic sensitivity. As a result, haptic feedback could be beneficial if included into interface design and complement the existing audio and visual feedback.

The next section discusses problems encountered with traditional pointing devices. To alleviate these problems, or at least reduce their effects, assistive techniques have been developed utilising haptic devices. These are discussed in Sections 2.5 onwards.

2.2 Problems encountered with Standard Pointing Devices

Many disabled computer users find traditional input devices difficult to use. According to Hwang et al. [HLKC03] symptoms such as tremor, spasm, muscle weakness, partial paralysis, or poor coordination can make standard pointing devices difficult, if not impossible, to use. A haptic device offers potential assistance in these areas but so far has not been utilised to its full potential. The traditional mouse used with a computer tends to move too quickly for people with uncoordinated movements. As a result, precise manipulations such as icon selection can be difficult and often takes a long time. The cursor speed can be slowed down but this means that the mouse physically has to move a much greater distance to perform the same displacement on the computer screen. For motion-impaired users this is obviously undesirable. The following subsections identify common difficulties encountered when clicking is required for icon selection.

2.2.1 Single Clicking

The standard mouse requires very fine motor control to operate as the user has to be able to position the cursor accurately on a target and maintain stability whilst clicking. In many applications the user needs to be able to click on the target accurately and release the button inside it for the process to execute successfully.

2.2.2 Double Clicking

Even greater control is required to perform additional tasks such as double-clicking. Many users find difficulty in maintaining stability during clicking and this can be amplified when a double-click is required. A possible solution is to add an external switch to perform the mouse button operations. The disadvantages of this method are that it requires additional hardware modifications to a traditional pointing device and it deranges interaction due to the separation of the switch from the device.

2.2.3 Drag-and-Drop

To drag and drop an item also requires a high level of motor control. Operators often have difficulties holding the device button down and positioning the cursor accurately when releasing.

2.3 Difficulties encountered with Cerebral Palsy

The following section describes common difficulties encountered with cerebral palsy and associated disabilities. Cerebral palsy is the term given for a series of incurable brain disorders that affect a person's basic motor skills. Approximately one in every four hundred babies born in the UK has cerebral palsy which equates to 1,500 people every year [Sco]. It is important to have an understanding of the disability so that areas of assistance can be identified. There are many different types of cerebral palsy and each can affect individuals in different ways. The list below [NHSa] covers each area and gives a brief description of the condition.

1. Spastic cerebral palsy - some of the muscles in the body are tight, stiff and weak due to permanent contraction. Controlled movement can be difficult due to jerky, unpredictable motion. Spastic cerebral palsy consists of these subcategories describing the affected area.

    (a) - Diplegia - Both arms or both legs are affected.

    (b) - Hemiplegia - Either the right arm and leg or left arm and leg are affected.

    (c) - Quadriplegia - All limbs are affected.

    (d) - Monoplegia - One arm or leg affected.

   (e) - Triplegia - Three limbs are affected.

2. Athetoid (dyskinetic) cerebral palsy - Muscle control is disrupted by spontaneous and uncontrolled, involuntary movements. Posture control is also affected.

3. Ataxic cerebral palsy - symptoms include difficulty with balance, shaky movements, and speech difficulty.

4. Mixed cerebral palsy - a combination of two or more of the above.

There is no cure for cerebral palsy but there are various forms of therapy that can help a person with the condition. These may include: physiotherapy, occupational therapy, speech therapy etc. A common misconception associated with sufferers of cerebral palsy is that they are less intelligent than those who are not sufferers. This is not the case as the definition of the condition implies that it only affects a person's motor skills. Learning difficulties may arise as a result of the disability but it is not the sole cause.

Learning techniques have also been established to aid sufferers. Many people have benefited from a technique called conductive education which has been specifically developed for children and adults who have neurological motor disorders. This technique helps people to overcome movement problems and gain some control through special education and rehabilitation [MH08]. The principles of conductive education can benefit many motor based tasks and there are many guidelines that may be useful when training operators to use pointing devices. Children usually gain the most from this technique but adults can gain a lot from it too.

2.4 Benefits of using the Phantom Omni

As computer haptics becomes more popular the range of devices also increases. This section identifies why the Phantom Omni [Tecc] has been chosen as the haptic interface to assist with the difficulties identified in the previous section.

Even at this stage of haptic development there has been little work utilising force feedback in HCI. If included into interface design, force feedback could potentially extend the existing interaction of just audio and visual feedback. Multimodal interaction utilises many of the human senses in one application. Previous work has proven that multimodal interfaces can improve computer access for disabled users and especially for people who are visually impaired [KYS+05]. Traditional pointing devices such as the mouse do not provide any force feedback and are limited to two degrees of freedom. However, there are haptic devices on the market that provide three or six DOF. These include the Phantom Omni [Tecc] and the Phantom Desktop [Tecb] respectively. Research by Langdon et al. [LKCR00] suggests that increasing the degrees-of-freedom can improve interaction rates. Increasing the DOF has to be carefully implemented so that the extra freedom does not over complicate the interface or increase the cognitive workload.

Given that nearly all graphical user interfaces (GUI) are based on 2D interaction, why would a 3D haptic device be necessary for this study? As previously stated increasing the DOF can significantly improve interaction and there are new haptic techniques that are discussed in this thesis that utilise the 3D attributes. In addition to this, many activity centres, such as NANSA, provide art lessons where people may perform drawing, painting or other various artwork. The Phantom Omni is supplied with a stylus type grip which provides a natural way of using the device. Previous studies [MW05] have shown that a stylus based control can be used as an effective interface for disabled users. The handle of the Phantom Omni is interchangeable which means that the grip can be altered to the individual's preference.

The following section identifies the early applications of haptic technology utilising varying DOF devices. This is then followed by haptic techniques that have been used to aid disabled users.

2.5 Early Haptic Applications

2.5.1 Computer Aided Design (CAD)

Modelling of complicated shapes using drawing packages can be a difficult and time-consuming process. Each vertex in a mesh has to be carefully positioned to produce the desired shape. With a standard pointing device this can only be achieved in a two-dimensional plane at any one time, e.g. the xy plane, xz plane, etc. As a result multiple viewports are required to map the vertex correctly in each dimension. There are devices now available that allow 3D modelling in a single viewport.

SensAble technologies have recently developed a piece of software named ClayTools [Tecd], which utilises the 3D capabilities of a haptic device for CAD applications. The ClayTools system includes the Phantom Omni haptic device, for 3D interaction with force feedback. This enables the artist to use their sense of touch to create and shape virtual clay models by pressing into the virtual clay using the probe. The artist can also manipulate each vertex in 3D in a single viewport if required. This system allows models to be created much quicker than traditional techniques whilst maintaining the same level of precision.

2.5.2 Virtual Environments (VE)

Haptic feedback devices are having a large impact on improving the realism of virtual worlds [GSK07][LD03a][UPK06]. The ability to touch, feel, and manipulate objects in virtual environments has a large number of applications and is leading to new innovative ideas. The following subsections cover areas in which haptics has been applied in virtual environments and then discusses the benefits to disabled people.

Training Simulations

There have been major developments in haptic training simulations in the dentistry, medical and veterinary professions. The ability to practice techniques and gain confidence without putting the patient at risk is a great asset to each of these professions.

UK Haptics [Hapa] are an example of a company looking primarily at medical environments and the benefits of practising techniques to refine student's skills. One of the applications they have produced is the Virtual Veins System [Hapb], which allows healthcare practitioners to acquire, develop and maintain the skills necessary to perform venepuncture in a range of realistic scenarios in a safe controlled environment. The NHS Technology Adoption Centre [NHSb] have included the simulation as part of one of their Technology Implementation Projects [Cen].

Other systems include dental training simulators [RHDK08]. This system offers a digital approach to practising techniques in a safe and cost effective environment. Previously, students would only be able to practice techniques on plastic teeth or sometimes patients whilst under supervision of a dental expert. Using this system the student can practice tooth cutting and drilling techniques whilst the software assesses their performance.

Simulations have also been introduced to the veterinary profession for pregnancy diagnosis and fertility examinations of cows [BCRB03]. Students using the system are able to learn skills to better prepare them for the experience with a real animal. One of the main benefits is that a student develops the skills needed to recognise important landmarks. Previously, the students would be unable to see what the teacher was demonstrating and so it would be difficult to learn from practical demonstrations. The system has proved to be a useful teaching aid as the teacher can visually see on screen what the student is doing and explain to them what they should be looking for.

These simulations have been well received in each profession and there are many more simulations being developed in each area. The main benefits are that they allow the procedure to be repeated many times to perfect techniques and skills whilst analysing the trainee's performance. To be successful they must perform an acceptable level of realism. When training with a simulator it could be impossible for the user to achieve the best performance if the interface does not provide adequate haptic information about the interaction with the virtual environment. This situation would be more serious if visual or other sensory information is also inadequate or absent [RDLT06].

The following subsection identifies how haptic feedback has been used in the gaming industry to improve the immersive experience.

Gaming

Haptics has had a large role to play in the gaming industry in the last 15 years. The first console to use haptic interaction on the mass market was the Nintendo 64 [NSF] with the “Rumble Pak” [RP]. The vibration feedback was well received by gamers and is now used by virtually every manufacturer in the industry. The various rumble packs are used to represent many aspects of a game. These can be activated as a result of an emotional cue e.g. anticipation, fear, excitement etc. Alternatively, they can be physical cues e.g. impact, turbulence, recoil etc. In certain scenarios the feedback may not represent the real life experience, but the degree of immersion is still increased in most cases. In a survey, conducted by Ipsos for the haptic company Immersion [Cora], it was found that almost three in four respondents (72 percent) agree that rumble/vibration feedback enhances their game experience.

The following section covers areas in which haptics has been used to benefit disabled computer users in virtual environments.

VE for the Disabled

Virtual environments can provide disabled people with experiences that they may not otherwise be able to realise due to the nature of their disability. This could prove to be a very exciting prospect for many people. It also has an important role in areas of rehabilitation or skills training. According to Broeren et al. [BSR07] virtual reality (VR) technology provides new opportunities for conducting motor assessment and training within computer-generated three dimensional (3D) environments for person's who recently suffered a stroke or have motor deficits such as cerebral palsy, Parkinson's disease or multiple sclerosis.

Virtual environments have already been included in some applications aimed towards disabled people. Recent broadcasts in the news have reported on the developments of Newcastle University's Institute of Neuroscience [Tel] utilising the functionality of the Nintendo Wii [NWI] games console to aid sufferers of hemiplegia cerebral palsy. Results from the research produced a vast improvement in arm function and in hand-eye co-ordination. After a certain amount of practice the people involved were able to use their affected hand without thinking about it.

With processing power and computer graphics improving rapidly, it is possible to create ever more realistic virtual environments. These could have applications in many aspects of life, many of which have yet to be explored. The following subsection identifies some applications that have been created to assist disabled computer users.

2.6 Haptic Aids for Disabled Computer Users

2.6.1 Aid for Visually Impaired Computer Users

A large amount of work in the field of haptic aids for disabled computer users has been aimed towards the visually impaired. Computer aids for visually impaired users are not a new concept. Screen readers have been on the market for several years such as JAWS [Sci], Window-Eyes [Mica], etc. However, these applications can only convey information about text written on the page. The sense of touch has much to benefit visually impaired computer users and has been incorporated into many systems. According to Sjöstrom [Sjö01] a haptic computer interface can be a great learning aid to a blind person. It gives the opportunity to learn important skills in mathematics by tracing touchable mathematical curves, playing haptic computer games, and gaining better access to GUI's like Windows.

For most people everyday tasks such as writing are a necessity whether it is at work, school or for leisure. For someone with little or no visual co-ordination the task of learning to write can be very difficult. The Phantom Omni has proved a valuable tool in providing force feedback to aid in this area. A system called McSig [PCBB08] has recently been tested at the University of Glasgow, which has been developed for teaching visually impaired children how to handwrite characters. Many of the visually impaired people involved in the study were unable to write at all before training with the device. The results produced from the experiment suggest that after 20 minutes of practice they were able to write recognisable letters. The study showed that the system could help visually impaired and particularly blind children to learn to produce better-shaped characters. This is an important life skill as it also allows a certain degree of independence for the individual if they can handwrite their own signature.

Haptic devices have also been used as a teaching aid in mathematics. Visualising a mathematical function can be very difficult and so haptic feedback has been utilised to guide a person through the shape of a function using force channels. Automatic conversion of printed information has been developed in other areas such as optical character recognition (OCR), which is a great assistance when combined with text to speech synthesisers. The Department of Computing Science at the University of Glasgow [YGB01] have also developed an automated system that produces a haptic channel for printed graphs. The system uses a flatbed scanner to acquire the graph data and then the image is stored as a bitmap (.bmp) format. A filtering process is applied to remove any unwanted data and then the key features are extracted. The operator can then explore the haptic representation of the graph through force feedback. This system has been applied to two haptic devices and these include the Phantom Omni and the Logitech Wingman.

Visually impaired computer users that have been involved in using a haptic device have found that it has given them greater access to a computer and has been hugely beneficial as a teaching aid. As more GUI's and haptic systems are developed the applications will cover a much wider range.

2.6.2 Stroke Patient Rehabilitation

It is reported that every year, an estimated 150,000 people in the UK have a stroke. Most people affected are over 65, but anyone can have a stroke, including children and in some cases even babies [Ass]. Each stroke and its effects are unique to each survivor. Rehabilitation is not a cure for a stroke in that it is not possible to reverse the effects of brain damage, but it may help patients relearn skills or teach other areas of the brain to take over the functions performed by the cells that have died. One side of the brain controls the opposite side of the body and so a stroke will result in neurological complications on the side of the body it affects. For example, if the stroke occurs in the right side of the brain, it will affect the left side of the body.

To regain mobility, on the side affected by the stroke, the patient is often required to repeat a series of tasks. To get stroke victims, of whom the majority are over 65, to repeat these tasks can be rather challenging for the people involved in the rehabilitation process. Tasks in which stroke patients are often encouraged to undertake include: jigsaws, box and block tests, Purdue pegboard tests, etc. According to Lövquist et al. [LD06] a stroke patient normally makes good progress at the beginning of the rehabilitation program. The reason for this is that whilst in hospital the patient will meet regularly with their therapists. Once the patient is back home it is often the case that they lose motivation and find the tasks mundane.

The Interaction Design Centre [LD06] at the University of Limerick, have produced a piece of software to aid in stroke rehabilitation utilising a haptic device. The reason why they introduced software and haptics into the rehabilitation process was the possibility of providing a wide range of exercises that were engaging, stimulating and fun. To achieve this they have developed a piece of software named "The Labyrinth" in which the user navigates a maze system using the Phantom Omni. The user is given rewards for reaching panels and penalties for hitting walls. At the end of the session the results are uploaded to a database so that the rehabilitation can be monitored.

Careful design of rehabilitation tasks needs to be addressed to keep the interest and attention of the user. If the task is mundanely repetitive then the patient will lose interest very quickly. This is especially the case if they could be performing the same task in reality. The software needs to change the way in which the task is addressed mentally but still maintain the same physical repetitive movements as part of the rehabilitation process. The patient also needs to understand the motivation behind the task being set. Further information on techniques to improve a patients' motivation have been explored by Loureiro et al. [MC01].

2.6.3 Haptic Aids for Motion Impaired Computer Users

Haptic Damping

As previously stated, disabled computer users can often suffer from tremor or spasm, which can make point and click tasks difficult. A haptic technique investigated to aid in these areas is non-directional viscous damping. This technique produces the sensation of moving the device through a viscous fluid. The aim of haptic damping is to reduce the effect of spasm or tremor. It ensures that the cursor will not suddenly move across the screen away from the target. This technique also helps to stabilize the hand as the user tries to achieve a desired position. Without this some operators may experience the device as feeling too free or loose and become frustrated when performing small or precise manipulations [MC95].

The Engineering Design Centre [LHK+02a], at the University of Cambridge set an experiment to test several damping conditions. This was performed under four damping conditions: none, acceleration damping, velocity damping and combined damping. The cursor speed of the device was then recorded as it had been noted that the threshold of three pixels/ms could capture the difference between controlled and uncontrolled movement [HLKC01]. The results of the study showed that haptic damping did not really improve the targeting time for most operators. There also seemed to be little difference between damping types. However, for one user who suffered from spasm it was shown to reduce the time to reach the target by over 50 percent. Results also showed reductions in the frequency of uncontrolled, high-speed movements by 70-90 percent.

The damping effect obviously has some benefits for disabled computer users that suffer from spasm or tremor but still have sufficient muscle strength. This technique may not be as useful for other symptoms, such as muscle weakness, because it will require extra force to manipulate the device. As a result, it is necessary to have a measure to determine whether damping techniques will be beneficial to a certain user.

Haptic Gravity Wells

Another technique that has been investigated to aid motion impaired computer users is the haptic gravity well. A bounding volume is placed around the target with a spring force that is designed to clamp the cursor inside the volume until the icon has been selected or the force placed on the device exceeds that limiting the gravity well. The gravity well is a useful UI convention for allowing the user to more readily select 3D points with the assistance of force feedback [CB05]. They are used to attract the device towards a point location and will typically have some radius of influence.

There are two techniques that have been explored using gravity wells. The first technique is to provide a larger bounding volume around the target with a spring force calculated to the target edge. Once the cursor passes inside the target the force is removed. The second technique uses a similar principle apart from when the cursor passes within the bounding volume a spring force is applied to attract the cursor towards the target centre. Langdon et al. [LHK+02c] investigated both techniques and found that the first improved the average time taken to complete the task by approximately 10-20 percent. Results from the second approach improved average time to target by levels approaching 50 percent. Further analysis of this technique suggested that the greatest improvement occurred with the most impaired users. The main reason for improvement is the stability provided to the operator by the clamping spring force.

The main drawback in which this technique suffers is if the targets are in close proximity of each other and the haptic wells overlap. This can cause conflict between the wells and make icon selection difficult. A technique that could be investigated to overcome this problem would be to use a weighting system for each icon. Icons that are used more frequently could be given a larger bounding volume or have a stronger attractive force associated with them. A study of the interface would be required to determine which icons are more regularly used.

Initial observations of the haptic well technique also suggest that the spring constant should not be too stiff. If it is too stiff then users can experience a large overshoot when trying to leave the well, which can impede on the next task. This problem can be amplified with wells in close proximity of each other because the overshoot can land the cursor into an undesired neighbouring well.

High-Friction Targets

High-friction targets are a technique that combines the damping and haptic well techniques discussed above. When the user passes over the bounding volume of a target then a high-friction force is applied to the device to ensure it cannot easily slip off the target. Laycock and Day [LD07] describe smooth and frictionless contact as hindering interaction as the user can slip off surfaces too easily. Unlike gravity wells this technique does not suffer problems with targets in close proximity. It does, however, encounter problems if the cursor needs to pass over several other targets to reach the destination.

This technique would be helpful for users who also struggle with finer movements. It may not be of great benefit if there are many icons spread across the screen and the user has to keep passing over them. However, if the layout of the icons is arranged into regular rows or columns the user could pass in and out of the rows reasonably easily to get to the correct target.

Haptic Tunnels

Another technique that has been investigated is the use of haptic tunnels. Haptic tunnels aim to guide the user directly to the target object via a tunnel or channel. If the cursor comes in contact with a wall of the tunnel then the device produces a restoring force to ensure that it cannot pass through.

Results from a study by Langdon et al. [LHK$^+$02b] suggest that haptic force channels may only improve targeting times for sufferers with high degrees of impairment. Haptic tunnels may be beneficial for suffers of spasm or tremor because the cursor cannot exit the channel under any uncontrolled movements. This will result in a more direct path to the target. The ability to traverse each path to reach the desired target may also benefit operators with poor motor navigation skills or muscle weakness.

A good understanding of the target layout is required to implement this technique successfully. Without sufficient knowledge of the GUI layout, haptic tunnels may not always be of great assistance. For example, if there are a series of buttons that are used regularly but not in the same channel it could prove a lengthy process navigating the network to get from one target to another. As a result tunnel layouts need to be selected in a careful manner. Path finding techniques could be useful in creating efficient networks.

The following section indentifies the important design considerations when using a pointing device for motion impaired operators.

2.7 Pointing Device Interface Design

There are important considerations to be made in the interface design. According to Reswick [Res90], it is important to involve consumers in the design of assistive devices, because the designer may not be familiar with the needs, constraints, and preferences of a disabled individual. It is also important to include the involvement of therapists and carers, as they will work regularly with the individuals and may be able to assist with design considerations.

One of the main difficulties when designing an interface is producing a system that will accommodate the needs of every operator. This area of research is often referred to as universal design. There is much debate between researchers of the best approach. Some researchers argue that with such a wide range of disabilities it is better to produce a system to meet the needs of the individual [Har07] [LBA00] [KLS05]. However, for a system to be commercially viable many researchers argue that this is impractical and that the system should be aimed at the majority of the target market [Van00] [Mac98]. Vanderheiden [Van00] refers to universal design as,“A focus on designing products so that they are usable by the widest range of people operating in the widest range of situations as is commercially practical.” It is important to prioritise when designing accessibility features, because of the multi-dimensional nature of disability (vision, hearing, physical, cognitive) and the large number of individual design techniques or strategies which might be implemented for each dimension.

Due to these design conflictions both approaches will be investigated within this study to determine if one technique produces better results. The effects of the level of assistance will be analysed to determine if tuning traditional techniques can significantly improve interaction. For the second approach a number of new haptic techniques are proposed that are designed specifically to assist targeting for motion impaired operators and do not require calibration. The implementation of these techniques is discussed in greater depth in Chapter 3.

2.8 Non-Calibrating Haptic Assistance

One area that has not been addressed in haptic assistance for motion impaired operators is the use of techniques that do not require calibration to optimise interaction. If techniques that do not require calibration produce similar or better results than traditional assistance then they may benefit a wider range of disabilities. Studies of traditional haptic assistance attempt to aid the individual by imposing a force on them. For example, gravity wells impose a spring force towards the centre of the well. A concern highlighted with traditional haptic assistive techniques such as gravity wells, haptic damping and haptic tunnels is the effect they will have on a complicated interface. The reason for this is that they can be intrusive on a user's interaction. For example, if someone accidentally enters a gravity well then they have to physically oppose the spring force to exit that well. Hwang et al. [HLKC03] have investigated the effects that target distracters have on interaction. Results showed that gravity wells can still improve times and error rates compared to an unassisted interface, even on occasions when the cursor is pulled into a distracter. However, for users with decreased muscle strength this intrusive force may benefit their clicking but hinder interaction because they cannot easily exit undesired wells. Gunn et al. [GMD09] also suggest that there may be valid reasons for a skilled user to want to ignore the advice provided by a computer system. They go on to argue that force feedback may limit the ability to ignore advice and therefore be less effective as an aid.

Some non-intrusive haptic techniques have been investigated that do not require force calibration. One of the most popular techniques is a haptic recess [MZ98][Ram95].

For example, Oakley et al. [OMBG00] used a recess effect where a hole is created in the back of the workspace, with a depth of 2 mm and edges sloped at 45°. This technique is designed to help users with icon selection as they can fall into the recess and have to physically climb the wall before exiting. This is used to provide stability for clicking and make it harder to accidentally slip-off a target (a problem noted by Brewster et al. [Bre98]). In their first experiment, gravity wells and haptic recesses produced the best results for reducing error rates and decreasing the workload. Their second experiment showed a significant reduction in the number of times a participant slipped on and off the scroll bar with the recess effect. Oakley et al. observed that when exiting a recess the operator had to make a conscious effort to lift off the back of the workspace. The action of lifting off was difficult to do by mistake. The results of this study were only performed on able bodied users but this non-intrusive technique may benefit interaction for motion impaired users as there are not any intrusive or opposing forces. This type of assistance can be used or ignored as required.

If techniques such as the recess effect can produce better or similar results compared to tuning traditional assistance then this will be a significant discovery because the new techniques do not require force calibration. This would eliminate one of the many calibration variables that arise when trying to tune a device for the individual e.g. gain, device positioning, etc. The following section discusses why calibration of traditional haptic assistance is necessary.

2.9 Calibrating Haptic Assistance

The range of disability for sufferers of cerebral palsy and associated disabilities can vary enormously from mild to severe. This will have a significant effect on the individual's ability to use a pointing device. Given that previous studies have shown that haptic assistive techniques can aid in many areas of disability why is further cursor analysis required? The reason for this is that the results produced from previous studies [KHL+02] [KLCR00] [LHK+02b] only show that haptic techniques with a static configuration may aid certain individuals in certain areas. This may not always be specific to the disability or the individual. Although two people may have the same diagnosis, their level of impairment could vary considerably and so a static calibration may help one individual and possibly hinder the other. For example, how does haptic damping affect a user's performance in a targeting task? It could be possible that a certain level of damping may be beneficial and dampen a person's involuntary movements. As a result they may be able to acquire the target more accurately and in less time. Alternatively, it could slow the user or make the system unusable due to the larger forces required to manipulate the device. Wall et al. [WPS+02] discuss the importance of achieving a suitable level of haptic assistance, without constraining the user too much.

One of the aims of this project is to analyse the effect of each type of haptic assistance using cursor analysis techniques and determine any areas of correlation between the two. If a correlation can be made between the level of assistance and the cursor measures, then a direct calibration will be possible by creating a model. Previous studies from Keates et al. [KHL+02] [HLKC01] have shown improvements in certain cursor measures [MKS01] with each type of assistance. Cursor measures will be used to give a detailed analysis of the individual's performance from which it will be possible to identify an appropriate type and level of assistance to suit that person. The system should aid areas of weakness and ensure that areas of strength are not hindered.

It is also important to determine the useful levels of assistance. It is thought that very low levels of assistance may have little effect on interaction due to the low force effect. At the opposite end of the scale it is thought that high levels of assistance could hamper performance due to the extra motor workload. According to Oakley et al. [OABG02] the maximum applied strength of assistance is likely to be highly dependent on individual differences. Therefore it is essential that the maximum strength of assistance is configurable.

As yet, the needs of the individual have not been incorporated into haptic interface design. LoPresti et al. [LBA00] discuss how each individual's disability is unique and tuning devices to a person's strengths and weaknesses can be critical for success. Koester et al. [KLS05] discuss that the level of assistance needs to be dynamic as a person's ability can change significantly in the short term due to factors such as fatigue or long term due to a progression in impairment. A dynamic system would be linked closely with machine learning, which is a technique used in computing to make intelligent decisions based on data. It has proven to be a successful tool in many aspects of computing such as speech recognition, gesture recognition, image reconstruction, etc. It is rapidly becoming one of the most important areas of research and development. An evaluation of user performance was taken by McGill, [McG90] who developed a force-sensing joystick which adapted to hand tremor using measurements of the user's tracking ability and tremor. If similar procedures could be applied to calibrate haptic assistance then the interaction rates of the individual could be significantly increased. To evaluate the effectiveness of the calibration it will be necessary to analyse a wide range of disabilities.

A comparison will be made between assistive techniques for both target homing and target acquisition. If one technique performs better than another then this will be chosen as the main type of assistance unless there is a valid reason for it not to be used. For example, gravity wells may perform better than high-friction targets but a person with joint difficulties may find that the gravitational pull of gravity wells causes discomfort. In this case high-friction targets may be more suitable as they do not impose a force that could cause discomfort. One type of assistance may only improve a single measure whilst other techniques may improve many. This will be taken into consideration in the selection stage of the final design.

To be able to calibrate each type of assistance successfully, it will be necessary to identify at least one measure that provides a strong correlation for each type of assistance. The reason for this is that the system requires an understanding of what settings are important, and how input device settings influence performance [KLS05]. An intuitive explanation is also required to help researchers understand why that measure is affected by the specified technique. The following section identifies studies that have attempted to calibrate traditional pointing devices for motion impaired users.

2.10 Traditional Pointing Device Calibration

Several studies have attempted to assist motion impaired operators in the use of pointing devices using calibration. These studies have produced software that attempts to evaluate an individual's performance and uses the data to calibrate a number of measures to assist them. Koester et al. [KLS05] investigated the gain settings of pointing devices for users with physical impairments. The gain or sensitivity determines how far the cursor moves on the screen for a given movement of the pointing device. It was shown that for certain individuals the gain level had a significant effect on throughput, percent of error-free trials, cursor entries, and overshoot. The results produced from attempting to configure the gain of the device did not provide a significant increase in performance compared to the Windows XP default. Fitts' law (See Section 4.1) provides the most logical reason for this. An increase in gain will reduce the target distance (A) by reducing the amount of movement required to travel that distance on screen. It will also reduce the effective target width and therefore increase the index of difficulty. The simultaneous changes in effective distance and width tend to cancel each other out resulting in little performance change.

Koester et al. [KLS06] also investigated other adjustments for pointing device calibration. These included enhanced pointer precision (EPP) [EPP], target size, target distance and input device. The cursor analysis was performed using the Compass software [KLA+03] package with the Aim test. In each trial the user was presented with a single target and had to move the mouse cursor inside the target and click to select it successfully. The first experiment was performed using enhanced pointer precision which is an algorithm designed by Microsoft to give more control over the cursor, especially when moved small distances on the screen. It also provides quicker deceleration of the cursor when the mouse is slowed down or stopped. The EPP technique was shown to assist the majority of physically impaired users. The study also confirmed that Fitts' Law is appropriate for motion impaired users where larger, closer targets can be selected more quickly. The study confirmed that choosing the correct input device to begin with is critical for success.

In 2005 IBM [LS05] researchers announced a mouse adapter that had been developed to aid users who suffer from hand tremors. The device is able to eliminate excessive cursor movement, thereby allowing more normal use of a mouse. This adapter aims to filter out the shaking movements of the hand by using a similar technique that is used in image stabilizing systems of some camera lenses. The results of the adapter have shown a much smoother movement of the cursor and significantly improved accuracy of mouse operations but this alone is not sufficient.

Gajos et al. [GWW08] investigated methods designed to improve the performance of motion impaired users with automatically generated, ability based interfaces. Most user interfaces are designed for the average user and so the components of that interface may not suit an impaired user. Gajos et al. suggest that a preferable solution would be to adapt user interfaces to the abilities of the individual. The system investigated was named SUPPLE++ and this models a user's motor abilities directly from a set of one time performance tests. The use of this system produced results 26.4% faster with the generated interfaces. There were also 73% fewer errors recorded.

The following section takes into consideration the safety of motion impaired operators when using a haptic device.

2.11 Safety Considerations

A haptic device may be used to interact with a virtual environment but the forces experienced by the user are real. Devices such as the Phantom Omni and Phantom Desktop are capable of exerting forces up to 3.3 and 8 Newton's respectively. These devices can perform large accelerations that could also cause injury. As a result precautions need to be taken to ensure the operators safety.

One technique often used is to have a manual switch or key-press that is available to both the patient and the therapist, which can stop the simulation in the event of any danger. Due to slow human response this is not sufficient alone. Other techniques can be integrated into the software. One technique used is to monitor the resultant force on the device and test if that exceeds a set threshold. If the threshold is exceeded then the simulation will shut down all forces to the device. Similar techniques can be used when monitoring the device's velocity and acceleration.

When applying forces to a user the system must produce a stable force. It is rare that a system becomes unstable to an extent that the device exhibits large forces on the user. It is much more common to observe cyclic behaviour of forces or discontinuities due to a reduction in frame rate. These problems have been an issue since the early developments of haptic simulations [MMS+90]. Hayward et al. [HM07] describe these problems as being very frustrating when attempting to implement any type of haptic simulation. Working in a discrete system with a limited sampling rate and limited quantization levels it is not always possible to avoid these problems with complete certainty. Where possible it is necessary to sustain a small sampling period (1000 Hz) and use more precise sensors giving a more continuous simulation. With the development of multi-core processors it is now possible to run tasks in parallel. The haptic and graphic processes are often performed in separate threads with the haptic simulation running at 1000Hz and the graphics thread running at 50Hz.

Hooke's law is often used as the spring equation for the restoring force of the HIP penetration and various haptic interactions. A common method used to stabilise cyclic behaviours encountered when using Hooke's law is to introduce a damping factor [GI05] [YTT06]. This technique reduces the amplitude of the oscillation until it comes to rest. Further information on stability damping is given in Section 3.2.

2.12 Summary

Chapter 2 has provided a description of the types of haptic feedback devices available and some of their uses for motion impaired operators. It is important to have an understanding of the difficulties that are encountered by motion impaired operators when using traditional input devices in order to produce suitable solutions. Section 2.5 provided details of the early uses of haptic feedback. This was then followed by a section that investigated haptic uses for improving HCI for motion impaired operators.

Section 2.7 onwards investigated the design considerations of universal access to produce systems that will benefit every operator. Many techniques have proven to be the greatest aid to those more severely impaired. As yet these findings have only been evaluated under experimental conditions. Further work could prove to be hugely beneficial in this area when applied to real world applications. If the computer could learn how the individual operated the device then it would be possible to automatically produce assistive techniques for areas of weakness. Previous work suggests that a system needs to address each individual's specific strengths and weaknesses.

Haptic technology has seen rapid development in recent years and has been applied to many applications. Many haptic devices used for HCI that are on the market are now relatively inexpensive. Initial research has proved that there is scope for haptic applications to be used to assist disabled computer users. The haptic assistance discussed in this chapter has previously been used to assist a wide range of disabilities. The following chapter shows how various traditional haptic techniques can be implemented and identifies the key variables used in their calibration. The implementation of new, non-calibrating haptic assistance is also presented.

Chapter 3

Implementation

This chapter describes algorithms that can be used to produce traditional haptic assistive techniques. Later in the chapter some new non-calibrating techniques are proposed along with their implementation. Each technique has been implemented in such a way that it can be easily automated for an existing interface.

3.1 Haptic Development tools - CHAI3D

To develop haptic techniques it is necessary to have an appropriate development environment. The projects developed in this thesis have been achieved using an Open Source API named CHAI3D [CBM+]. This API is based on C++ and OpenGL libraries and contains many features that allow fast development.

The package supports many commercial devices including the Phantom Omni, Phantom Desktop and Novint Falcon, which provides scope for further development. Many key techniques have been implemented which saves time in re-writing some of the standard rendering algorithms. These include:

- Zilles and Salisbury's God-object algorithm with friction
- .3DS and .OBJ mesh loader
- .BMP and .TGA image loader

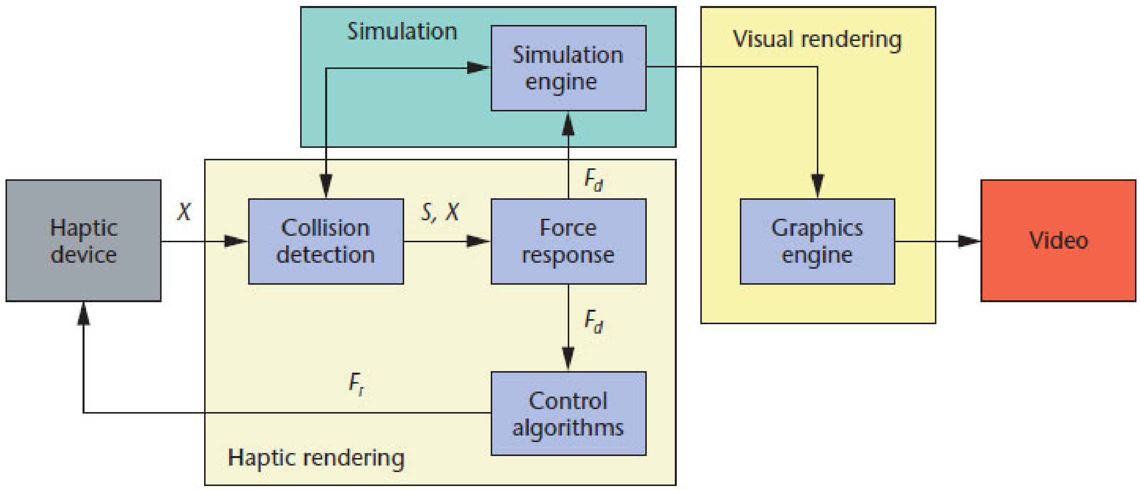

Figure 3.1: The CHAI3D system block diagram. (adapted from Barbagli et al. [BCS])

- Integrated Open Dynamics Engine (ODE)
- Integrated Deformable Models (GEL)
- Integrated Bass Audio Library
- Efficient Collision Detection

The CHAI3D API uses Zilles and Salisbury's [ZS95] God-object algorithm which was originally designed to overcome the problem of object push through when the HIP undesirably passes through a thin mesh. The God-object algorithm tracks a history of contact with a surface. The position of the God-object (proxy) is then chosen to be the point which locally minimizes the distance to the HIP along a surface. A restoring spring force is calculated between the HIP and the proxy. The CHAI package is also supplied with a virtual haptic device which allows the HIP to be moved in three dimensions using a mouse. This is very useful when a physical device is not available and for debugging purposes. A visual representation of the force amplitude and vector is displayed in a workspace window. An example of the user interface is given in Figure 3.2.

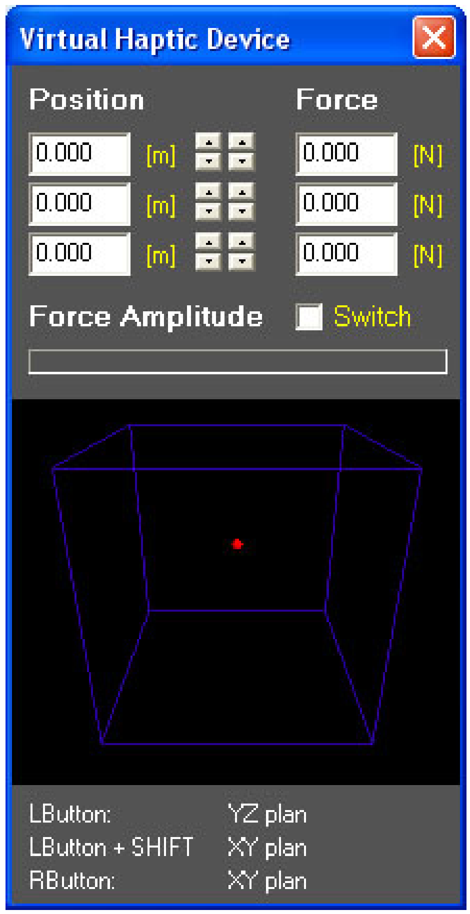

Figure 3.2: The CHAI3D virtual device interface.

The following sections describe how each technique was implemented using the CHAI3D API. Each technique has been implemented in such a way that it can be easily integrated into an existing interface using the co-ordinates of the key features.

3.2 Gravity Wells

3.2.1 Regular Shaped

A gravity well can be considered as a bounding volume with an inward spring force towards the centre of that volume. The spring force is calculated to the proxy using Hooke's law, $\mathbf{f} = k\mathbf{x}$, where $\mathbf{f}$ is the force, k is the spring constant and $\mathbf{x}$ is the extension of the spring. Figure 3.3 gives a physical representation of this system.

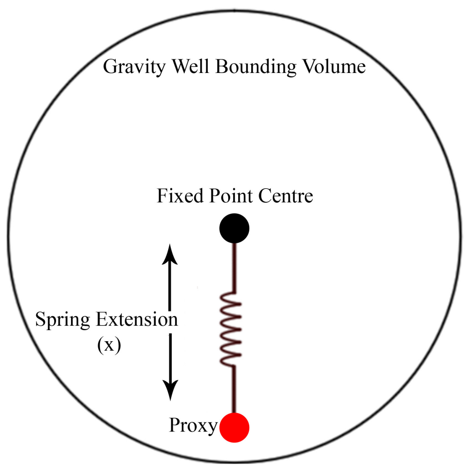

Figure 3.3: A physical representation of a circular shaped gravity well.

In a study by Salisbury et al. [SBM+95], it was shown that stiffer contacts can be perceived by introducing a damping factor into the equation. This damping is also crucial to maintaining stability of the spring force. If the device were to begin to oscillate, when a well is entered, then the damper will reduce this effect until the motion comes to rest. This is given by Equation 3.2.1.

$$
\begin{aligned}
\mathbf{f} &= k\mathbf{x} - b\mathbf{v} \qquad (3.2.1)\\
\text{where } \mathbf{f} &= \text{force}\\
k &= \text{spring constant, } \mathbf{x} = \text{displacement}\\
b &= \text{damping coefficient, } \mathbf{v} = \text{velocity of proxy}
\end{aligned}
$$

A physical representation of this configuration can be observed in Figure 3.4.

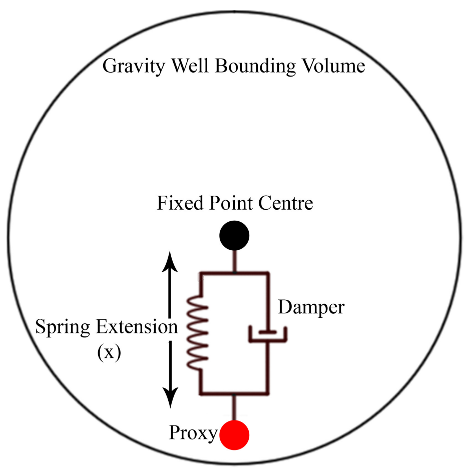

Figure 3.4: A physical representation of a circular shaped gravity well with damping.

The first stage in the implementation of gravity wells is to create and position a bounding volume. Currently all wells that have been tested under experimental conditions have been circular in shape and provide a spring force towards the well centre. A circular bounding volume can be defined by its position and radius. Before a force is calculated it is necessary to test if the proxy lies within that volume. This is achieved using 2D collision detection techniques. To determine if a collision has occurred within a bounding circle the squared sum of the difference between the proxy and the position of the circle is taken. If this is less than the squared sum of the radii then a collision has occurred. The implementation of this as shown in Figure 3.5 and Condition 3.2.2.

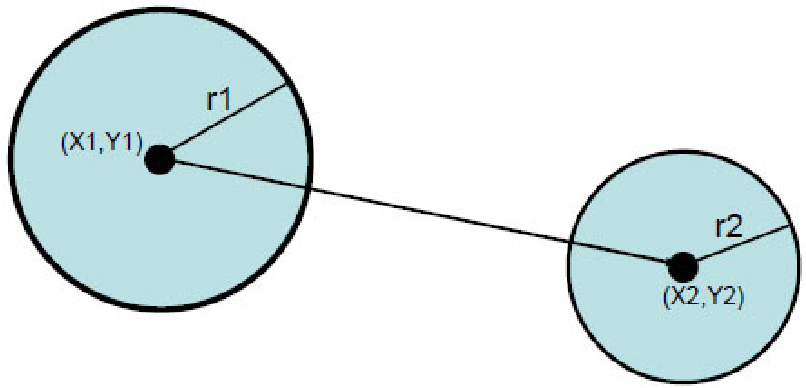

Figure 3.5: Circle-circle collision detection based on Condition 3.2.2.

```
if((X1-X2)^2 + (Y1-Y2)^2 < (r1+r2)^2)
                        Then Collision
```
(3.2.2)

With the collision detection for circular volumes in place it is then necessary to respond appropriately when that volume is entered. This is achieved by calculating and sending a force vector to the device based on Hooke's Law. If the proxy lies inside a well then the displacement vector is calculated directly as the difference between the centre of the well and the position of the proxy. The force vector is calculated as the product of the displacement and the spring constant and is sent to the device.

In initial studies of using gravity wells it was observed that exiting a well could cause a large overshoot due to the opposing spring force. The effect of this was worsened if the cursor overshot into a neighbouring well. As a result it was decided that once the target had been successfully clicked (and released) the well would be disabled until the cursor has exited the bounding volume. This will resolve the problem of overshoot when exiting a well and improve interaction as the user does not have to oppose the spring force unnecessarily. Algorithm 3.1 shows how this technique is implemented.

Algorithm 3.1 Circular Gravity Well Implementation. The variables correspond to those shown in Figure 3.4.

```
Require: The state of the device button - deviceButton
  if (deviceButton == 1) then
    buttonDown = true
  end if
  if (deviceButton == 0 && buttonDown) then
    buttonUp = true
  end if
  if (insideWell && !(buttonUp && buttonDown)) then
    displacement = wellPosition - proxyPosition
    force = (springConstant × displacement)+(damper × proxyVelocity)
  else
    force = 0
  end if
  if !(insideWell && (buttonUp && buttonDown)) then
    buttonUp = false
    buttonDown = false
  end if
  return force
```

Figure 3.6 gives a representation of the force magnitude of circular shaped gravity wells.

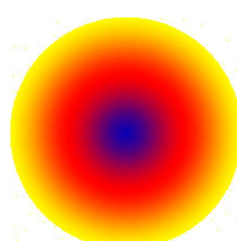

Figure 3.6: Force amplitude representation of circular shaped gravity wells, where yellow is the greatest force and blue is the least.

Many of the icons within GUI's are square shaped and so an additional technique is proposed within this thesis to map them correctly. This technique can be thought of as a square bounding volume embedded with a circular volume. If the proxy lies within the square volume but not the circular one, then the spring displacement is clamped to the circle's radius. This technique allows a greater area of a square shaped icon to be covered whilst maintaining a uniform force. If the spring extension of Hooke's law was calculated just based on a square volume then the resultant force would not be uniform across the edges of the well, i.e. there would be greater extension (and therefore force) at the four corners.

The first stage in the implementation of this technique is to determine whether the square bounding volume has been entered. This can be achieved using its lower and upper extremities, as shown in Condition 3.2.3.

```
if((x > minX) && (x < maxX) && (y > minY) && (y < maxY))
                                          Then Collision
```
(3.2.3)

The blue sphere in Figure 3.7 lies between the two y extremities but not the x and so a collision is not registered. Whereas the red sphere lies between both and so a collision is registered.

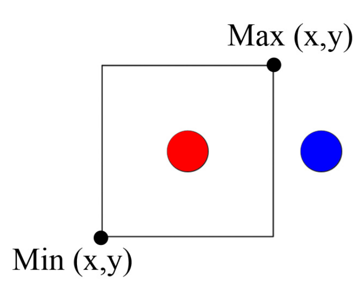

Figure 3.7: Point-square collision detection, where the red point lies within the two x-y extremities and the blue point lies outside.

If this test returns true and the difference of the proxy to the centre of the well is less than the radius of the inner circle then the displacement can be calculated directly as the difference between the centre of the well and the proxy. If the square volume has been entered but the magnitude of the displacement is greater than the radius of the inner circle then the displacement is clamped to that of the circle's radius. The benefit of a square shaped well is that it will cover a greater area over a square shaped target, without overlap. The representation of the force magnitude is shown in Figure 3.8.

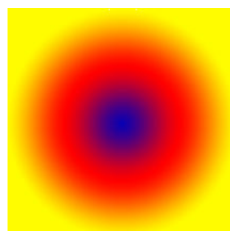

Figure 3.8: Force amplitude representation of square shaped gravity wells, where yellow is the greatest force and blue is the least.

For both regular shaped wells the spring force is only disabled once the device button has been released within the well. The well is only re-enabled once it has been exited. The user interface is based on a two-dimensional plane so the z component of the force vector is omitted.

3.2.2 Elliptical Shaped

In most GUI's some icons will not be equilateral in shape and so a circular or square shaped well may not provide suitable mapping. The alternative proposed in this thesis is an elliptical shaped bounding volume. The physical representation of this technique can be thought of as a ring with a wire running through the middle of it, similar to the game often referred to as buzz wire. When the ring comes in contact with the wire it cannot pass any further in that direction. The position of the proxy would be defined as the centre of the ring, as shown in Figure 3.9.

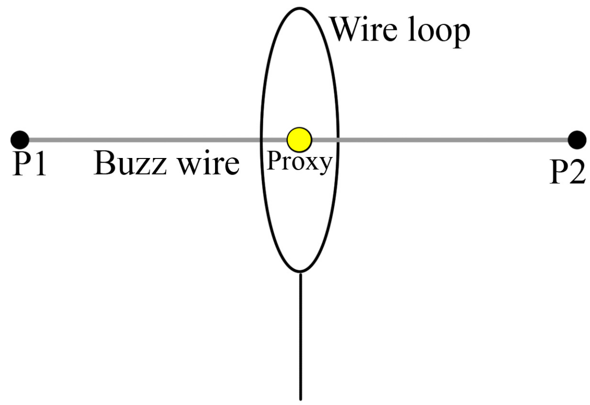

Figure 3.9: Elliptical shaped gravity well representation where the proxy is positioned at the centre of the loop.

The theory behind this technique is based on the point to line segment test [Sun]. This technique can be used to return the distance from the line segment and its position in relation to the line, as shown in Algorithm 3.2. This information can then be used to calculate the displacement vector required for Hooke's law.

Algorithm 3.2 Point to Line Segment Calculation. The variables correspond to those shown in Figure 3.10.

Require: The position of the proxy - `proxyPosition`
Require: The line segment end points - `P1 P2`

```
v̄ = P2 - P1
w̄ = proxyPosition - P1
if w̄ · v̄ <= 0 then
  state = 1
  return abs(proxyPosition - P1)
end if
if v̄ · v̄ <= w̄ · v̄ then
  state = 2
  return abs(proxyPosition - P2)
end if
state = 3
return w̄ · n̄
```

The three line states are shown in Figure 3.10.

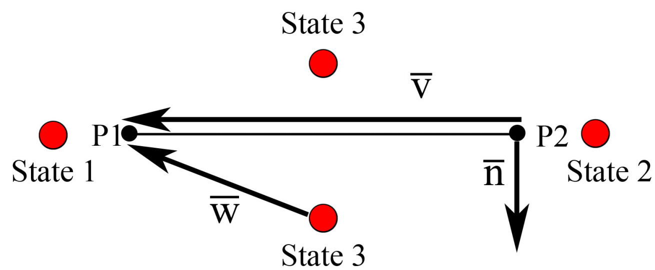

Figure 3.10: The three possible states represent the proxy position in relation to the line segment. The proxy positions are represented by the red circles. This is then used to calculate the distance from the line.

The elliptical shaped well is initialised by setting the position of the two end points of the line and the desired radius. Once initialised it is necessary to test the distance from the line and its state. With a displacement vector it is then possible to calculate the Hooke's law force vector. The method for this is shown in Algorithm 3.3.

3.2.3 Calibration Variables

The main variables of importance in calibrating gravity wells are the spring constant and the size of the bounding volume. The size of the gravity well is very much dependent on the target layout. If two buttons are in close proximity then the bounding volumes will need to be much smaller in area than two with greater spacing between. Hwang et al. [HKLC05] performed a study to determine the effects of increasing the size of gravity wells. The results indicated that increasing the size of the bounding volume reduced the time to target successfully. The greatest improvements were observed when a larger well was positioned around a small target. Increasing the size of each well increases the effective width of the target which reduces the task difficulty. For more information on these measures see Fitts' law in Section 4.1. The target size will have a bearing on the level of extension that is used in Hooke's law.

Algorithm 3.3 Elliptical Shaped Gravity Well Implementation. The variables correspond to those shown in Figure 3.9 and 3.10.

Require: The state of the device button - `deviceButton`
Require: The distance of the Proxy from the line segment - `pointLineSegmentDistance`
Require: The line state from Algorithm 3.2 - `state`

```
if (deviceButton == 1) then
  buttonDown = true
end if
if (deviceButton == 0 && buttonDown) then
  buttonUp = true
end if
if ((abs(pointLineSegmentDistance) < wellRadius) && !(buttonUp &&
buttonDown)) then
  if (state == 1) then {the proxy lies off the P1 end of the line}
    force = (-springConstant × pointLineSegmentDistance ×
    (P1 - proxyPosition))
          +(-damper × proxyVelocity)

  end if
  if (state == 2) then {the proxy lies off the P2 end of the line}
    force = (-springConstant × pointLineSegmentDistance ×
    (proxyPosition - P2))
          +(-damper × proxyVelocity)

  end if
  if (state == 3) then {the proxy lies either side of the line between P1 and P2}
    force = (-springConstant × pointLineDistance × n)
          +(-damper × proxyVelocity)

  end if
else
  (force = 0)
end if
if !(abs(pointLineSegmentDistance) < wellRadius) && (buttonUp &&
buttonDown)) then
  buttonUp = false
  buttonDown = false
end if
return force
```

The spring constant governs the strength of the well and the attractive force towards its centre. The range of the upper limit of the spring constant is governed by the ability to produce a stable force at greater spring stiffness. Higher spring stiffnesses could cause overshoot due to the greater force exerted on the device and therefore increased momentum. Lower spring stiffness may have little effect as the forces exerted on the device will be low. This will be investigated within the study.

3.3 High-Friction Targets

High-friction targets are designed to send a frictional force to the haptic device once the proxy passes over that target. A bounding volume is placed around the target object and the frictional force is intended to aid in icon selection by dampening the proxy's movement.

As yet very little research has been undertaken to determine the effect of high-friction targets on user performance. A large criticism of this technique is that if the cursor has to pass over many targets then this can seriously hamper interaction [KHL+02], especially when using a two DOF device. This thesis proposes a solution utilising the three-dimensional attributes of the Phantom Omni. The technique proposed can be thought of as using a pen in contact with a smooth surface that has high-friction targets overlaid on it. If the cursor needs to pass over many targets then the user can lift the pen off the surface and place it back on again, when and where required.

The technique often used for a damping frictional force is dependant on the device velocity. However, this alone does not give a realistic representation of friction. To apply realistic friction to a surface a friction model is required. One of the most popular models used in haptic applications is based on Zilles and Salisbury's God-object with friction [ZS95]. The CHAI3D package offers this friction model which is based on a stiction (static friction) point to provide stick-slip friction. This friction model was chosen to be used with high-friction targets because it provides good device stability. A static frictional component is used when the tangential force is not strong enough to overcome the coefficient of friction for that surface. This will result in the proxy remaining stationary. If there is sufficient tangential force to overcome the static friction threshold then the proxy will slip along the surface, but will be opposed by a smaller, dynamic friction force. This technique is often explained as a spring with a mass attached to it. Up until the spring reaches its elastic limit the mass will not move due to the static friction component. Once the elastic limit has been met then the motion of the mass is opposed by the dynamic frictional force between the two surfaces. A representation of this model is shown in Figure 3.11.

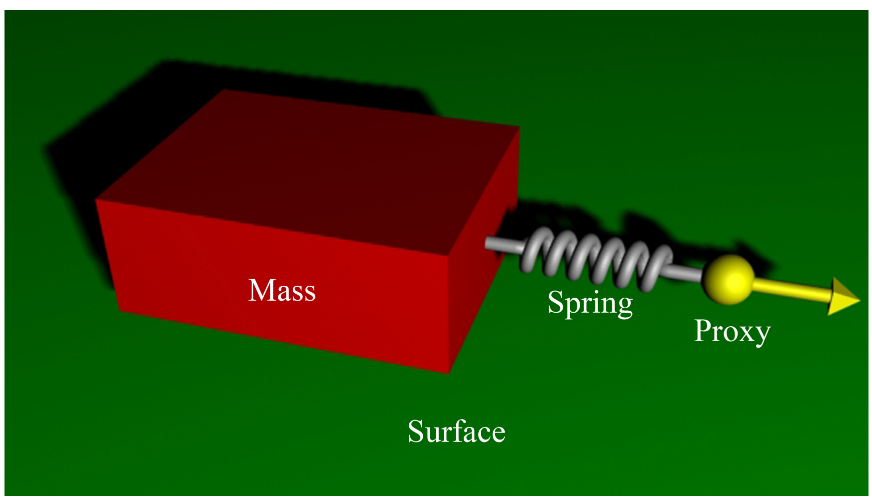

Figure 3.11: A physical stick-slip representation of friction. Until the spring has met its elastic limit the mass will not move. Once in motion the mass will slip along the surface opposed by a dynamic friction force between the two surfaces.

When using this technique the proxy is tracked, rather than the HIP, because it is this object that is affected by the result of the frictional force. Figure 3.12 gives an example of where the HIP is moving with the proxy following it along the target surface. Tracking the proxy ensures that the user feels the resistance of the friction and the corresponding result is observed visually on screen.

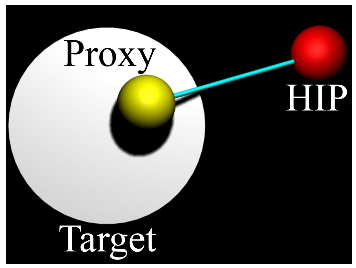

Figure 3.12: The tracking of the proxy and the HIP along a high-friction target. The HIP may lay outside of the target region whilst the proxy slides along the high friction surface.

To create a mesh in CHAI3D a cMesh class is provided. Each mesh must be constructed by a series of triangles. The haptic virtual plane in which the targets are overlaid is constructed from two joined triangles. Additional information on the haptic virtual plane can be found in Subsection 5.1.1. The material attributes of the mesh can then be altered such as its shininess, transparency level, stiffness level [N/m], static and dynamic friction levels. This allows the frictional properties of the plane to be altered when the cursor enters a target region. Collision detection techniques are required to determine when that region is entered. The circular and square shaped targets are based on the same collision detection techniques used for gravity wells. If either collision technique returns true (i.e. the proxy lies within a target) then the dynamic and static friction levels of the plane are adjusted to that of the high-friction target. If they do not return true then the friction levels are set low to that of the haptic virtual plane. This technique saves on the amount of processing required as compared to when each target were to be constructed of a series of triangles and directly laid upon the plane.

3.3.1 Calibration Variables

The calibration of high-friction targets is based on their dynamic and static friction components. The static friction will have a bearing on the stability of the device when the threshold is not exceeded. Once in motion the dynamic friction component is enforced which will have a bearing on how easy it is to slide over a target. As yet it is unknown what effects high-friction targets have on point and click tasks using a 3DOF device.

3.4 Haptic Damping

Damping is often referred to as the resistance to movement dependent on an object's velocity. The force magnitude is proportional to that of the object's velocity but in the opposite direction to its motion. If the damping force is linearly related then it will be equal to the product of the damping coefficient and object velocity, as shown in Equation 3.4.1.

$$\begin{aligned} \mathbf{f} &= -b\mathbf{v} \qquad (3.4.1) \\ \text{Where } \mathbf{f} &= \text{is a force vector} \\ b &= \text{damping coefficient,} \\ \mathbf{v} &= \text{velocity of object (proxy),} \end{aligned}$$

As previously discussed in Subsection 2.11, it is important that the resultant force experienced by the user is stable. This is especially the case for disabled users with motion impairments as an unstable device could cause serious injury. Unfortunately, the viscous damping method described above is not sufficient as it suffers from force discontinuities with higher damping coefficients. Simulations using this model are prone to oscillate when the device velocity is around zero. These discontinuities arise due to the digital nature of the system. An exact zero velocity does not occur in discrete time because of the encoder's quantization and a discrete sampling period. According to Hayward et al. [HM07] to achieve stable control, friction modelling can be complex, particularly to account for the details of friction around velocity reversals, at very low velocity or for very small motions.

For this reason an alternative technique is often used when haptic damping is required. This technique can be considered as a damped spring where the displacement is calculated between the current position and the previous position.

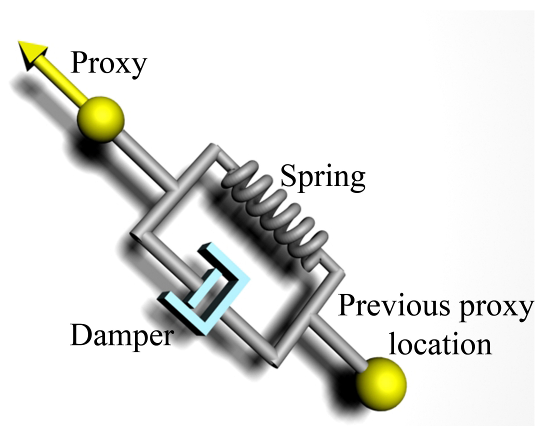

Figure 3.13: A physical representation haptic damping. A linear spring force is calculated between the current position and previous position of the proxy. The device velocity is not used in the equation but the force experienced by the operator will be dependent on velocity in terms of the distance travelled between the current position and the previous position.

Using this method it is possible to create damping that does not suffer from force discontinuities at low velocities. It will provide a significant amount of damping stiffness whilst maintaining stability. The implementation of this technique is shown in Algorithm 3.4.

Algorithm 3.4 Haptic Damping Implementation

```
displacement -= (proxyPosition - previousProxyPosition)
force = (stiffness × displacement)-(damper × proxyVelocity)
previousProxyPosition = proxyPosition
return force
```

3.4.1 Calibration Variables

The main calibration variable for haptic damping is the level of viscosity. The level of damping or viscosity will have a direct bearing on how easily the device can be manipulated. At higher damping values the device will provide a greater resistance to motion compared to lower damping values that will provide less resistance. Certain levels of damping may assist in reducing the effects of spasm or tremor. However, if the individual suffers from decreased muscle strength then this technique may not benefit them due to the increased motor workload. This will be investigated in Chapter 5.

3.5 Haptic Tunnels

A simple method of creating haptic tunnels would be to create and position a plane for each wall using the CHAI3D cMesh class. This technique would work well for individual tunnels or a network that can be manually constructed. The user could specify the points in which they want the tunnel to be positioned and the CHAI3D package would deal with the collision detection and response. Unfortunately, this technique suffers from a number of problems when automating a tunnel network from a set of coordinates. The main problem is dealing with tunnel overlap. For example, if a cluster of three buttons are configured as in Figure 3.14 then a junction is required where the two tunnels meet.

To automate this network each intersection would need to be calculated and the tunnels recreated. The software would need to know which direction the tunnel was travelling to delete the correct intersections. Tunnels that run in a diagonal direction

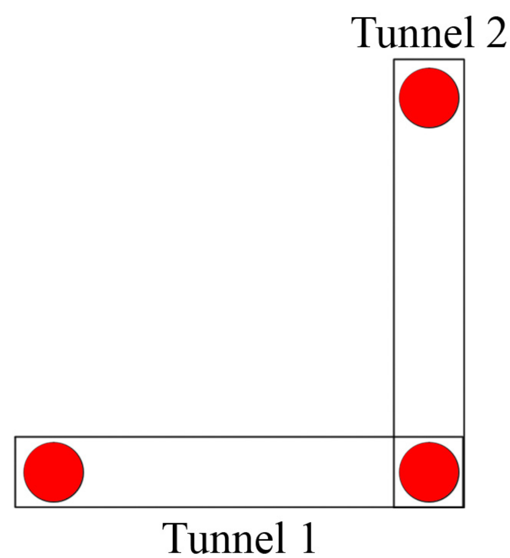

Figure 3.14: Tunnel intersection difficulties where two or more tunnels overlap and a junction is required.

would require specific intersection calculations. Further tests would need to determine where the end of the tunnel was to ensure that a plane is created to block the exits.

This thesis proposes another method for automating haptic tunnel networks that does not require intersection calculation. The technique is based on the same principles as the elliptical gravity wells where the proxy can be thought of as the centre of a ring with a wire running through the middle of it. When the ring comes in contact with the wire it cannot pass any further in that direction. Each tunnel is constructed from a line with a bounding area (tunnel width) in which the proxy cannot pass. The algorithm is again based on the point to line segment test.

The first stage in the implementation of this technique is to identify the closest tunnel to the proxy. The implementation of this is shown in Algorithm 3.5. Using this it will be possible to calculate the correct force and clamp the proxy to the tunnel wall if required. To achieve this, the difference between each line segment and the proxy is taken. The line with the smallest displacement is registered as the closest tunnel. The distance from the line segment is calculated in the same way as elliptical gravity wells. Once the closest tunnel has been established then its index can be used to calculate the restoring spring force in the same way as gravity wells.

Algorithm 3.5 Closest Tunnel to Proxy Calculation

Require: A list of the tunnels in the network - `tunnel[]`
Require: The distance of the proxy from the line segment - `pointLineSegmentDistance`

```
currentSmallest = ∞
for i = 0 to numberOfTunnels do
  if (abs(tunnel[i]->pointLineSegmentDistance < currentSmallest) then
    currentSmallest = abs(tunnel[i]->pointLineSegmentDistance)
    index = i
  end if
end for
return index
```

The final stage of the haptic tunnel technique is to clamp the proxy to the tunnel wall. This ensures that the proxy does not exceed the tunnel width if the operator tries to push out of a wall. The user will experience an opposing spring force and the proxy will remain at the edge of the wall. A representation of this is shown in Figure 3.16. The reason why manual clamping is required is because CHAI3D will only clamp the proxy to the surface of a mesh or CHAI3D object. The clamping technique shown in Algorithm 3.6 makes use of the closest point to the line segment test [Sun].

Where two or more tunnels meet there will be an overlap which creates a dead spot. The dead spot is useful because it allows the operator to navigate between different channels. The tunnel radius will determine the size of this dead spot and will have a direct bearing on the ease of navigating the desired tunnel. For example, a network of four wider tunnels as shown on the left in Figure 3.17 will initially be easier to navigate but will provide less clamping compared to the network shown on the right.

Algorithm 3.6 Proxy Clamping to Tunnel Wall Implementation. The variables correspond to those shown in Figure 3.15 and 3.16.

Require: The current closest tunnel line segment from Algorithm 3.5.
Require: The distance of the proxy from the line segment - `pointLineSegmentDistance`
Require: The line state from Algorithm 3.2 - `state`

```
if state == 1 then {the proxy lies off the P1 end of the line}
  scale = tunnelWidth / abs(pointLineSegmentDistance)
  proxyPosition = P1 + (HIP - P1) × scale)
  return proxyPosition
end if
if state == 2 then {the proxy lies off the P2 end of the line}
  scale = tunnelWidth / abs(pointLineSegmentDistance)
  proxyPosition = P2 + ((HIP - P2) × scale)
  return proxyPosition
end if
if state == 3 then {the proxy lies either side of the line between P1 and P2}
  v̄ = P2 - P1
  w̄ = HIP - P1
  closestPoint = (P1 + v̄ × ((w̄ • v̄) × (1 / v̄ • v̄)))
  proxyPosition = closestPoint + n̄ × sgn(pointLineDistance) ×
  tunnelWidth
  return proxyPosition
end if
```

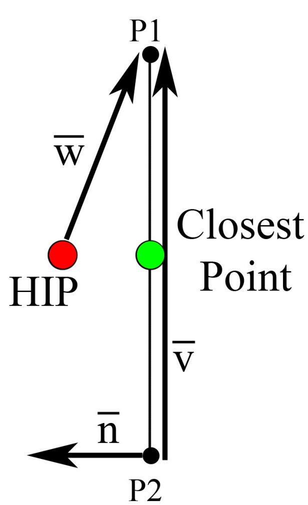

Figure 3.15: The process of clamping of the Proxy to the tunnel wall. The closest point represents the closest point on the line to the HIP.

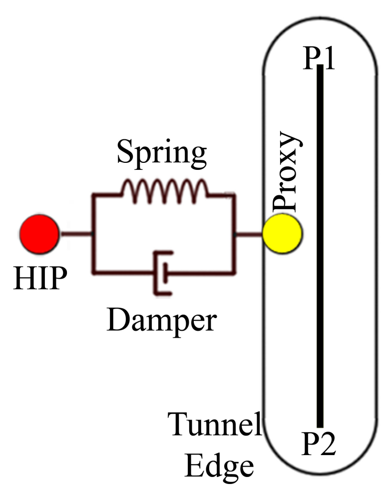

Figure 3.16: Physical representation of a haptic tunnel. The proxy is clamped to the tunnel wall and a restoring spring force is calculated to the HIP.

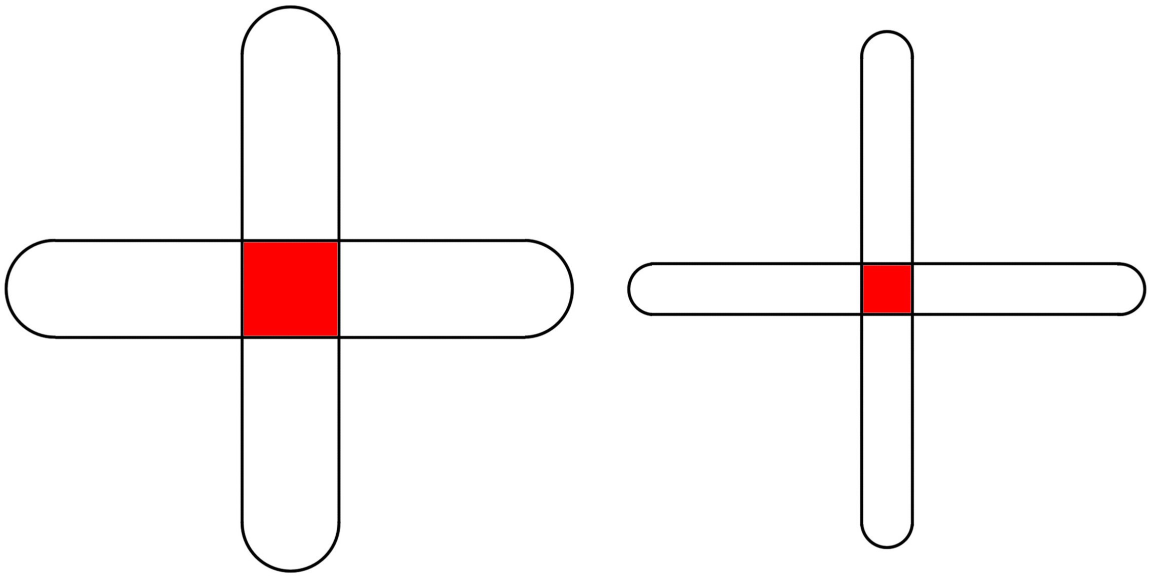

Figure 3.17: Tunnel overlap dead spot where two or more tunnels intersect at the same point.

3.5.1 Calibration Variables

The primary calibration variable of haptic tunnels is the tunnel width. This will determine the movement restriction when navigating a tunnel. Very thin tunnels may ensure a direct path but will have a greater restriction on the user. Added to this if many tunnels meet at the same point then it may be difficult to choose the correct one to navigate, especially if the dead spot is very small.

3.6 Haptic Cones

In Section 2.7 there were many concerns addressed about traditional haptic techniques. These included the imposing forces of traditional assistance and the calibration requirement to optimise interaction. To overcome these difficulties a new technique is proposed in this study based on haptic cones. This technique does not require calibration and is designed to be non-intrusive whilst still providing significant clicking stability for the operator. Each haptic cone is positioned around each target and embedded into the haptic virtual plane, as shown in Figure 3.18. The user can then fall into these cones when trying to select a target. The point of the cone is positioned at the centre of the target to assist selection. The X-Y positions of the proxy can then be projected onto the 2D plane of the GUI to give the correct position of the cursor on screen.

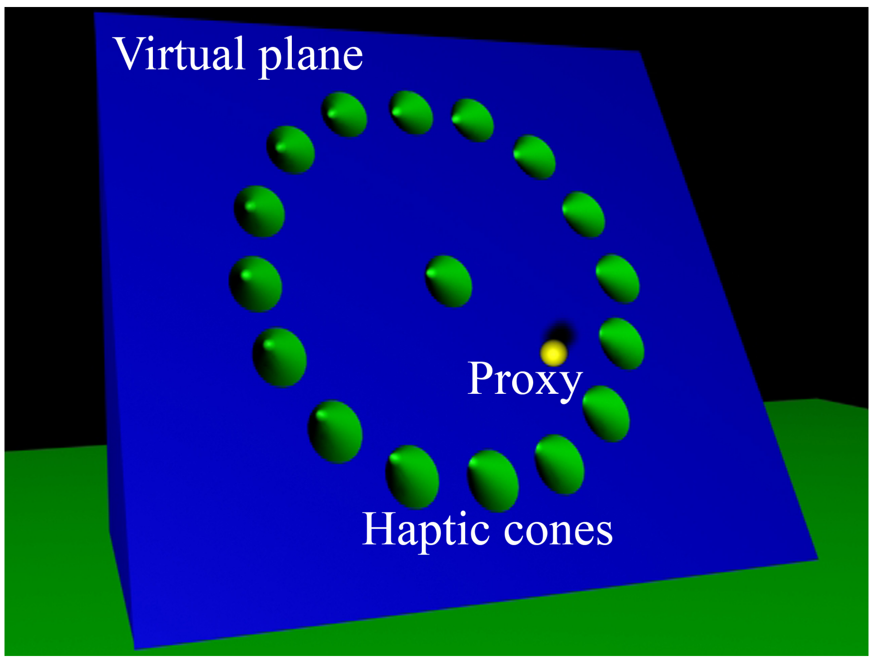

Figure 3.18: A view of haptic cones embedded into the virtual plane. The operator can lean against the plane when navigating to a target and fall into a cone to select it.

Whilst inside the cone the HIP is clamped to the apex which provides good stability for clicking. An example of this is shown in Figure 3.19 where the HIP may lie outside of the cone but the proxy remains positioned at the centre. The z-depth of the HIP is deeper than the apex of the cone.

It is believed that this technique will significantly improve the clicking measures. The reason for this is that haptic cones are non-intrusive and utilise the 3D capabilities

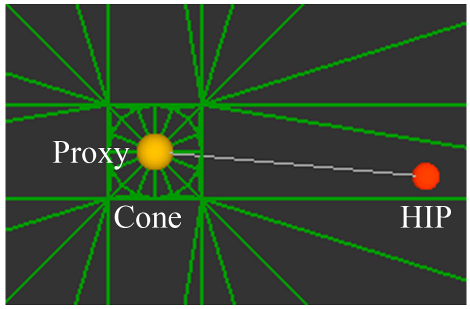

Figure 3.19: The clamping of the proxy at a cone apex with the HIP laying outside of a target region. Any unwanted movements in the x-y plane will be filtered out without any loss in fidelity.

of the device. They should be suitable for a larger range of users because unlike gravity wells there is no spring force required to exit an undesired target. For this reason it would be hugely beneficial for users with decreased muscle strength. It is also a good alternative for users with joint problems because unlike gravity wells there are not any imposing forces that could cause discomfort. The imposing force of gravity wells is the snatching effect when the proxy first enters a target region. This does not occur with haptic cones and there are other advantages such as being able to ignore the assistance off the plane if desired.

To implement this technique the cones are created by a series of triangles. For a circular cone the triangles are constructed as shown in Figure 3.20. For a pyramid shaped cone the triangles are configured as shown in Figure 3.21. The depth of the cone is equal to its diameter providing uniform dimensions. A uniform cone was chosen because a cone with a wide radius and small depth would have a low slant angle. This would mean that the proxy could easily slide off the apex and not clamp to the centre of the target very well. Alternatively a cone with a small radius and large depth would require a large device displacement in the z-axis to reach the cone apex, which would feel unnatural.

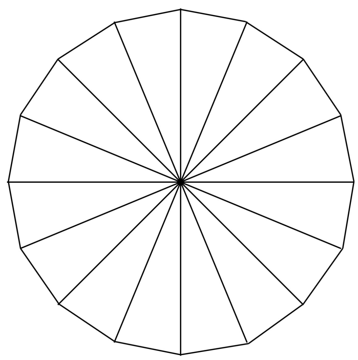

Figure 3.20: Circular shaped cone triangulation.

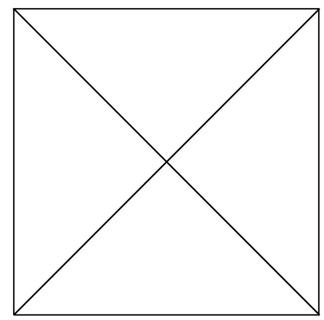

Figure 3.21: Pyramid shaped cone triangulation.

To automate the layout of the cones a triangulation technique is required to create the mesh. Delaunay triangulation [She96] is a technique often used to create a mesh from a series of data points. This technique has been used to embed the cones correctly within the haptic virtual plane, as shown in Figure 3.22. This Delaunay implementation is based on a 2D technique to position each vertex correctly in the XY plane. The Z component is finally added to give the correct depth of the backboard and each cone apex. Haptic devices sometimes have problems with small points such as those observed at the cone apex. This is not an issue in the implementation of haptic cones due to the CHAI3D implementation of Zilles and Salisbury's God-object algorithm [ZS95].

The haptic cone technique also has many benefits that gravity wells do not have. One of these is that once a gravity well has been clicked it will not reinitialise again until the well has been exited. If the task requires a double click then on the second click there will not be any assistance provided by the well. Cones do not suffer from this shortcoming. Additionally, if a drag and drop operation is required when using a gravity well then the user will have to oppose the spring force to exit it. This is because the well will only disable once a click and release has been completed. When using a cone the operator can simply exit a cone in the z-axis and drag the object to

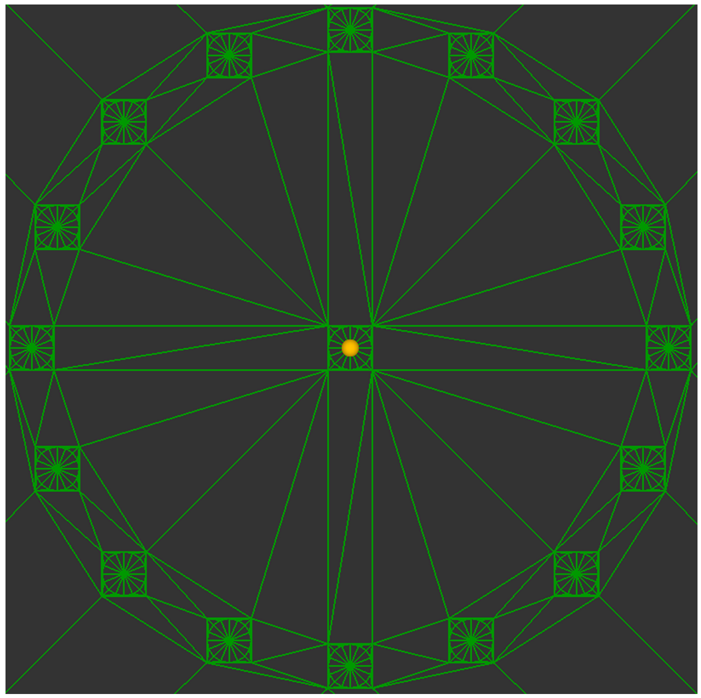

Figure 3.22: The Delaunay triangulation of multiple, circular shaped, haptic cones.

the desired destination.

3.6.1 Calibration Variables

One of the main advantages of this technique is that it does not impose a force on the operator and as a result does not require any calibration. If successful this technique should be able to assist a greater number of users. All that is required to implement the technique is the position and radius of each target. This means that if the user understands the concept of using the technique then they can use the assistance immediately.

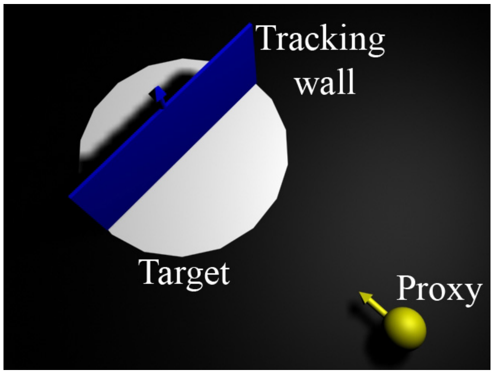

Figure 3.23: As the cursor approaches the target the haptic wall orientates its face towards the location of the proxy.

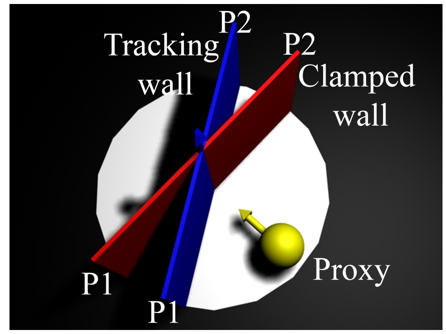

Figure 3.24: The haptic wall orientation clamps once the proxy has entered the target.

3.7 Haptic Wall

A new non-calibrating technique proposed in this thesis is a haptic wall. The aim of this technique is to create a wall through a target in which the proxy cannot easily pass. This will attempt to assist users who have diffculties with overshooting a target. It may also be useful in the clicking phase as the user can lean against the wall for additional stability.

The implementation of this technique is based on orienting two walls in relation to the proxy. The first wall is rotated so that its face is always facing towards the proxy. In effect the plane normal points to the exact opposite direction of the proxy velocity vector (maximum negative dot product). The second wall operates in the same way apart from its orientation is clamped once the target is first entered. The assumption here is that the user will continue moving in the same direction once the target has been entered. Figure 3.23 shows the single wall just before the target is entered. Figure 3.24 shows the clamped second wall once the target region has been entered.

The main benefit of this technique is that it does not impose a force on the operator. The only force experienced is the restoring spring force of the wall which is governed by how hard the operator pushes against it. Once the target is entered the wall orientation is clamped at its centre. The user can simply exit the target in the opposite direction to which they entered it and continue interaction. The second wall is used as the reference to calculate the restoring forces, as shown in Algorithm 3.7.

Algorithm 3.7 Haptic Wall Implementation

Require: a line segment for the tracking wall `trackingWall`.
Require: a line segment for the clamped wall `clampedWall`.

```
rotation = (atan2(proxyY - wallY,proxyX - wallX))
trackingWall->P1.set(-wallWidth*sin(rotate)+wallX,width*cos(rotate)+wallY)
trackingWall->P2.set(wallWidth*sin(rotate)+wallX,-width*cos(rotate)+wallY)
trackingWall->setNormal()
if (pointLineDistance > wallWidth) then
  clampedWall->set(trackLine->P1,trackLine->P2)
end if
if ((clampedWall->pointLineSegmentDistance < 0) && (clampedWall->state ==
3)) then
  force = (-stiffness × clampedWall->pointLineDistance ×
  clampedWall->normal)+(-damper × proxyVelocity)
else
  force = 0
end if
return force
```

3.7.1 Calibration Variables

The main benefit of this technique is that there are no calibration variables. As a result this technique should be suitable for a large number of users if overshoot is a problem. The wall should be useful in reducing target overshoot and will give the operator another surface to lean against when clicking.

3.8 Summary

Chapter 3 has covered the design and implementation of haptic assistance. The two traditional haptic techniques that are designed to aid target acquisition are gravity wells and high-friction targets. Two new target acquisition techniques are proposed which includes haptic cones and haptic walls. Haptic damping and haptic tunnels were the two traditional techniques that have been implemented to aid target homing. The key calibration variables have been identified for each technique that may require tuning to optimise interaction. The following chapter investigates cursor analysis techniques that are used in the evaluation of pointing device operations. A number of new techniques are also proposed that are designed to capture the benefits of the haptic assistance.

Chapter 4

Cursor Analysis Techniques

To be able to select and calibrate a suitable level of assistance it is first necessary to identify areas in which a user may have weakness. It is also important to determine what effect varying the level of assistance has on each technique. To achieve this a series of cursor analysis techniques are required to give a measure of performance. The techniques discussed in this section will cover the analysis of both target homing and target selection in a point and click task. It will be important to determine which measures will be most useful in analysing each type of assistance.

4.1 Fitts' Law

Fitts' law is often used as the model for cursor movement in HCI. The movement time (MT) of a task can be predicted using the target width (W) and target distance (A) (or amplitude). The index of difficulty (ID) is calculated as the logarithm of the ratio of target distance (A) to target width (W) and is linearly related to the MT. The empirical constants a and b are found using a regression analysis on the movement time data. a represents the start/stop time of the device and b represents the inherent speed of the device.

$MT = (a + b)ID$

where

$ID = \log((A/W) + 1)$

Fitts' law is also used to give a measure of the trade off between the time taken to select a target and accuracy. This is known as throughput (TP) and is measured in bits/sec. The numerator is the "effective index of difficulty" and includes Ae as the distance or amplitude of movements.

$$TP = \frac{\log(\frac{Ae}{4.133 \times SDx} + 1)}{MT}$$

where

$SDx =$ is the measure of accuracy.

$Ae =$ is the distance or amplitude of movements.

Using the Fitts' Law equation it is possible to conclude that closer targets can be acquired faster than more distant ones. It also shows that it is faster to acquire larger targets compared to smaller ones. More detailed information on how throughput is calculated can be found in [MKS01]. The Phantom Omni may be used in three-dimensions but the task will still require target acquisition in the two-dimensional X-Y plane of the GUI.

How does Fitts' law apply to haptic assistive techniques? As previously stated Fitts' law will give a measure of the trade off between speed and accuracy. As a result the assistive technique must aid in either or both aspects without significantly hampering the other. The level of assistance required to achieve the greatest accuracy and throughput may alter depending on each user. It is for this reason the software must be flexible to accommodate the needs of the individual.

4.2 Mackenzie's Cursor Measures

Although Fitts' law indicates that differences exist in movement time and accuracy, it does not give an explanation as to why these exist. If it is possible to understand the reasons why difficulties arise it should be possible to produce better solutions. Research indicates that a series of measures produced by MacKenzie et al. [MKS01] are often used in the cursor analysis of pointing devices. To ensure that these techniques are relevant in analysing the performance of disabled computer users further studies have been taken [WG07][WFL09][KHL+02]. Other studies from Mauri et al. [MG07] use these cursor techniques specifically to analyse the performance of people with cerebral palsy. The measures proposed by Mackenzie are also very similar to those used in the cursor analysis designed for disabled people using the Compass software [KLA+03] described in Subsection 2.10.

4.2.1 Target Re-Entry (TRE)

If the cursor enters the target region, leaves, then re-enters the same region, then a target re-entry is registered. This measure is recorded as a frequency of the number of re-entries.

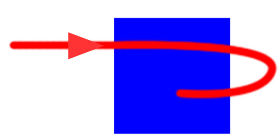

Figure 4.1: The cursor path re-entering a target region. The red line represents the path of the cursor and the blue square represents the target.

Collision detection is performed on a bounding volume to capture a target re-entry. If the test determines that the proxy has entered the bounding volume more than once then a TRE variable is incremented. A Boolean value is triggered on entry to ensure that only a single TRE is registered whilst the proxy lies inside the target.

4.2.2 Task Axis Crossing (TAC)

The task axis is defined as a straight line from the starting position to the target. If the cursor crosses this axis then a task axis crossing is registered.

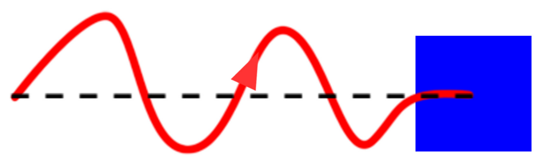

Figure 4.2: The cursor path crossing the task axis when navigating towards a target. The red line represents the path of the cursor and the blue square represents the target. The dotted black line is the task axis.

To determine if the task axis is crossed it is necessary to create an axis between the starting position (p1) and the target (p2). The point to line test can then be used to give the perpendicular distance of the proxy to the task axis line. A positive or negative distance will be returned depending on which side of the line the proxy is positioned. If the sign of the test changes then the task axis has been crossed and this is registered.

4.2.3 Movement Direction Change (MDC)

If the cursor's path relative to the task axis changes direction then a movement direction change is registered. This is recorded when the tangent of the cursor path is parallel to the task axis.

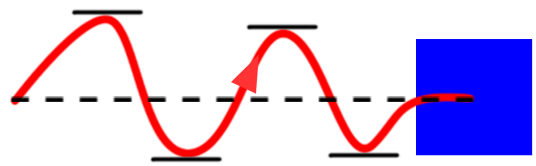

Figure 4.3: Movement direction changes when navigating towards a target. The red line represents the path of the cursor and the blue square represents the target. The solid black lines identify where a MDC has occurred.

4.2.4 Orthogonal Direction Change (ODC)

An orthogonal direction change is registered when the tangent to the cursor path is perpendicular to the task axis.

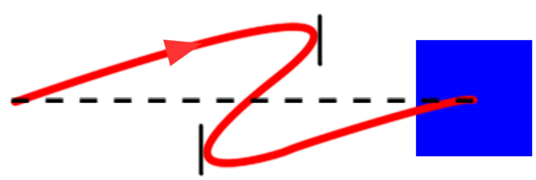

Figure 4.4: Orthogonal direction changes when navigating towards a target. The red line represents the path of the cursor and the blue square represents the target. The solid black lines identify where an ODC has occurred.

4.2.5 Movement Variability (MV)

Movement variability gives a measure as to the extent in which the points recorded lie in a straight line along an axis parallel to the task axis.

4.2.6 Movement Error (ME)

The Movement error is defined as the mean absolute displacement of the cursor to the task axis. It is irrespective of the points location in relation to the axis line.

4.2.7 Movement Offset (MO)

Movement offset gives a mean displacement of sample points to the task axis. It is used to capture the tendency of the pointer to veer left or right of the task axis during a movement.

4.3 Commonly used Cursor Measures

4.3.1 Missed-Click

The missed-click measure is recorded if a click or release (or both) lie outside of a target region. Although the haptic techniques are designed to reduce this measure there may be occasions where the operator may still miss the target region. The measure will be used to determine if certain techniques are better at reducing the number of missed-click errors.

Figure 4.5: A missed-click is recorded when the operator clicks and/or releases outside of a target region.

4.3.2 Overshoot

Overshoot is a measure of how far the cursor passes through a target region before re-entering. This is shown as the distance between the two crosses in Figure 4.6.

Figure 4.6: A cursor overshoot through a target region. The magnitude of the overshoot measure is recorded as the distance between the two green crosses.

4.4 New Cursor Measures

Mackenzie's Cursor Measures are useful in analysing how the device is used but provide little information on the operators' characteristics. Langdon et al. [LHK+02b] suggest that the majority of difficulties in performing point and click tasks often lie primarily in the clicking phase rather than in navigating to the target. The missed-click measure alone is not very useful in analysing what effects haptic assistance has on targeting. For example, if a person miss-clicks without entering a gravity well then it would be unfair to mark this against the technique as it has not been given a chance to assist. The missed-click measure also does not provide any indication as to why a missed-click has occurred. It would not be adequate to say that just because someone is prone to miss-clicking that gravity wells will certainly help them.

To select an icon in a Microsoft application it is necessary to click and release inside that icon for the process to register and execute. The previous studies discussed in this thesis do not provide any evidence that this has been taken into consideration. If someone is prone to miss-click on click or on release then why not adjust the clicking events so that a full clicking phase is registered on the successful stage? For example, if someone clicks accurately then fire both the click and release events. The reason for this is that it would be impossible to drag and drop items because both the down and up events would be fired sequentially. Given this and the fact that Mackenzie's cursor measures provide very little information on the clicking phase, a series of additional measures have been proposed in this thesis that attempt to record why missed-clicks occur and determine if haptic assistance will aid in these areas.

4.4.1 Missed-Click on Click

A missed-click on click is recorded if the user clicks outside of the target but releases inside it accurately.

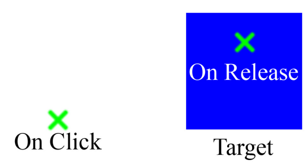

Figure 4.7: A missed-click on click is recorded when the operator clicks outside of a target region but releases accurately.

This measure will be useful in identifying individuals that have difficulty in maintaining stability when muscles contract on the button press but are able to release accurately.

4.4.2 Missed-Click on Release

A missed-click on release is recorded if the user clicks inside the target but releases outside of it.

Figure 4.8: A missed-click on release is recorded when an operator clicks accurately but releases outside of the target region.

This measure will be useful in identifying users that have difficulties in maintaining stability between the click and release.

4.4.3 Click-Release Distance Travelled

The click-release distance travelled technique gives a measure of the distance the proxy has travelled between the click and its release.

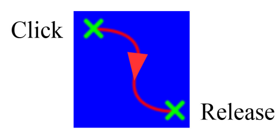

Figure 4.9: The click-release distance travelled gives a measure of the distance the cursor has travelled between the click and its release.

This measure will be useful in determining how stable a person is during the clicking phase. For example, if an individual moves a large distance during clicking then it is unlikely they will be able to select a target accurately. If that individual has a tendency to miss-click on click (or release) this measure will give an indication why this is the case.

4.4.4 Click-Release Displacement

The click-release displacement measure gives the absolute displacement between where the click begins and where it ends.

When introducing haptic assistance it is possible for artefacts to be introduced into the analysis. This could be the case for the click-release distance travelled measure when used with stiffer gravity wells. The reason for this is that the well may pull the user towards the centre of the target but the momentum may cause a slight overshoot inside the well. This can result in a slight oscillation until the damping has taken

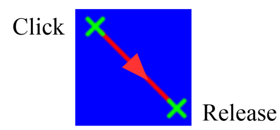

Figure 4.10: The click-release displacement gives a measure of the absolute displacement between the click and its release.

full effect. This will produce an increase in the click-release distance travelled. As a result the absolute distance between the click and release is taken as an additional measure.

The size of the target will have a bearing on the effect of this measure. For example, if a user has a click-release displacement of 1mm and the target width is 7mm, then they are less likely to miss-click compared to someone that has a click-release displacement of 5mm for the same sized target. An example of this is shown in Figure 4.11. All measures are given in device displacement.

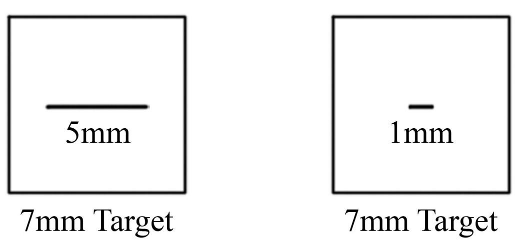

Figure 4.11: The bearing click-release displacement has on the selection of a target. If an operator has difficulty in maintaining stability then they are much more likely to miss-click.

It should be noted that later in the study (Section 6.1) it was shown that operators with a low click-release displacement and low click-release distance travelled were much less likely to miss-click a target with a 7mm diameter. A strong linear relationship was found between the click-release measures and the number of missed-clicks. Therefore if a haptic assistive technique significantly reduces these measures it should also help in reducing the number of missed-clicks.

4.4.5 Pre-Click Distance Travelled

Some users experience difficulties just before clicking and so a measure of the distance travelled one second before a click begins will be taken. The homing phase of target acquisition is expected to be a smaller controlled movement and so it would be expected that the distance travelled in this phase would be lower. It could be expected that individuals with a higher distance travelled in this predefined time before clicking may find target selection more difficult.

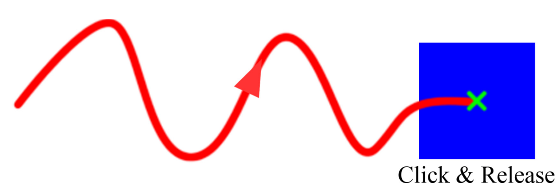

Figure 4.12: The pre-click distance travelled provides a measure of the distance travelled by the cursor in a given time period before the click begins.

4.5 Result Recording

The results will be recorded to a .txt document and delimited to provide easy conversion into Microsoft Excel for further analysis. The stream class `fstream` is used in C++ to perform read and write file operations. The `ofstream` type is used to write file operations and an example of this is given in the following code snippet.

```
#include<iostream>
#include<fstream>
using namespace std;
```

```
int totalMeasures;                  // Total number of cursor measures
String measureName[totalMeasures]; // Each cursor measure name
float measure[totalMeasures];      // Each cursor measure value

int main
{
   ofstream outFile("output.txt");    // Creates an ofstream called outFile
   for(int i = 0; i < totalMeasures; i++) // Loop through each cursor measure
 {
   outFile<<measureName#<<" "<<measure[i]<<endl; // Write delimited result to txt
 }
outFile.close();      // Close ofstream outFile
}
```

The output file can then be opened in Microsoft Excel with the correct delimiter inserted as shown in Figure 4.13. The resulting output in the Excel spreadsheet is shown in Figure 4.14.

Figure 4.13: How to open a .txt file containing cursor results in Microsoft Excel. The correct delimiter is then inserted to separate the data into cells.

	A	B
1	unassisted	1
2	missed clicks	0
3	missed clicks on click	0
4	missed clicks on release	0
5	target re-entry	2

Figure 4.14: The delimited result of the cursor results in a Microsoft Excel spreadsheet.

4.6 Summary

The cursor analysis techniques discussed in this chapter are designed to identify errors within the target homing and target acquisition phases. Fitts' Law will be useful in determining if certain haptic techniques affect the difficulty of the task or the time taken to complete it. Mackenzie's cursor measures provide useful information on the homing phase and have proven useful in previous studies for analysing motion-impaired operators. The new cursor measures discussed in this chapter are designed to provide more useful information on a person's clicking characteristics. The following chapter investigates the effect that each type and level of assistance has on these cursor measures.

Chapter 5

Experiments - Analysis of Haptic Techniques

5.1 Preparation

The aim of this chapter is to use cursor analysis on the haptic techniques discussed earlier to help identify areas of improvement provided by each technique and determine the effects of the level of assistance. This is crucial in selecting and calibrating the correct type of assistance for the individual. When conducting an experiment it is necessary to ensure that the correct preparation has been made before implementation. To ensure that the results produced from the experiment were not impaired due to unfamiliarity of using the Phantom Omni, a group of ten members of the NANSA day centre were exposed to twelve, two hour, practice sessions. The tasks included were designed to be engaging such as a virtual Xylophone, 3D object exploration, 2D/3D breakout, clay-pigeon shooting, colour pairing, haptic basketball and haptic archery. In these sessions each person was also exposed to the haptic assistive techniques previously discussed. By practising the use of these techniques it ensured that each individual was familiar with each type of feedback. Visual representations of each technique were shown to the group to help demonstrate how they are designed to assist. A visual representation will not be possible in existing interfaces and so this will not be displayed in the experiments.

5.1.1 Device comfort - Haptic Virtual Plane

When operating a pointing device it must be comfortable to use for long periods of time. The operator's comfort is essential for disabled users with motion impairments. The Phantom Omni has an ergonomically moulded-rubber stylus and a wrist / elbow rest, for long term use, to maximize user comfort. Even with these measures in place some participants commented that some tasks caused arm ache due to not having a surface to lean the stylus against. A response to this problem was to introduce a haptic virtual plane in which users are able to lean against, providing additional support. This technique is especially useful when working at the upper extremities of the Y axis of the workspace (where the wrist rest has less effect) as the user can rest their elbow on the desk and lean against the plane.

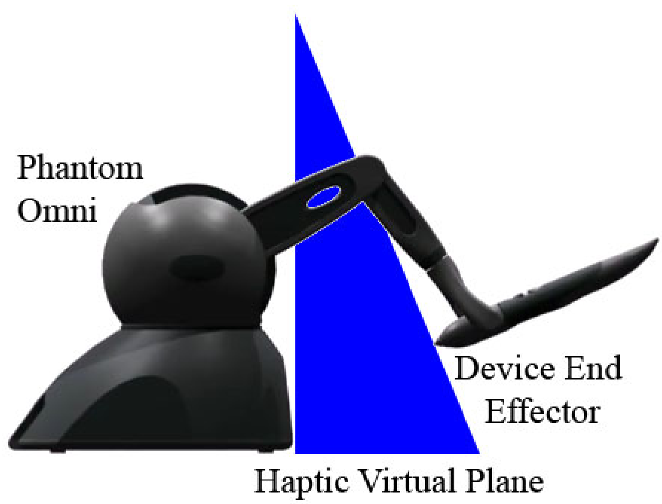

Figure 5.1: The concept of a haptic virtual plane. The operator will experience leaning against a surface when the proxy comes in contact with the virtual plane.

A vertical plane was not chosen because it would not allow a comfortable leaning position and the proxy would slide up and down it too easily. A diagonal plane helps reduce the effect of gravity on the users arm. A subwindow was also created to display a side view of the interaction. This will then give the user a visual representation of the depth of the haptic virtual plane and help them understand the concept of it.

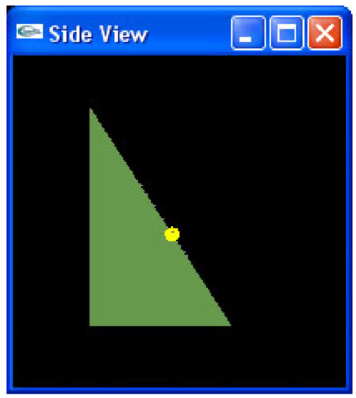

Figure 5.2: Side view interaction of the proxy with the haptic virtual plane. The operator can get a feel for the depth of the plane in the z-axis.

5.2 Procedure / Method

The experiment suggested by Mackenzie et al. to be conducted with the cursor analysis techniques is based on the ISO 9241-9 standard for pointing device evaluation [PDE98]. The experiment consists of sixteen circular targets arranged in a circular layout around a centre target, as shown in Figure 5.3. The task requires the user to click on the red highlighted target circle which is selected at random by the software. Data collection begins once the first target is selected. Each experiment stage requires fifteen successful selections. The operator will be asked to perform this task unassisted and then repeat it with haptic assistance enabled. Data collection was continuous between the unassisted experiment and the haptic experiments that followed.

For each of the haptic experiments that requires calibration the task was performed

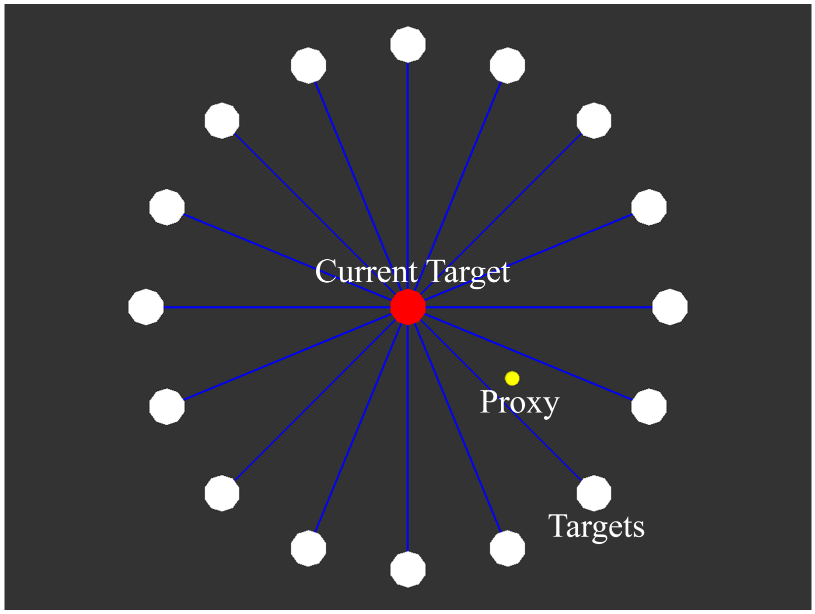

Figure 5.3: ISO 9241-9 based experiment layout. The red circle represents the current target and will move randomly to another location once selected.

under eleven different conditions. The first condition was unassisted and the next ten assisted experiments ranged equally to the upper stable limit. Any areas of correlation found in the cursor analysis techniques may be useful in the calibration of that assistance. Before each experiment was undertaken an explanation of the task and the type of assistance was given to the participants. Each operator was asked to perform the task as quickly and as accurately as possible to determine if Fitts' law holds true. It was also decided that the successful click operations would be recorded for pre-click distance travelled, click-release distance travelled and click-release displacement. The reason this is required is because it would not be possible to capture the effects of click assisted techniques if the person does not enter a target assisted region. Each experiment was observed by an assistant to ensure that it was completed without any complications. For each cursor measure discussed in Chapter 4 (apart from throughput) a reduction in their magnitude is desirable and will signify an improvement.

5.2.1 The Users

Seven users took part in the data collection, four of which were male and the other three female. The participants were all adults in an age range of 35-58. Each session was two hours in length and as many experiments were undertaken in that time as possible. A brief summary of the participants background has been produced in Table 5.1. Please note that as a result of patient confidentiality, access to medical records and assessments was not permitted.

5.3 Experiment Aims

The key aims of each haptic experiment are listed as follows:

- Confirm that performance will alter depending on the level of assistance.
- Determine if the level of assistance is dependent on the individual.
- Identify the cursor measures most improved by each level of assistance.
- Determine if there are any significant detrimental effects of each assistance.
- Identify areas of correlation between assistance and cursor measures.
- Ascertain the usable range of each type of assistance.
- Determine if techniques designed to assist in similar areas significantly improve more than one measure.
- Determine if techniques designed to assist in similar areas have different performance levels.

Participant	Gender	Age	Disability	Details
1	Female	35	Cerebral Palsy	Can walk unaided. Has speech difficulties and communicates through a communication aid. Principal impairment is tremor which makes finer movements difficult. Experienced mouse user.
2	Male	49	Cerebral Palsy	Can walk unaided. Has poor co-ordination and as a result finds it difficult to perform finer motor control. Experienced mouse and trackball user.
3	Male	38	Cerebral Palsy	Can walk unaided. Has good motor control and co-ordination. Difficulties can occur when trying to maintain the cursor on the target for selection. Experienced mouse user.
4	Female	49	Spina Bifida	Is an electric wheelchair user. Has very good fine motor control but often takes a long time to complete the task. Experienced mouse user.
5	Male	58	Cerebral Palsy	Is an electric wheelchair user. Principle impairments are muscle stiffness, spasm and co-ordination difficulties. Difficulties are often encountered when trying to locate the device switch. Experienced mouse user.
6	Female	52	Cerebral Palsy	Is a manual wheelchair user. Movements can be quite slow but are well controlled. As a result error rates are low but the task can take longer to complete. Experienced mouse user.
7	Male	38	Syringomyelia, Apert Syndrome	Can walk using a walking frame. Large movements are often fast and uncontrolled due to stiffness around the joints. Finer movements appear to be easier to perform. Experienced mouse user.

Table 5.1: A brief summary of the background of the participants within the study.

The ability of an motion-impaired operator can vary significantly on a weekly basis between analysis. As a result the unassisted experiment will be repeated for each type of assistance. This will later be used to give a performance comparison between techniques to show the improvement of each technique over an unassisted interface.

In the results section for each experiment the key measures that are designed to capture the effects of that assistance will be taken. If other results from the experiment show additional information that requires inclusion then this will also be addressed. For example, it would be unnecessary to perform a detailed analysis of a homing measure for a click assisted task unless that measure is significantly affected.

5.4 Experiment 1 - Gravity Well Stiffness

The first haptic experiment was to determine the effect of gravity well spring stiffness on the performance of the point and click task described above. The group at NANSA were asked to perform the experiment after an initial practice session to familiarise themselves with the task. The task was repeated under eleven different conditions. The first condition was unaided and the next ten ranged in spring stiffness up to the maximum stable limit. Sixteen successful selections were performed for each condition and data analysis began after the first selection.

The target acquisition measures will be the main concentration in the analysis of gravity wells as they are designed to assist in this area. One of the main advantages of using gravity wells is that very little understanding of the technique is required by the operator for them to assist successfully.

5.4.1 Results

Successful Click-Release Displacement

It would be expected that the click-release displacement measure should be directly improved by the introduction of gravity wells. The reason for this is because gravity wells are designed to stabilise the user whilst clicking and releasing.

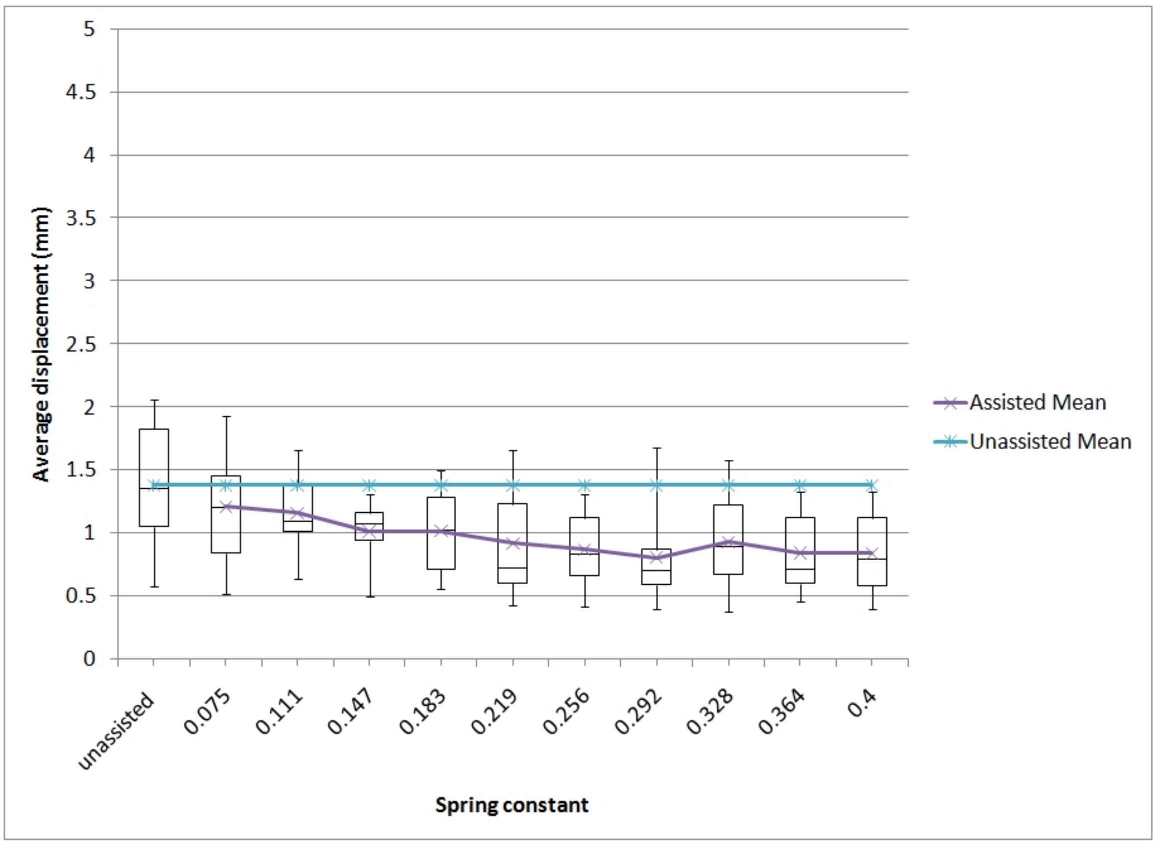

Figure 5.4: The average successful click-release displacement of seven motion impaired operators over fifteen successful selections is plotted against the varying spring stiffness of gravity wells.

The results from Figure 5.4 indicate that there is a strong negative correlation between spring stiffness and click-release displacement. Pearson product-moment correlation coefficient (PPMCC) is often used to give a measure of the strength of a linear relationship. The result of the PPMCC measure between average click-release displacement and spring stiffness was -0.885. This confirms a strong negative correlation between the two variables. This would be expected because as the spring stiffness increases there will be a greater clamping effect at the centre of the target which will produce a small displacement between click and release. All levels of gravity well stiffness have shown to give an improvement in click-release displacement on average compared to the average result in the unassisted experiment.

Successful Click-Release Distance Travelled

It would be expected that if the click-release displacement shows strong correlation that the click-release distance travelled would also show correlation. However, this is not represented in the results shown in Figure 5.5. Up until a stiffness of 0.219 there is a decrease in the distance travelled but after this it begins to increase.

The reason for this increase is likely to be due to artefacts introduced by the nature of gravity wells. As the spring stiffness is increased the stronger attractive force causes a slight overshoot inside the well due to the momentum of the device. This may result in a slight oscillation inside the well until the damping takes full effect. The click and release may be in close proximity of each other as the force pulls the cursor tightly towards the target centre but the oscillation will increase the distance travelled by the cursor. An example of this is shown in Figure 5.6 with a strong spring stiffness of 0.4.

Missed-Click on Release

An increase in the spring stiffness should reduce the number of missed-clicks on release because the stronger attractive force will clamp the cursor within the well. Although the results of Figure 5.7 do not show any correlation it is apparent that missed-clicks on release are significantly reduced when gravity wells are enabled. This is credited to

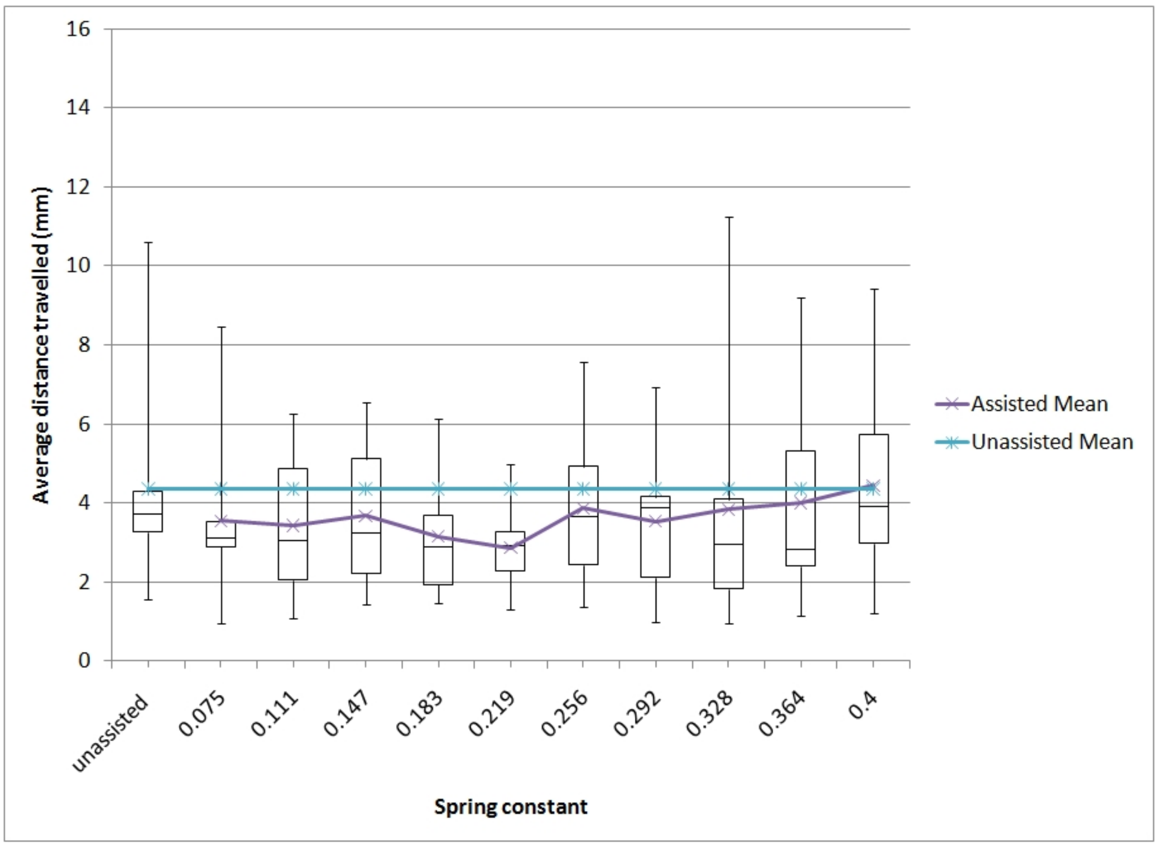

Figure 5.5: The average successful click-release distance travelled of seven motion impaired operators over fifteen successful selections is plotted against the varying spring stiffness of gravity wells.

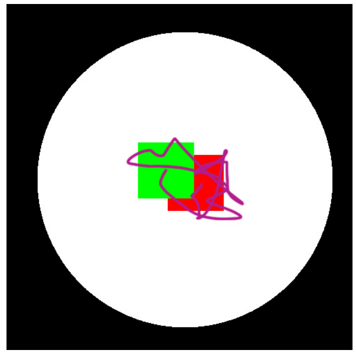

Figure 5.6: The spring force of gravity wells can cause a small oscillation that will result in artefacts in the cursor analysis. The green square represents the position on click and the red square represents the position on release. The purple line shows the distance travelled in between.

the fact that the well has already been entered and so a clamping force is attracting the proxy to the target centre. For each gravity well stiffness the average number of missed-clicks on release is below that of the unassisted average. For some stiffness levels the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph. For other stiffness levels only one operator performed a missed-click on release and as a result only the maximum whisker is visible.

Missed-Click on Click

It would be expected that the number of missed-clicks on click would be reduced by the effect of gravity wells. The reason for this would be that once the well has been entered it will clamp the proxy within the target. However, a gravity well can only take effect if the target region has been entered. If the operator miss-clicks on click without entering the target region then the well will not have been given an opportunity to assist. It is unsurprising that there is not any correlation shown in the results of Figure 5.8. The missed-click on click measure may not be useful in the

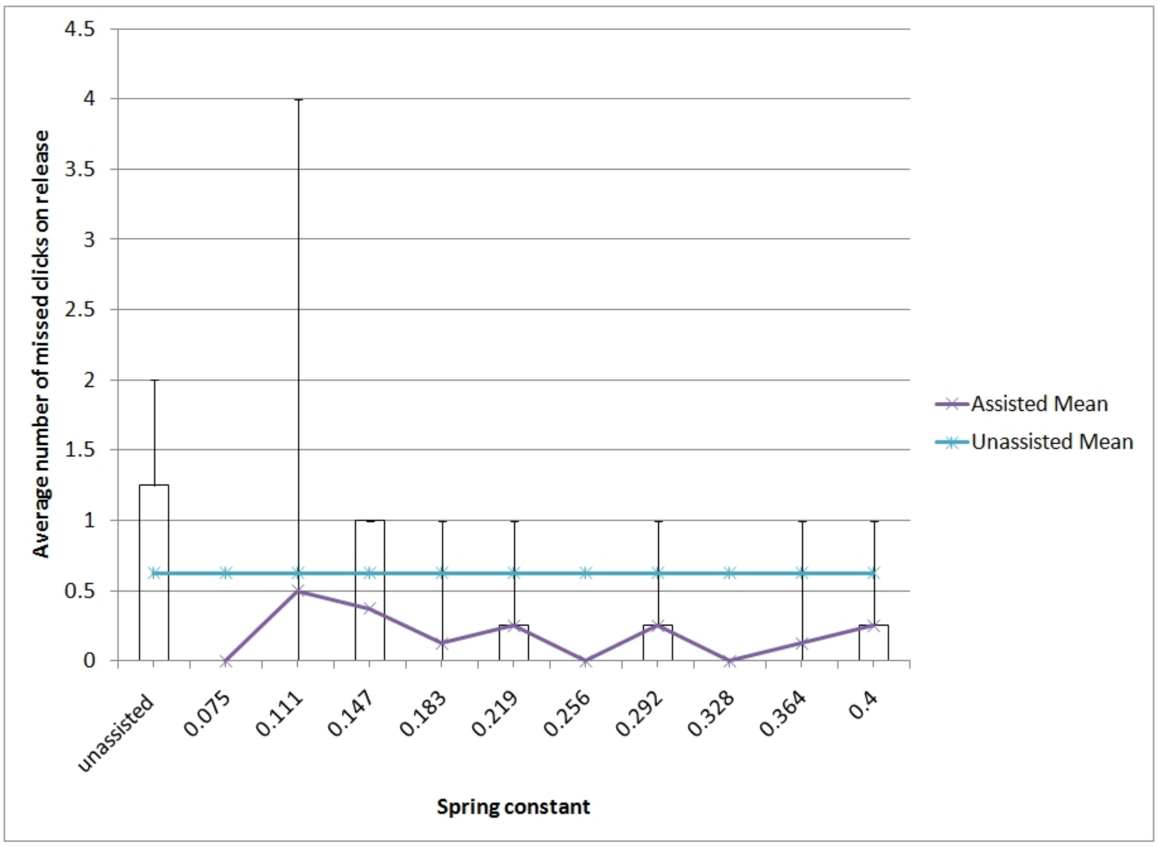

Figure 5.7: The average number of missed-clicks on release of seven motion impaired operators over fifteen successful selections is plotted against the varying spring stiffness of gravity wells.

calibration stage but is useful in showing a reduction in errors. It is clear from the results that the average missed-click on click is the same or reduced for all but one stiffness level when compared to the unassisted measure. For some stiffness levels the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph. For other stiffness levels only one operator performed a missed-click on click and as a result only the maximum whisker is visible.

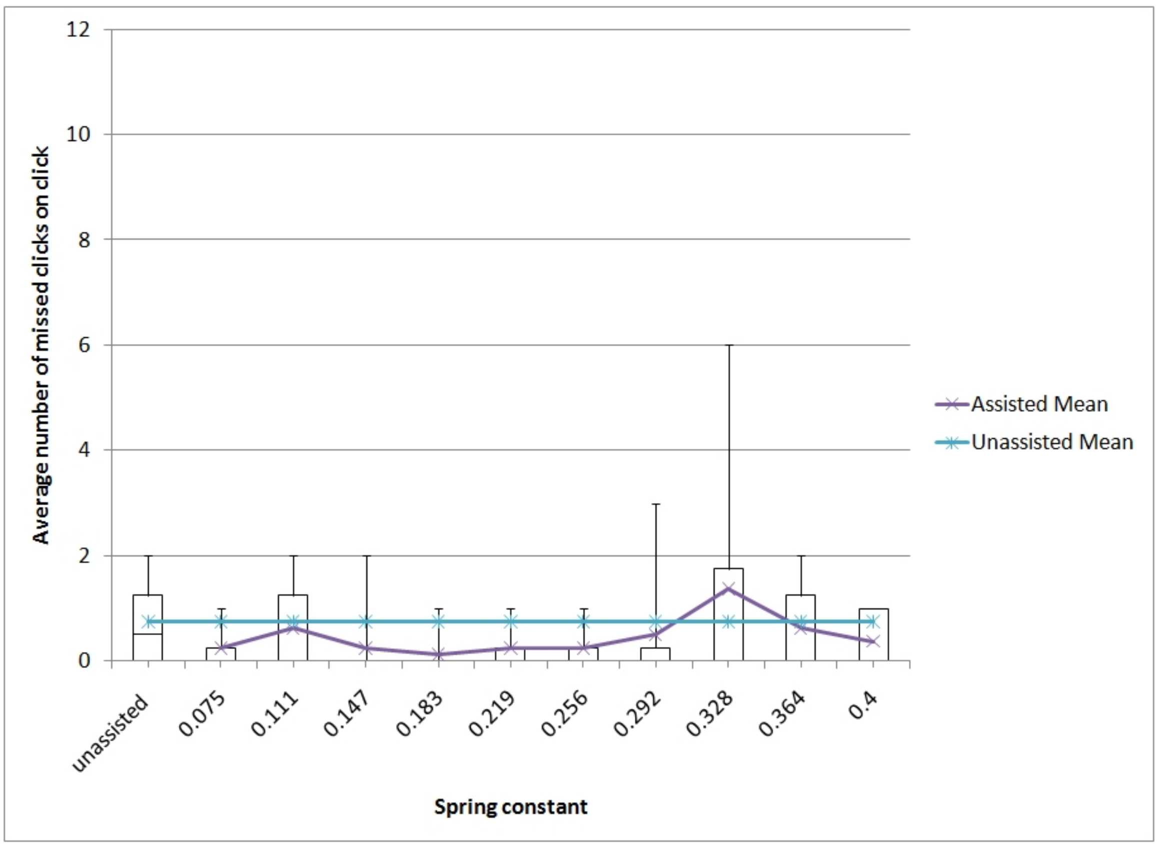

Figure 5.8: The average number of missed-clicks on click of seven motion impaired operators over fifteen successful selections is plotted against the varying spring stiffness of gravity wells.

Overshoot

There does not appear to be a correlation between spring stiffness and overshoot but the effects of gravity wells do seem to significantly reduce this measure, as shown in Figure 5.9. The reason for this is likely to be due to the braking effect of the spring force. The tail off as the spring stiffness reaches its upper levels could be caused by the increase in momentum of the device. This may result in a slight overshoot out the other side of the well. For each stiffness level the average overshoot measure is significantly below the unassisted average. For some stiffness levels the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph.

Throughput

Fitts' law can be used to give a measure of the trade off between speed and accuracy. Gravity wells are designed to assist the accuracy measures and so it is important that the speed component is not adversely affected. If this was the case then the overall benefits of the assistance may not outweigh the negatives. The results from Figure 5.10 are promising as it shows that the average throughput for each stiffness level is above the unassisted level. The reason for this increase is that gravity wells increase the effective width of the target [HKLC05] and so the user can flick between targets more easily than when unassisted.

5.4.2 Conclusions

The results from the experiment confirm that the spring stiffness of gravity wells can have a significant impact on the performance of point and click tasks. There was no single spring stiffness that had a significant improvement across all key measures for each user. All of the measures discussed have shown improvement when gravity wells

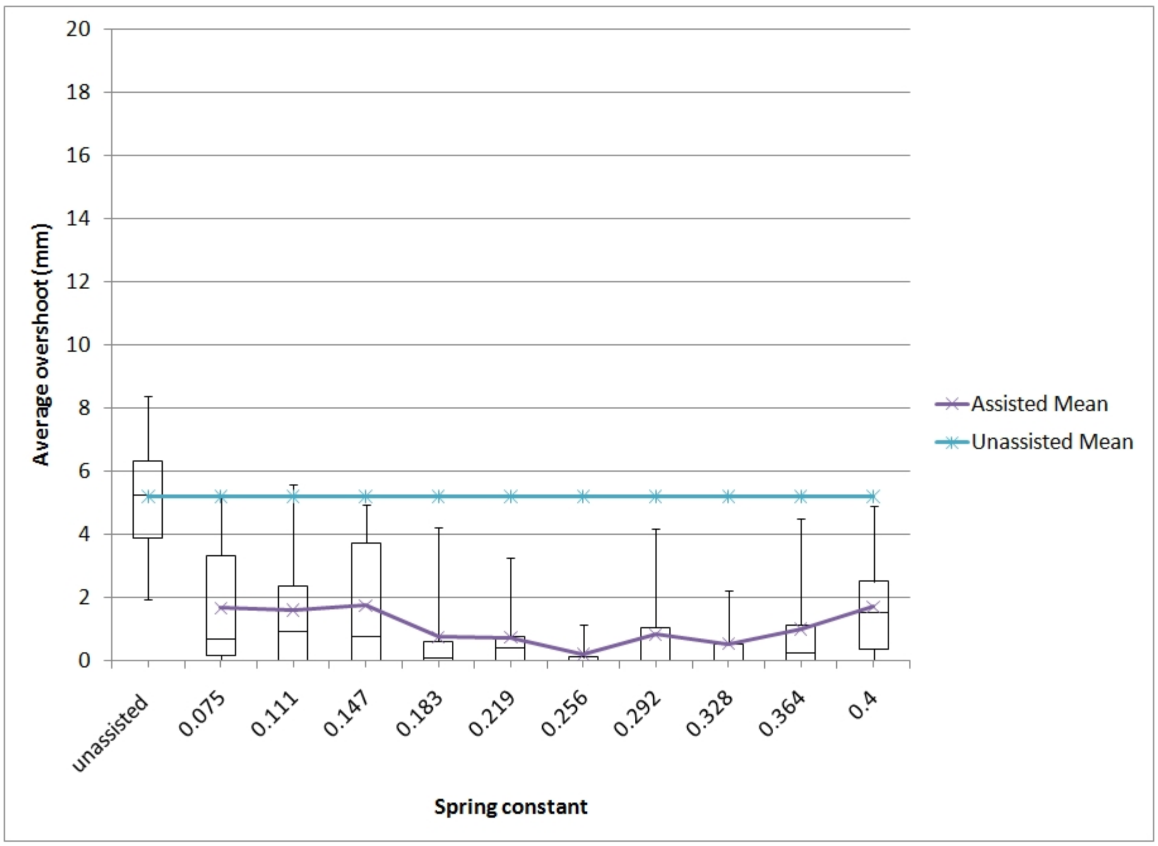

Figure 5.9: The average overshoot of seven motion impaired operators over fifteen successful selections is plotted against the varying spring stiffness of gravity wells.

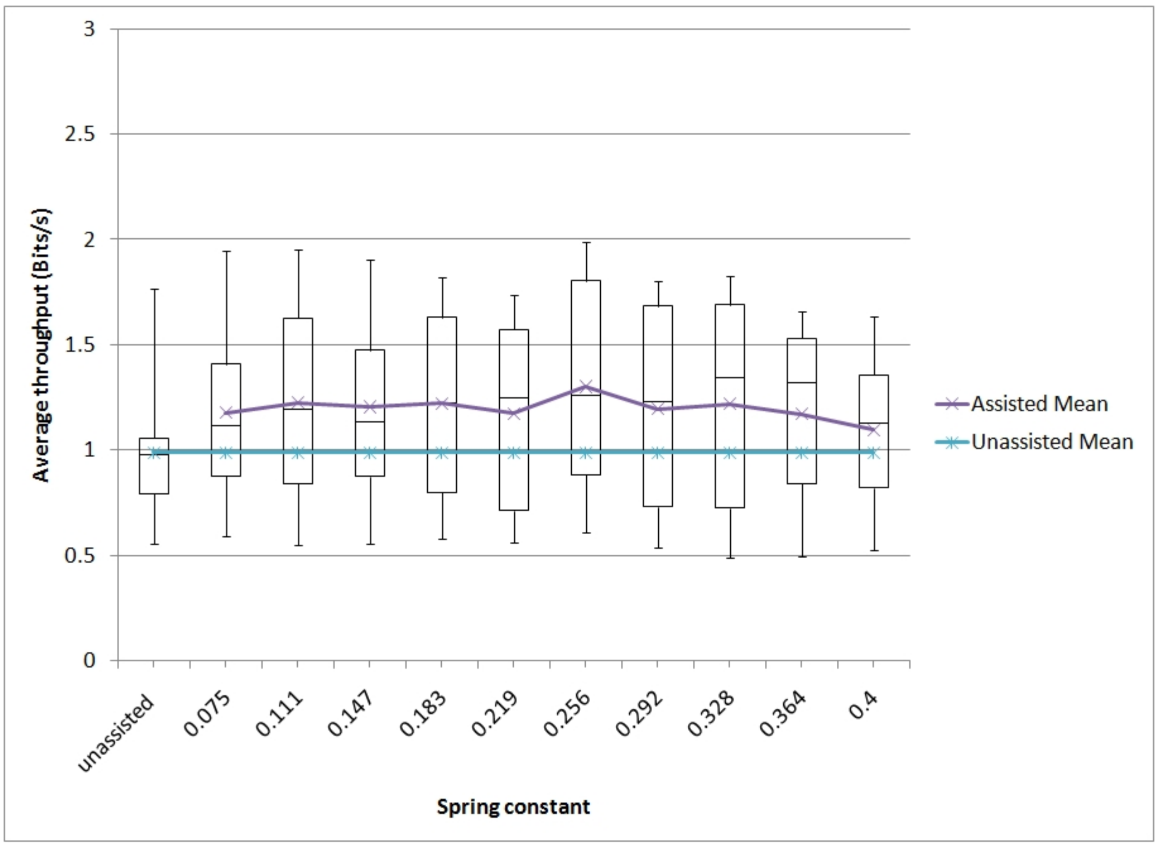

Figure 5.10: The average throughput of seven motion impaired operators over fifteen successful selections is plotted against the varying spring stiffness of gravity wells.

are enabled compared to the unassisted experiment. There do not appear to be any detrimental effects of the technique within the analysis.

One of the main objectives was to identify measures that would be useful in the calibration of the spring stiffness. The measure that proved most useful was the average successful click-release displacement. This was because it produced a strong negative correlation with spring stiffness. Four participants in the study had a strong correlation. The results from the other three were not so strong but improvements were still observed. The missed-click measures show a significant reduction in errors compared to the unassisted experiment.

Another area of interest was to determine if there was a useful range in the level of assistance. The results of click-release displacement show that even low levels of spring stiffness can significantly improve error rates. Performance appears to drop off as the stiffness exceeds 0.219. This could be due to the oscillation increase with greater spring stiffness'. An improvement is still observed for some users and so the whole range may still be useful.

The ideal result of a gravity well is to assist to a suitable level without being excessive. They can be intrusive on an interface and so the level of assistance needs to be carefully selected. Although they can be intrusive it appears there is little effect on throughput when varying the stiffness. The likely reason for this is that the targets are evenly spaced and so there are not any problems encountered with target distracters. The performance increase is slightly less at greater stiffness but it is still an improvement over the unassisted equivalent.

5.5 Experiment 2 - High-Friction Targets

The stick-slip friction model proposed by Zilles et al. [ZS95] is based on the two constraints of dynamic and static friction. To fully understand the results of the experiment only one constraint can be adjusted at any one time. The static component of friction needs to remain low to ensure that the user can slide off a target easily once the clicking process is complete. For this reason the static friction component was clamped low to a value of 0.1. The dynamic friction component is more useful to investigate as it is designed to dampen a person's movements.

During this task a successful click and release was only registered if the operator was in contact with the haptic virtual plane. This was to ensure that the full attributes of high-friction targets were recorded. The operator could still pull off the plane in between clicking.

5.5.1 Results

Successful Click-Release Displacement

It is apparent from Figure 5.11 that high-friction targets can reduce the click-release displacement. There appears to be a level of negative correlation between the level of dynamic friction and the average click-release displacement measure. The result of Pearson's product-moment correlation coefficient produced a value of -0.703. This shows a strong negative linear relationship between the two variables.

Successful Click-Release Distance Travelled

The results for the average click-release distance travelled show a significant improvement on the unassisted experiment but do not appear to provide any significant areas of correlation. The lack of correlation is likely to be caused by a slight oscillation that can occur when using the stick-slip effect of friction. The results are shown in Figure

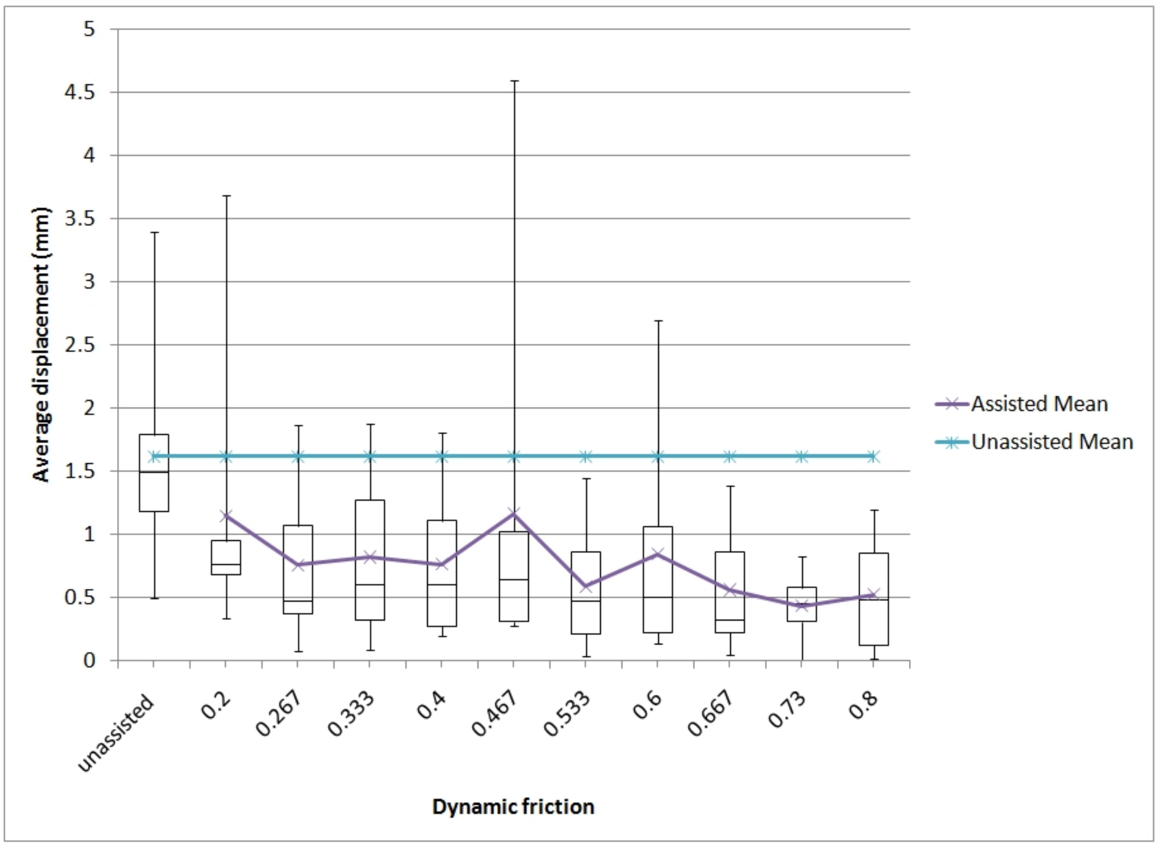

Figure 5.11: The average successful click-release displacement of seven motion impaired operators over fifteen successful selections is plotted against the varying dynamic friction level of each target.

5.12.

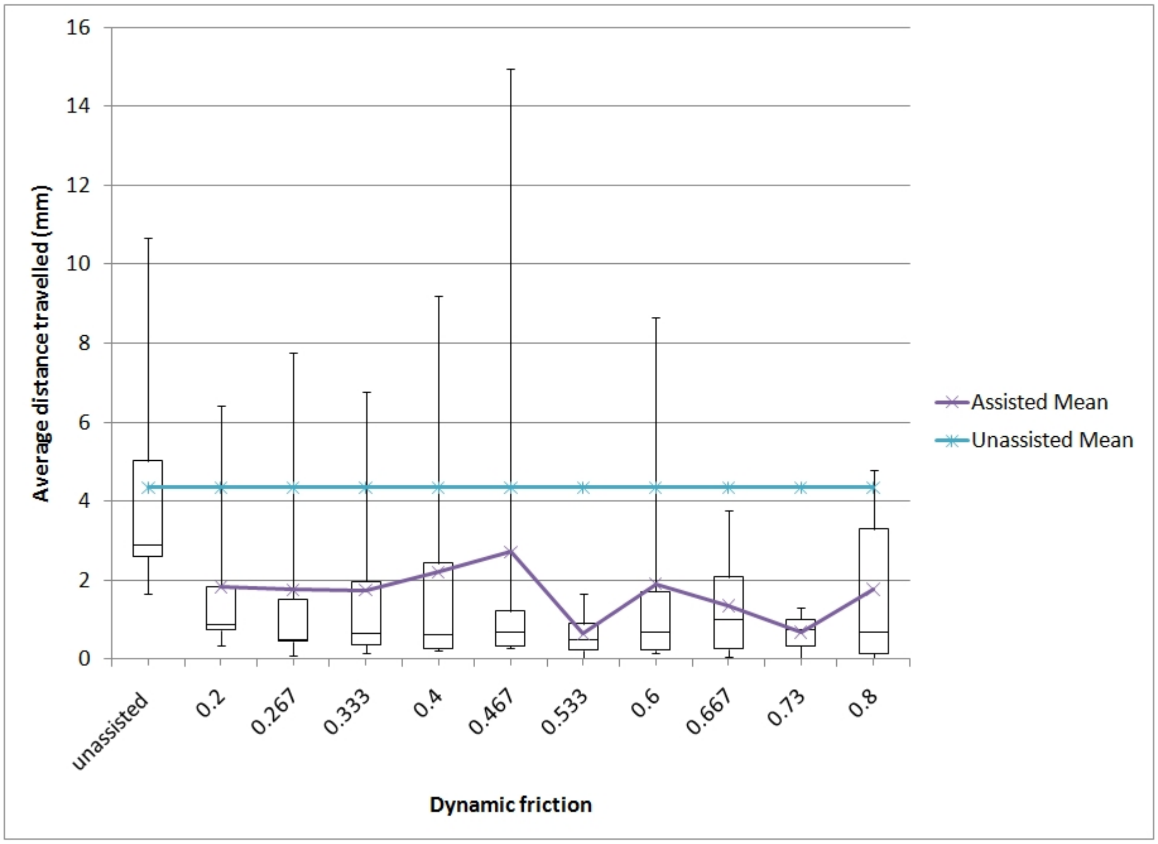

Figure 5.12: The average successful click-release distance travelled of seven motion impaired operators over fifteen successful selections is plotted against the varying dynamic friction level of each target.

Missed-Click on Release

The average number of missed-clicks on release show a significant improvement with high-friction targets enabled compared to the unassisted experiment. This confirms that this technique helps to improve the accuracy and stability during a click. The results are shown in Figure 5.13. For some dynamic friction levels the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph. For other dynamic friction levels only one operator performed a missed-click on release and as a result only the maximum whisker is visible.

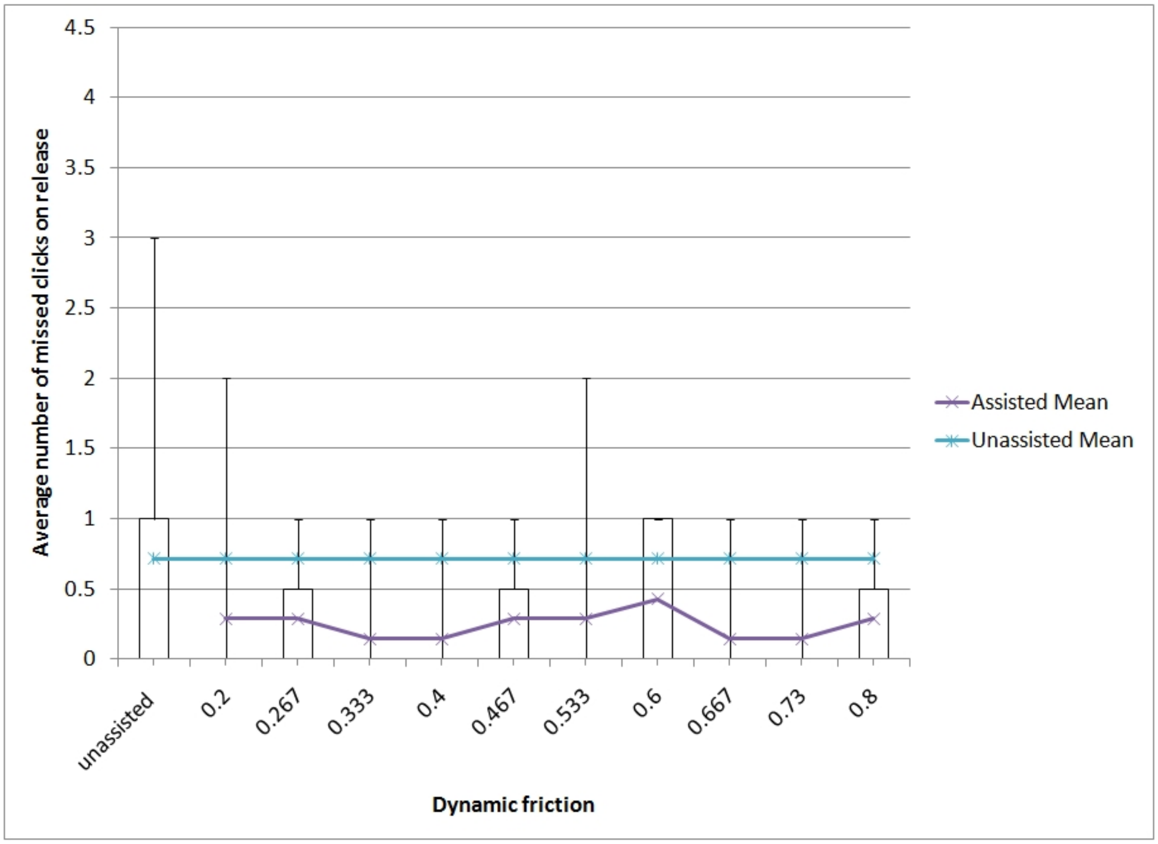

Figure 5.13: The average number of missed-clicks on release of seven motion impaired operators over fifteen successful selections is plotted against the varying dynamic friction level of each target.

Missed-Click on Click

The missed-click on click measure does not appear to provide any improvement on the unassisted experiment, as shown in Figure 5.14. At this stage it is unknown whether the results are less promising because the technique has not been given a chance to assist or whether it is actually detrimental to this measure. This will be addressed later in the study. For some dynamic friction levels the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph. For other dynamic friction levels only one operator performed a missed-click on click and as a result only the maximum whisker is visible.

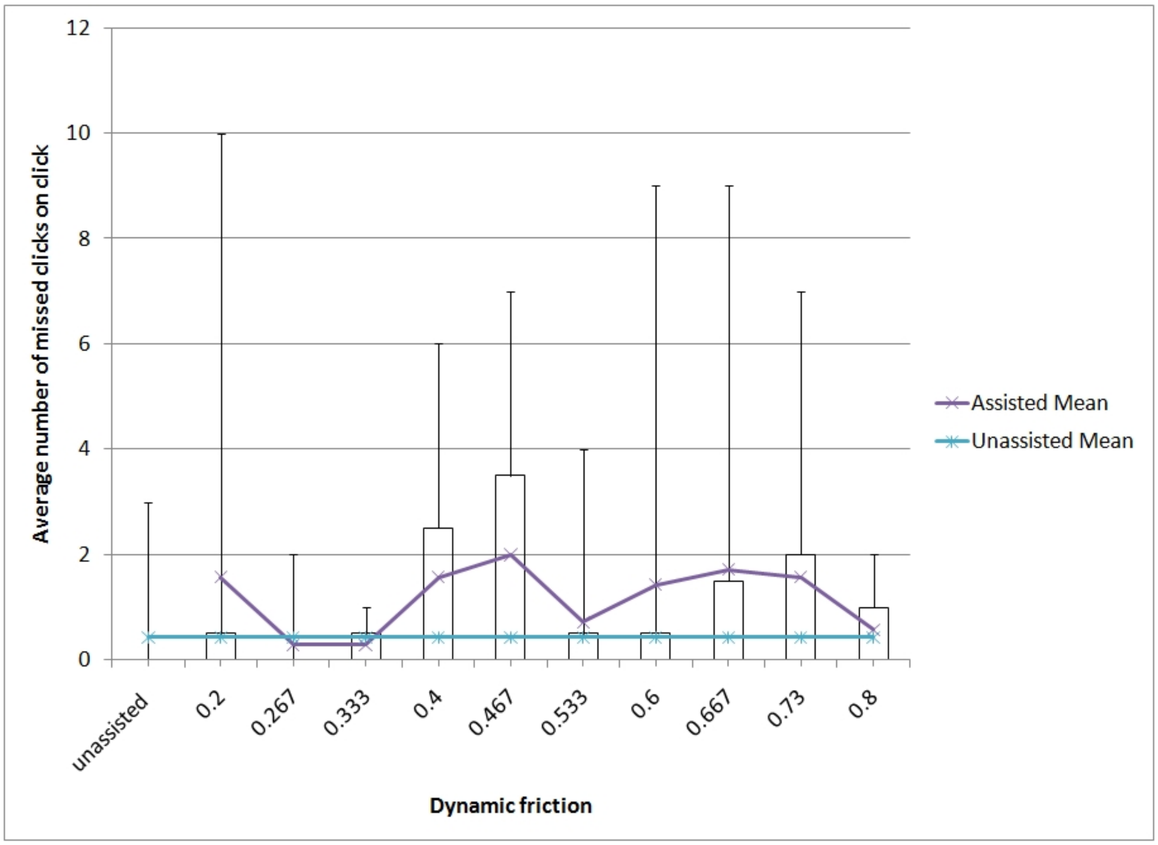

Figure 5.14: The average number of missed-clicks on click of seven motion impaired operators over fifteen successful selections is plotted against the varying dynamic friction level of each target.

Overshoot

High-friction targets have shown to significantly improve target overshoot as shown in Figure 5.15. This will be credited to the damping effect that the user experiences when coming in contact with the target. The level of friction does not seem to significantly affect the performance. At higher friction levels it appears that the overshoot increases. This is likely to be caused by the effect of stick-slip friction. At higher friction levels the operator has to apply greater force to pass over the target. If the device then slips then the cursor may overshoot out of the target region.

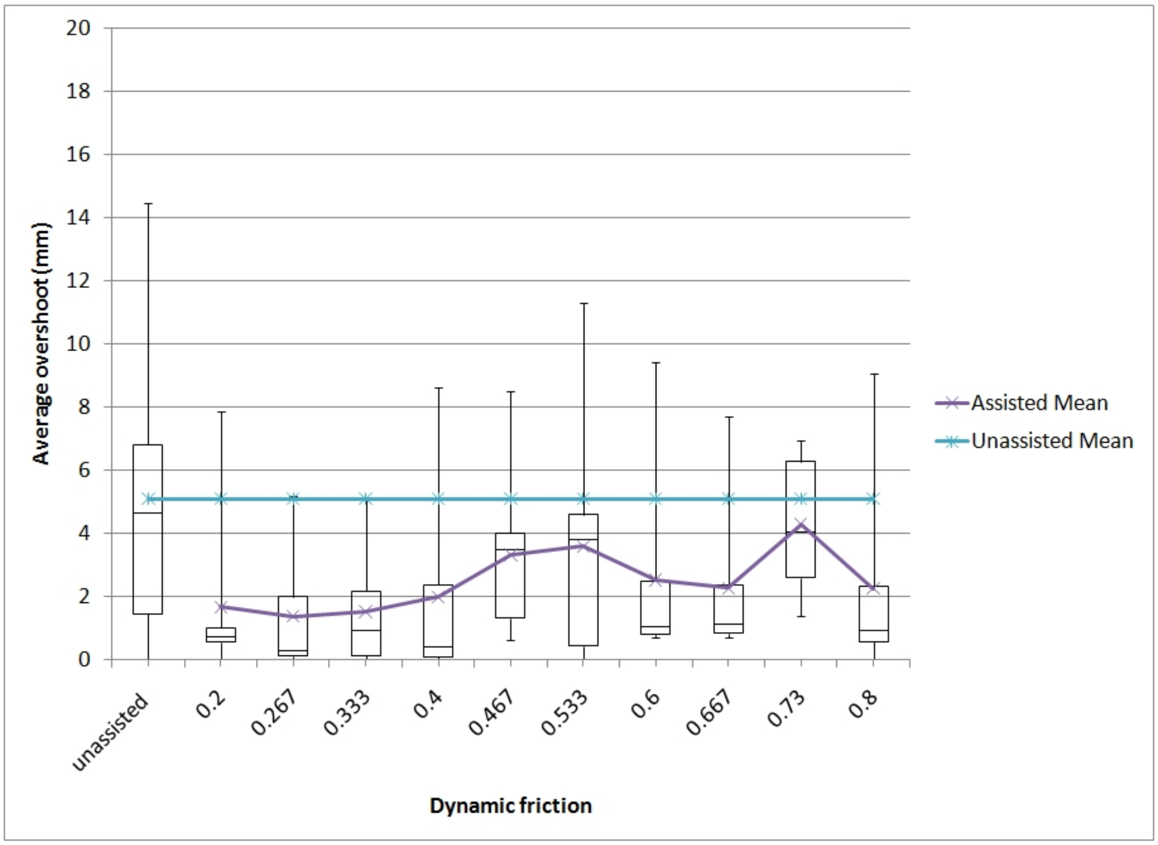

Figure 5.15: The average overshoot of seven motion impaired operators over fifteen successful selections is plotted against the varying dynamic friction level of each target.

Throughput

There appears to be a certain amount of improvement on throughput with high-friction targets enabled, as shown in Figure 5.16. This is likely to be credited to the fact that the technique increases the effective width of the target in a similar way as gravity wells. It also confirms that there are no adverse effects of the technique on the task difficulty or the time taken to complete it.

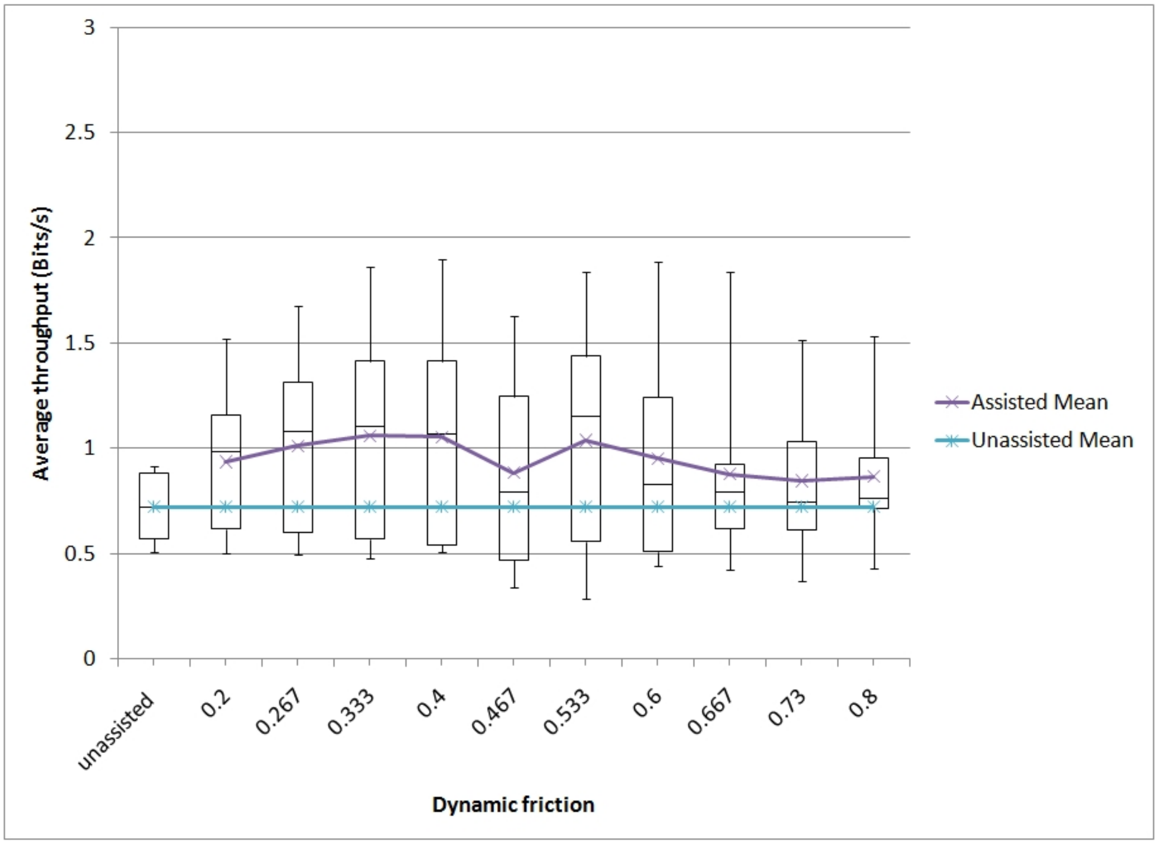

Figure 5.16: The average throughput of seven motion impaired operators over fifteen successful selections is plotted against the varying dynamic friction level of each target.

5.5.2 Conclusions

The results of the study indicate that high-friction targets can help with the selection of icons. The concept of the haptic plane took a couple of practice experiments for a few participants to grasp but each person managed to complete the task.

The results show that the level of dynamic friction will also have a bearing on the operator's performance. The click-release displacement and click-release distance travelled measures seemed to be significantly reduced by the introduction of high-friction targets. There does not appear to be a single friction level that increases the performance of all measures.

There do not appear to be any significant detrimental effects of the assistance shown in the results analysis. Each dynamic friction level produced an improvement in the cursor measures apart from missed-clicks on click. It is not always possible to get an accurate account of the assistance performance from the missed-click on click measure because if the operator does not enter a target region then the assistance cannot take effect. One difficulty that was observed in the experiments was that as the friction level increases it becomes more difficult to navigate to the middle of a target. As a result many participants were trying to select at the target's edge which meant that a slight movement could result in a miss-click.

A strong negative correlation was found between the level of dynamic friction and the average click-release displacement. As a result this measure will be useful in the calibration stage of high-friction targets.

One user commented that the technique caused arm ache after a duration of use. The likely reason for this is that the penetration depth of the HIP on the plane will have a bearing on the frictional force. For example, the firmer you push your finger against a surface the more force required to slide across that surface. This operator had a habit of pressing quite hard against the haptic virtual plane and so would be opposing the restoring spring force as well as an increase in friction. A solution to this could be to produce a friction model that is purely based on the tangential force without the penetration depth being taken into consideration.

5.6 Experiment 3 - Haptic Cones

The main interest in this study is to compare the effects of haptic cones to traditional haptic assistance. If haptic cones perform significantly better than high-friction targets then they will be chosen as the main type of assistance to be used with the haptic virtual plane. Both techniques are designed to be less intrusive than gravity wells and they are both based on similar principles in that their effect is applied directly to the haptic virtual plane. In the experiment a click was only registered if the operator was in contact with a cone or the plane. This was to ensure that the full attributes of haptic cones were recorded. The operator could still pull off the plane in between clicking. A physical model of a haptic cone and the proxy were shown to the participants to help them understand the concept of the technique.

5.6.1 Results

Successful Click-Release Displacement

Haptic cones provided a significant improvement in the click-release displacement measure. The reason for this would be credited to the proxy clamping caused by Zilles et al. [ZS95] God-object algorithm. As the cone is entered the position of the proxy is interpolated along its surface. Once the cone has been fully entered the closest surface contact point to the HIP is the cone apex. This results in the proxy being clamped to the centre of the target. The results are shown in Figure 5.17.

Successful Click-Release Distance Travelled

Haptic cones also produced a significant performance improvement in the click-release distance travelled measure. Unlike gravity wells there are no oscillation problems encountered with haptic cones. Once the proxy is clamped to the cone apex the operator is provided with good device stability whilst clicking and releasing. The results are shown in Figure 5.18.

Missed-Click on Release

Haptic cones produced the best results of all types of assistance in the missed-click on release measure. This can be credited to the fact that the proxy is clamped to

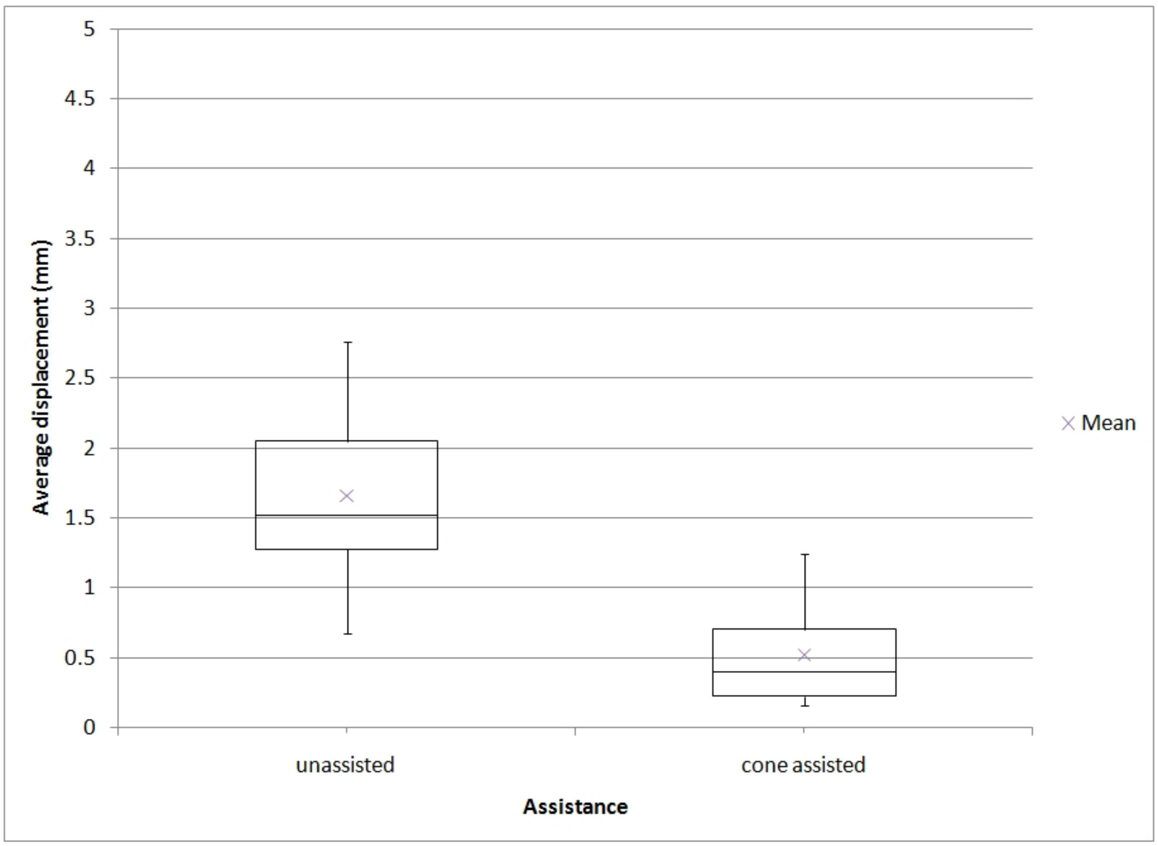

Figure 5.17: The average successful click-release displacement of seven motion impaired operators over fifteen successful selections is shown for an unassisted experiment and using haptic cones.

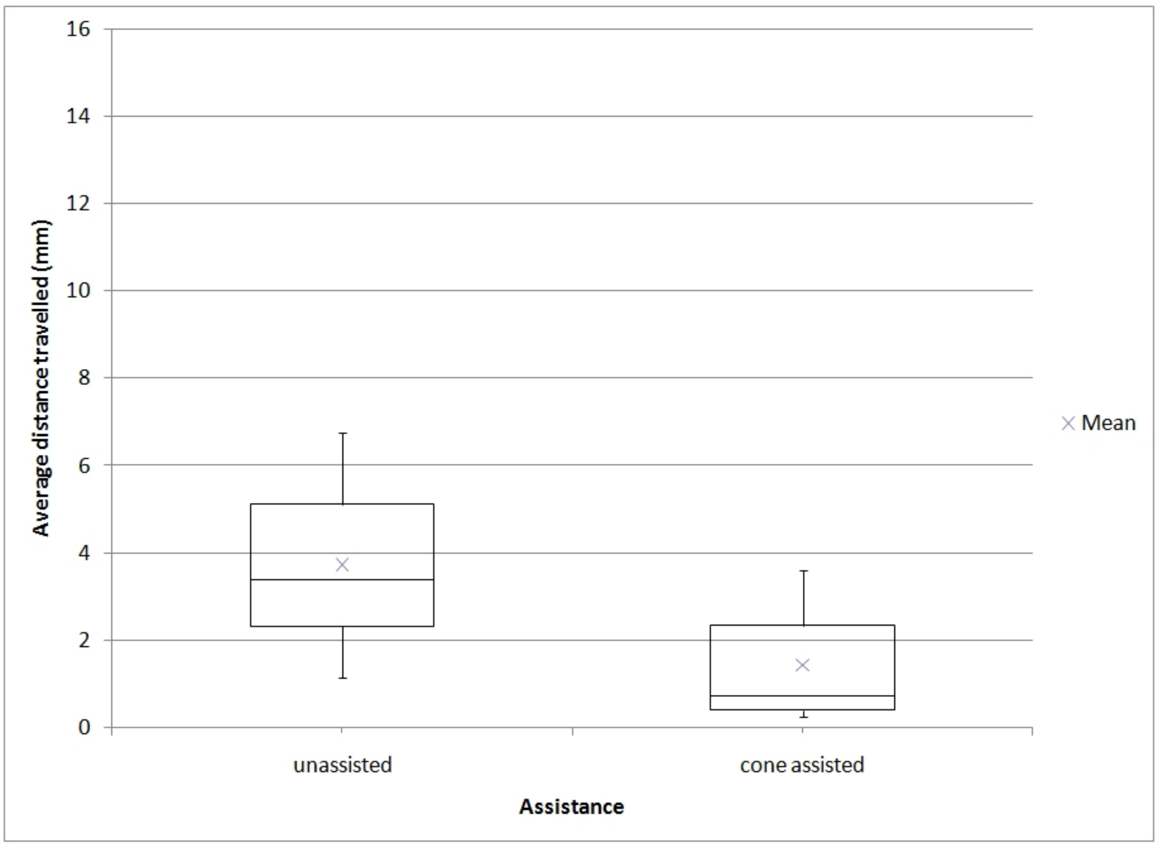

Figure 5.18: The average successful click-release distance travelled of seven motion impaired operators over fifteen successful selections is shown for an unassisted experiment and using haptic cones.

the apex of the cone and so it cannot easily slide off a target. The operator can only exit the target by pulling out of the cone in the z-axis or navigating a wall, both of which require a conscious effort. For the unassisted experiment the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the chart. There were no missed-clicks on release recorded for the cone assisted experiment. The results of the missed-click on release measure are shown in Figure 5.19.

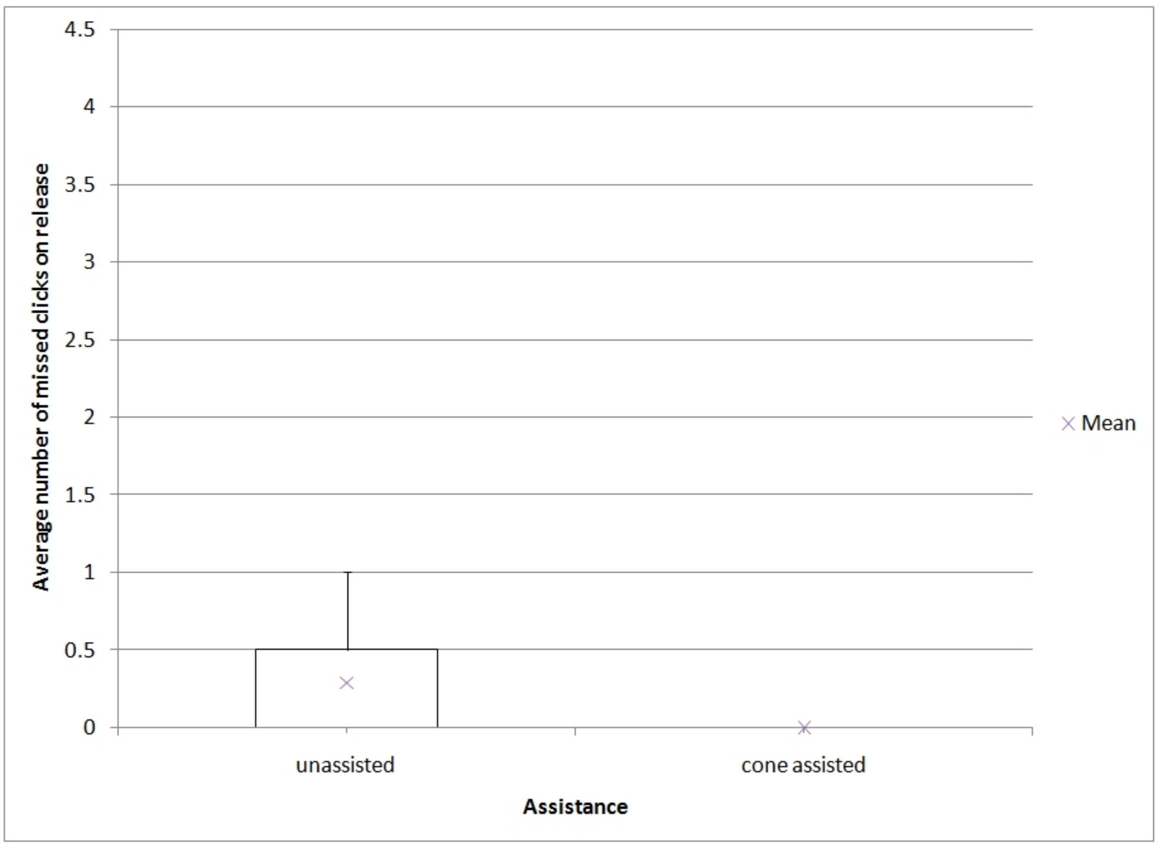

Figure 5.19: The average number of missed-clicks on release of seven motion impaired operators over fifteen successful selections is shown for an unassisted experiment and using haptic cones.

Missed-Click on Click

There does not appear to be an improvement in the missed-click on click measure with haptic cones enabled. This technique will only be able to assist the operator if they actually enter the cone before clicking. It is for this reason that the results are not as good as those seen for the missed-click on release. There is not a significant difference compared to the unassisted experiment and so it does not appear that cones worsen this measure. For both experiments the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the chart. The results are shown in Figure 5.20.

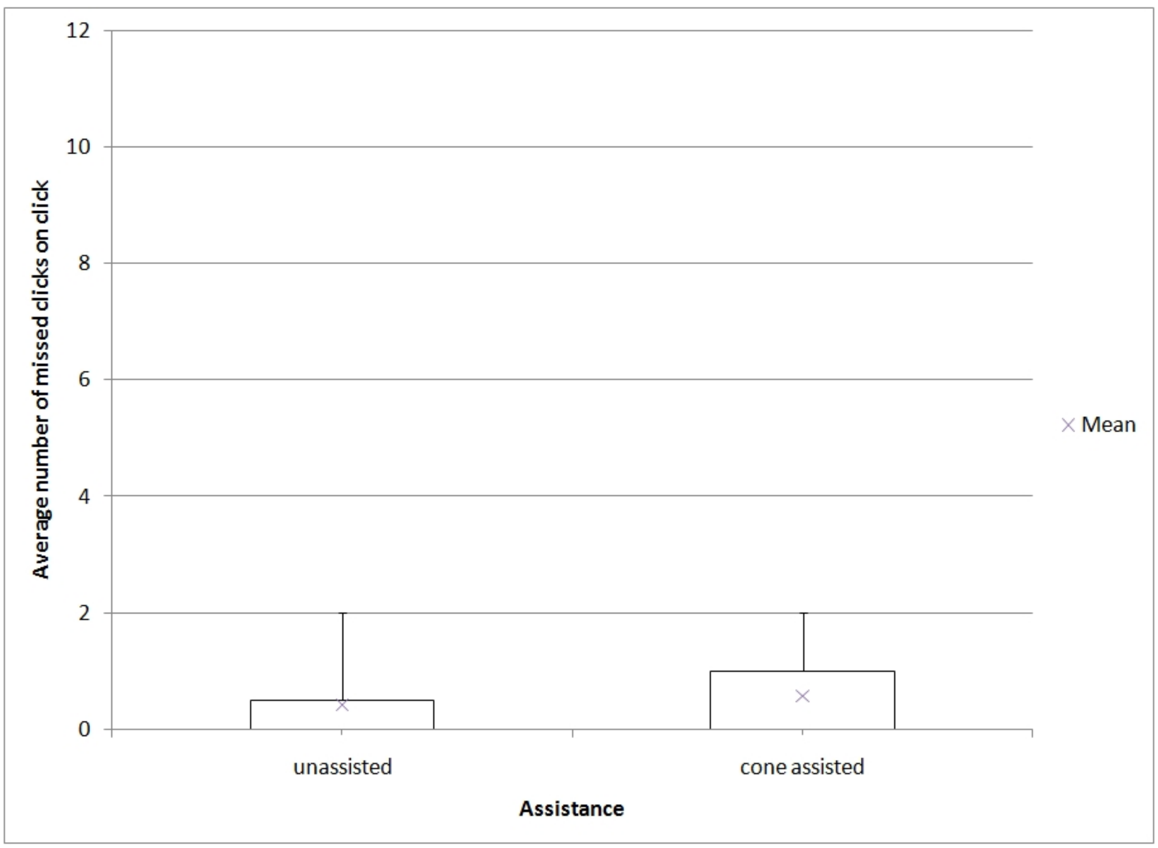

Figure 5.20: The average number of missed-clicks on click of seven motion impaired operators over fifteen successful selections is shown for an unassisted experiment and using haptic cones.

Overshoot

The overshoot results of haptic cones shown in Figure 5.21 also show improvements compared to the unassisted experiments. The reason for this is that as the cone is entered it acts as a brake. It is for this reason that equal dimensions were chosen for the cone width and depth. This ensures that the cone slant angle is not too low and the proxy will not slip off the apex too easily.

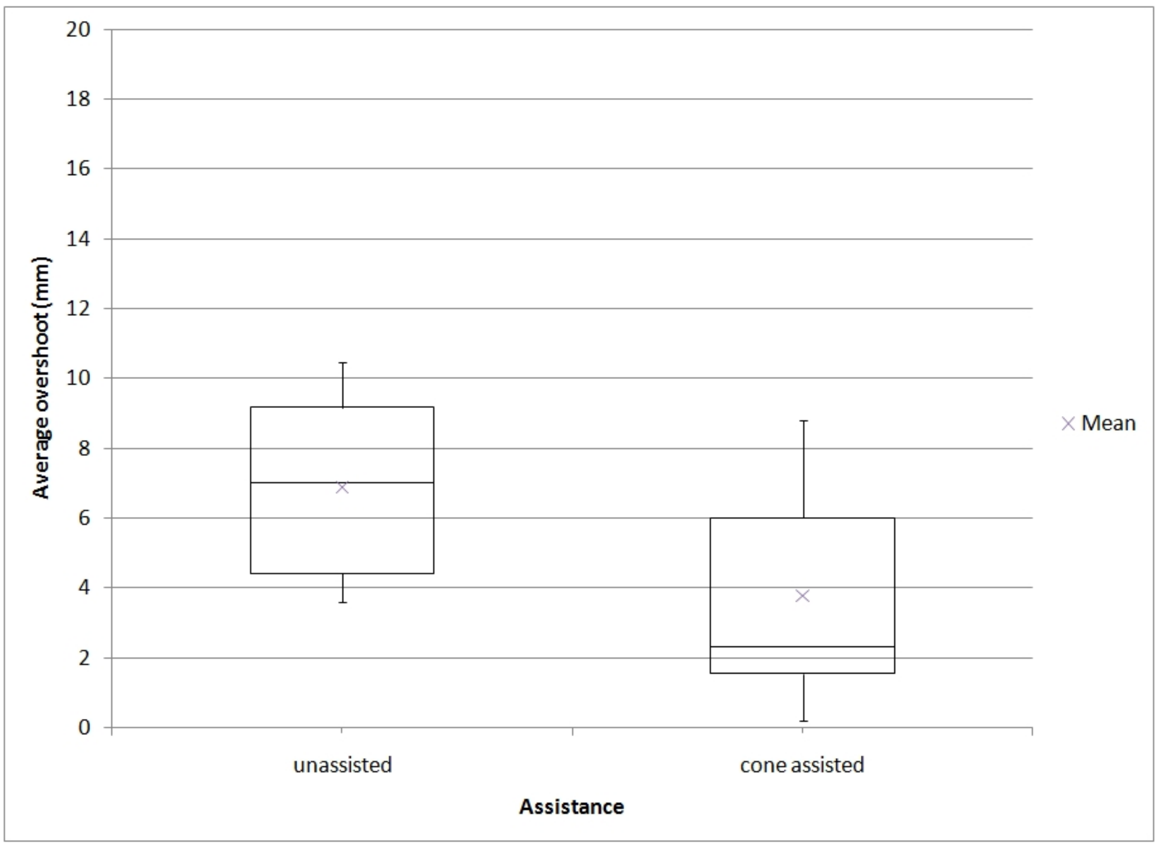

Figure 5.21: The average overshoot of seven motion impaired operators over fifteen successful selections is shown for an unassisted experiment and using haptic cones.

Throughput

The results shown in Figure 5.22 show a performance decrease [1] in average throughput when compared to the unassisted experiment. The reason for this decrease is likely to be due to the fact that many users decided to pull out of the z-axis and re-apply the proxy to the plane before continuing interaction. This decrease in throughput equates to a 0.8 second increase per clicking operation. Cones were the least practised of all the haptic techniques and so this may have some bearing on the results.

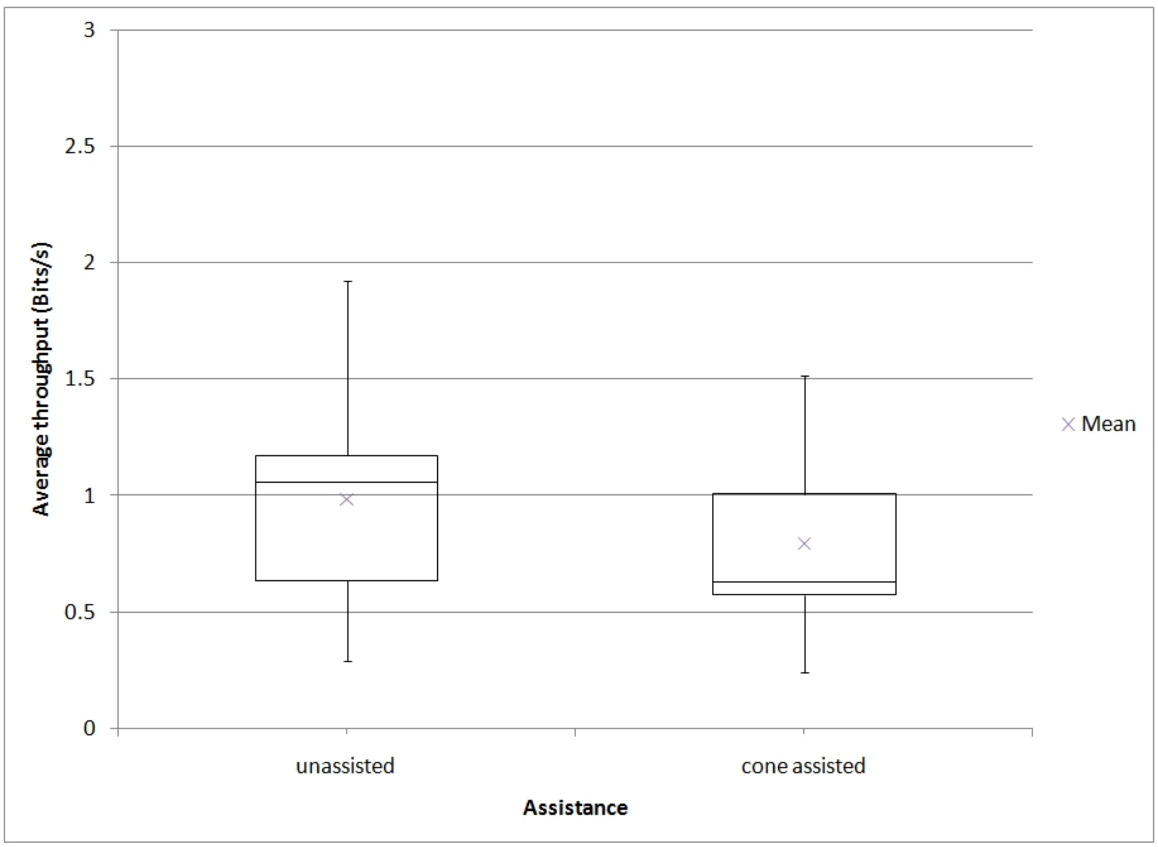

Figure 5.22: The average throughput of seven motion impaired operators over fifteen successful selections is shown for an unassisted experiment and using haptic cones.

[1] Note that this decrease is not statistically significant.

5.6.2 Conclusions

The results from the experiment confirm that haptic cones can have a significant impact on the clicking accuracy and stability. The click-release distance travelled and click-release displacement were significantly improved for each user. As a result no missed-clicks on release were recorded by any participant in the experiment.

It appears that throughput may be hindered as there is a decrease compared to the unassisted equivalent. The likely reason for this is that the movement time takes longer due to the fact that the user must pull out of a cone before continuing with interaction. The overall error rate improvement of the haptic cones far outweighs this decrease in throughput. If the task takes more time but there are fewer clicking errors then the overall error rate will have improved. This will be especially important in an existing interface where a missed-click could lead to an undesired operation that the user must cancel. This technique was the least practised of all the assistance and so it may be found that with more practice this level improves.

The click-release displacement will once again be useful in the selection of haptic cones as it was significantly improved by the technique. The reason why haptic cones produced such significant improvements in the click related measures is that once the proxy is clamped to the apex of the cone many unwanted movements are largely filtered out. In most cases filters are not ideal or lose key information. However, using a haptic device allows the operator to continue operation without any loss in fidelity. This technique fully utilises the 3D capabilities of the Phantom device and confirms Langdon's [LKCR00] theory that increasing the degrees of freedom can improve interaction rates if implemented carefully.

Unlike gravity wells there are no issues with oscillations or stiffness limitations. There are no forces imposed on the operator and so there is no force calibration required. The main difficulty of this technique arises in the concept because the operator will not have a visual representation of the plane and the cones within the final interface. This means that the operator is reliant on using their sense of touch and previous experience of using the technique to use it successfully. The overall success of haptic cones will lie in whether the operator understands the concept of the cones embedded in the plane and will actually use the assistance when automated in existing interfaces.

5.7 Experiment 4 - Haptic Wall

The main interest in this experiment was to determine what effects haptic walls have on user performance. The target overshoot measure will be the main concentration as haptic walls are designed to assist in this area. If the wall technique performs significantly better in improving overshoot then it will be used as the main type of assistance for this measure. A graphical representation of the walls was shown to the participants to give them a more detailed understanding of how the assistance works. The clicking measures will also be analysed as the operator will be able to lean against the haptic walls which may provide further stability when targeting.

5.7.1 Results

Successful Click-Release Displacement

For the average click-release displacement measure, haptic walls only provided a small improvement on the unassisted experiment. The results are shown in Figure 5.23. The likely reason for this is that there are no clamping forces that help stabilise the click and release. The restoring force of the wall is always in one direction and so if the operator does not lean against it, at the target centre, then they will not be provided with any assistance.

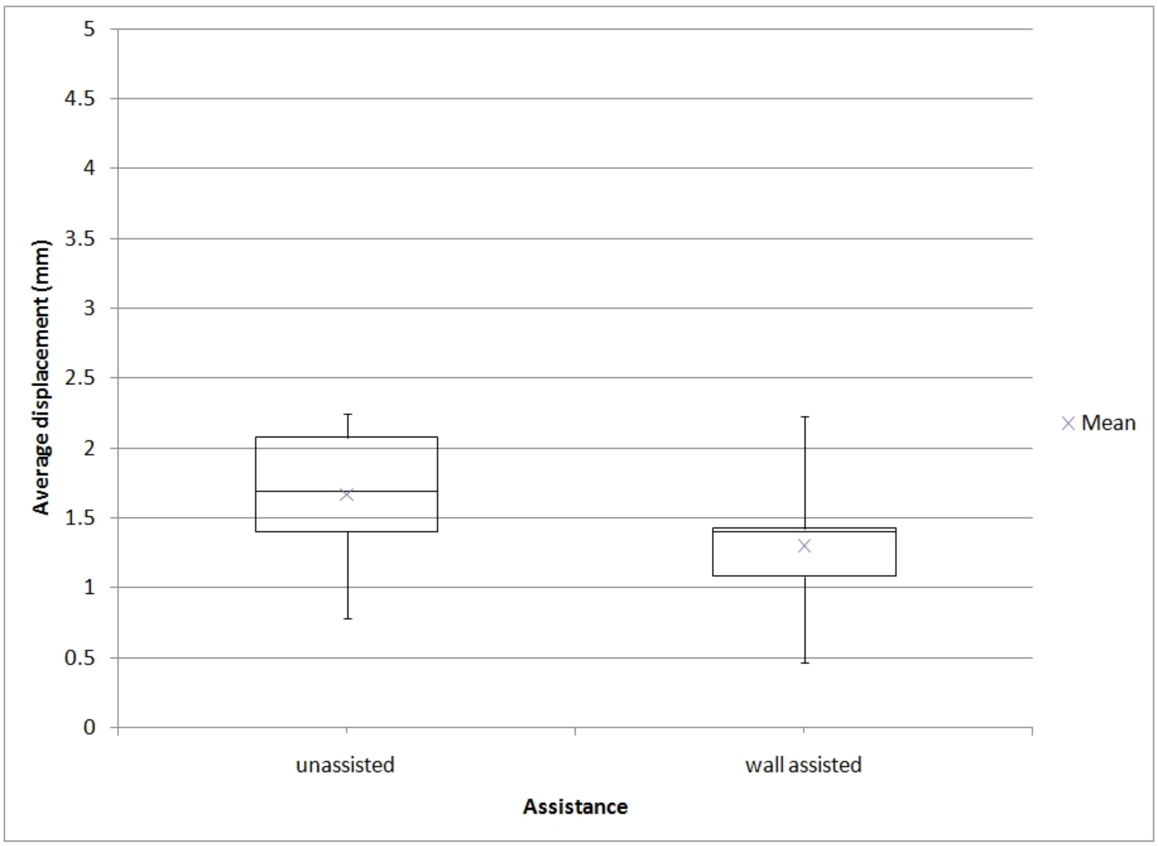

Figure 5.23: The average successful click-release displacement of seven motion impaired operators over fifteen successful selections is shown for an unassisted experiment and using haptic walls.

Successful Click-Release Distance Travelled

Haptic walls do not appear to provide a significant performance increase for the click-release distance travelled measure compared to the unassisted experiment. This is shown in Figure 5.24. The lack of clamping will be a contributing factor in the small improvement for this measure. Another contributing factor could be that the wall is flat and frictionless and so the operator may slide along its surface too easily.

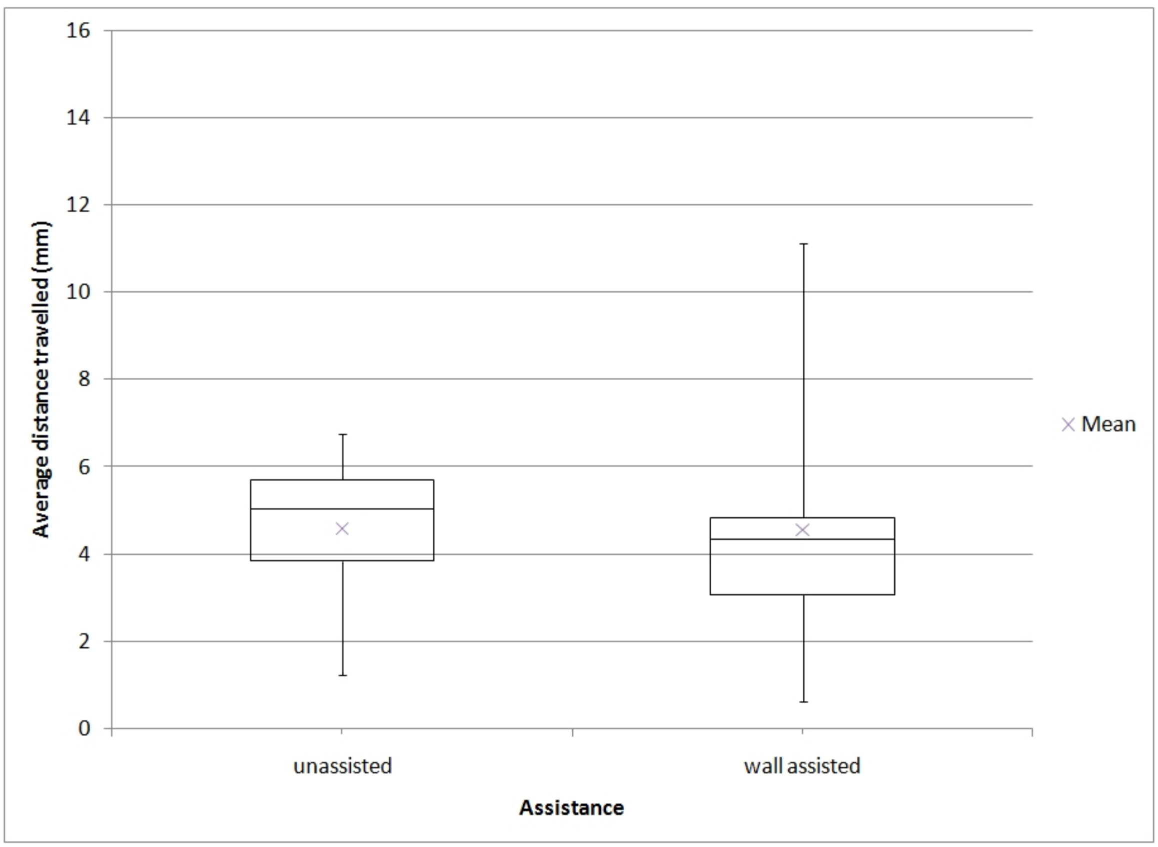

Figure 5.24: The average successful click-release distance travelled of seven motion impaired operators over fifteen successful selections is shown for an unassisted experiment and using haptic walls.

Missed-Click on Release

Given that haptic walls did not provide much of a performance difference for the other clicking measures it is unsurprising that the missed-click on release measure remained the same. This is shown in Figure 5.25. Techniques such as haptic cones and gravity wells clamp the cursor at the centre of the target which means that if the cursor slips or moves slightly there is still a greater chance of acquiring it successfully. This type of assistance is not provided by haptic walls. For both experiments the minimum whisker, lower quartile and the median are zero and as a result they are not visible on the chart. The upper quartile and the maximum whisker were recorded to be the same in both experiments.

Missed-Click on Click

The missed-click on click measure was reduced with haptic walls enabled, as shown in Figure 5.26. However, the previous experiments have shown that this measure may not always be reliable as operators may miss-click on click before entering a target which means that the technique is not given an opportunity to assist. For both experiments the minimum whisker, lower quartile and the median are zero and as a result they are not visible on the chart. The upper quartile and the maximum whisker were recorded to be the same in the cone assisted experiment.

Overshoot

One of the main areas of interest when using haptic walls was their effect on overshoot. It is clear from Figure 5.27 that overshoot measure is more than halved when haptic walls are enabled. The reason for this is that the spring force is always in one direction and so it is possible to create a stiffer contact (without oscillation) in which the operator cannot easily overshoot. This is not possible with gravity wells due to the fact that the cursor can be thrown out of the other side of the target with the increased

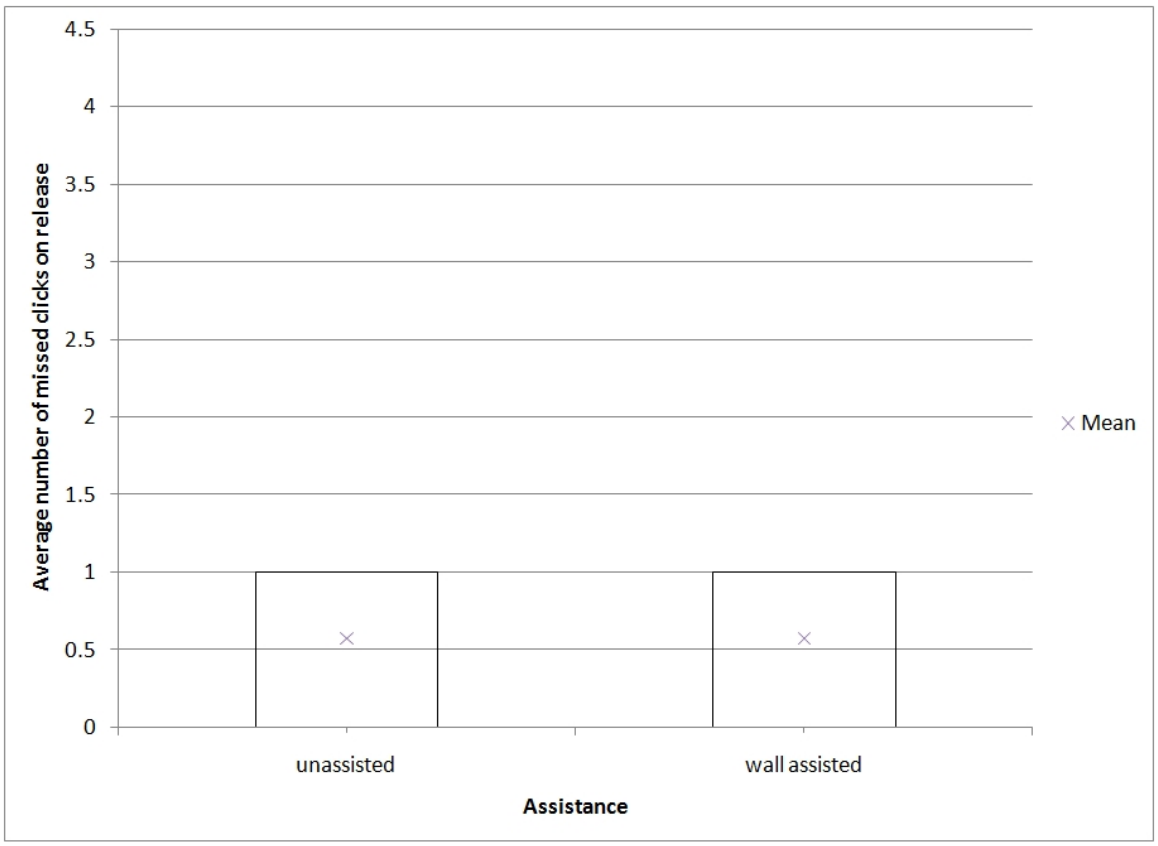

Figure 5.25: The average number of missed-clicks on release of seven motion impaired operators over fifteen successful selections for an unassisted experiment and using haptic walls.

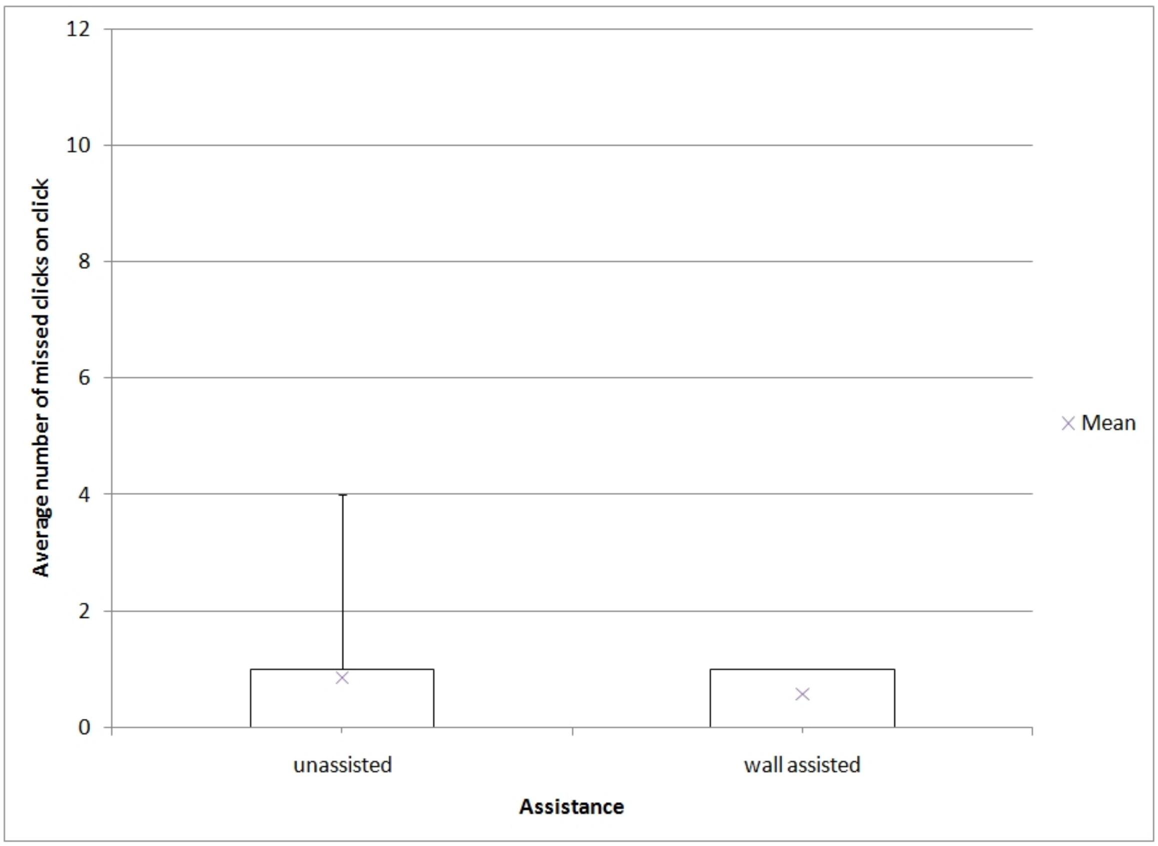

Figure 5.26: The average number of missed-clicks on click of seven motion impaired operators over fifteen successful selections for an unassisted experiment and using haptic walls.

momentum of the device.

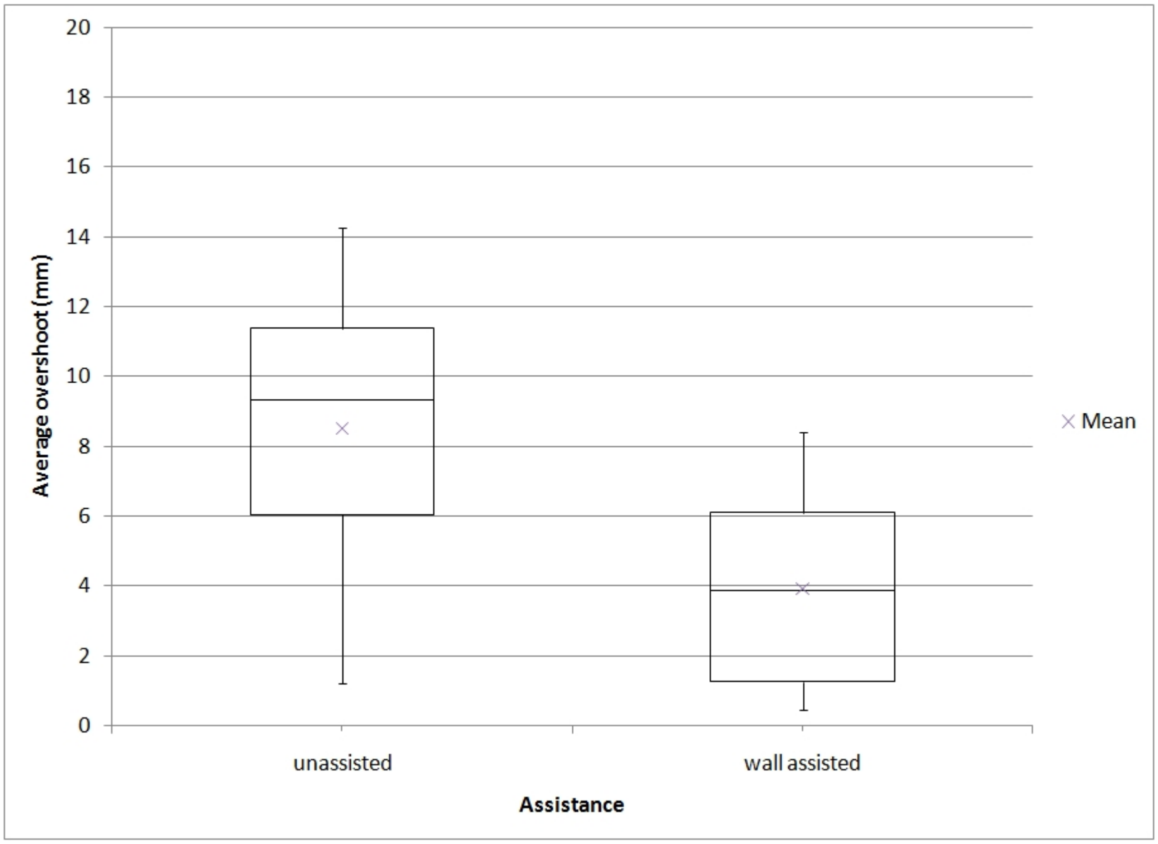

Figure 5.27: The average overshoot of seven motion impaired operators over fifteen successful selections for an unassisted experiment and using haptic walls.

Each participant in the study produced a better result for overshoot using haptic walls when compared to the unassisted experiment. This supports the theory that techniques that are non-intrusive may be better at assisting a greater range of disability.

Throughput

The results in Figure 5.28 show that the average throughput seems to improve slightly with the introduction of haptic walls. This confirms that haptic walls do not adversely affect the task difficulty or the time taken to target.

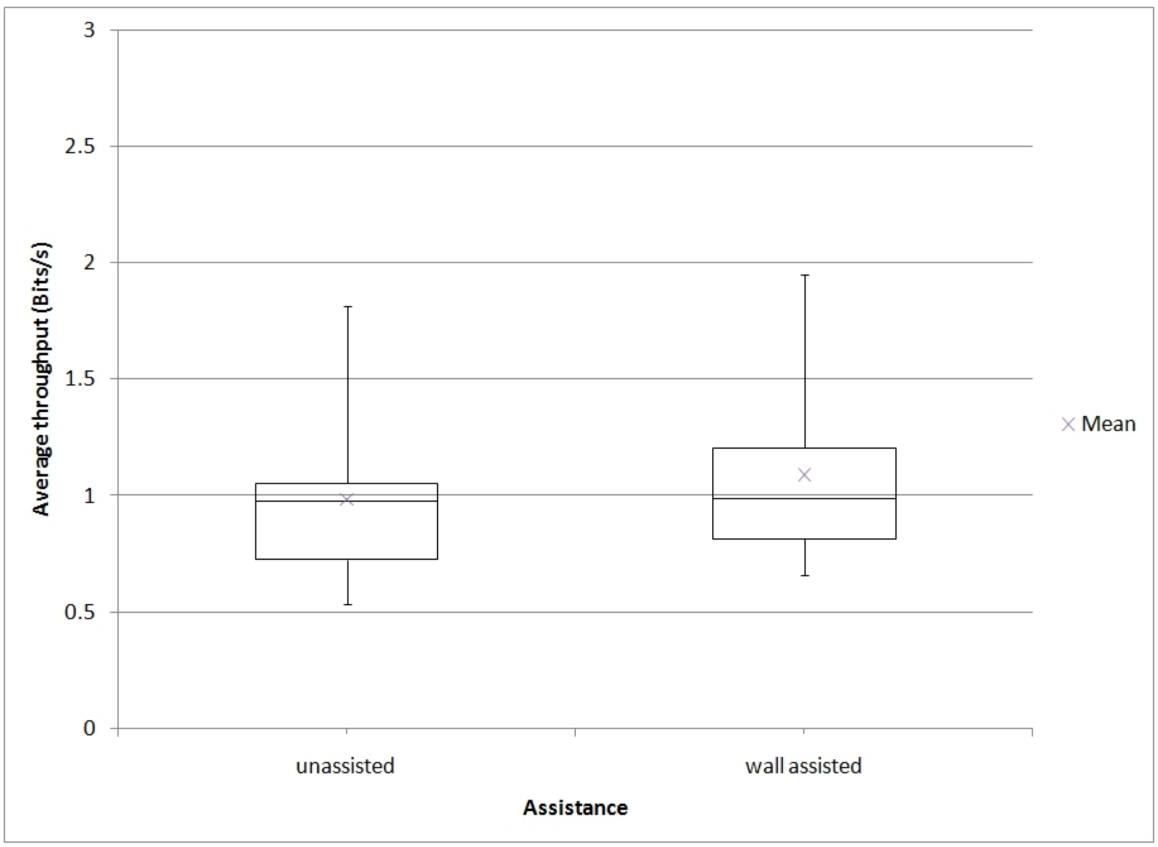

Figure 5.28: The average throughput of seven motion impaired operators over fifteen successful selections for an unassisted experiment and using haptic walls.

5.7.2 Conclusions

The results from the experiment confirm that haptic walls can significantly reduce the overshoot measure. The click-release displacement and distance travelled seem to be improved slightly but not to any great extent. A possible reason for this is that the wall is flat and frictionless and so the proxy may slip along its surface too easily. If the wall surface was given a friction level it may help users maintain stability on it when clicking. Alternatively, if the wall was curved or V shaped then it may be less easy to slip off its edge. The results show that there do not appear to be any detrimental effects caused by haptic walls but the technique does not appear to provide much assistance in the clicking phase.

The improvement in overshoot will be credited to the wall stopping the cursor from passing out the other side of a target. The results were promising in that each participants' overshoot measure improved when walls were enabled.

It was observed that entering an undesired target was less of a problem than with gravity wells. This was because the operator can simply exit the target in the opposite direction to which they entered it and continue interaction.

5.8 Experiment 5 - Haptic Damping

Haptic damping is a technique that is designed to stabilise movement both in terms of target homing and target acquisition. As a result both areas will be analysed in the study. The assistance is in operation all the time and so it is not necessary to only analyse the successful clicking operations. The standard click measures will provide a suitable analysis of the technique's performance.

5.8.1 Results

Click-Release Displacement

It appears, from the results shown in Figure 5.29, that a damping level lower than 0.2 may improve the average click-release displacement in comparison to the unassisted experiment. However, as the stiffness increases above this level there is a steep increase in the click-release displacement where the damping results become worse than those recorded in the unassisted experiment. This is likely to be caused by the operator fighting against the damping effect. It was observed that some operators had to apply greater forces to manipulate the device which resulted in an increase in the number of uncontrolled movements.

Click-Release Distance Travelled

Similar results are shown in Figure 5.30 for the average click-release distance travelled measure. After a damping level of 0.2 the click-release distance travelled measure significantly deteriorates. Detrimental effects on these two measures is undesirable as it was shown later in the study (Section 6.1) that higher levels can significantly increase the chances of miss-clicking.

Missed-Click on Release

There does not appear to be any significant areas of correlation for the missed-click on release measure with damping enabled. Some damping levels produced improvement on the unassisted experiment whilst others did not. This is shown in Figure 5.31. As the click-release displacement and distance travelled measures were worsened by this technique the lack of significant improvement in the number of missed-clicks on release is unsurprising. For some damping levels the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph. For other damping levels only one operator

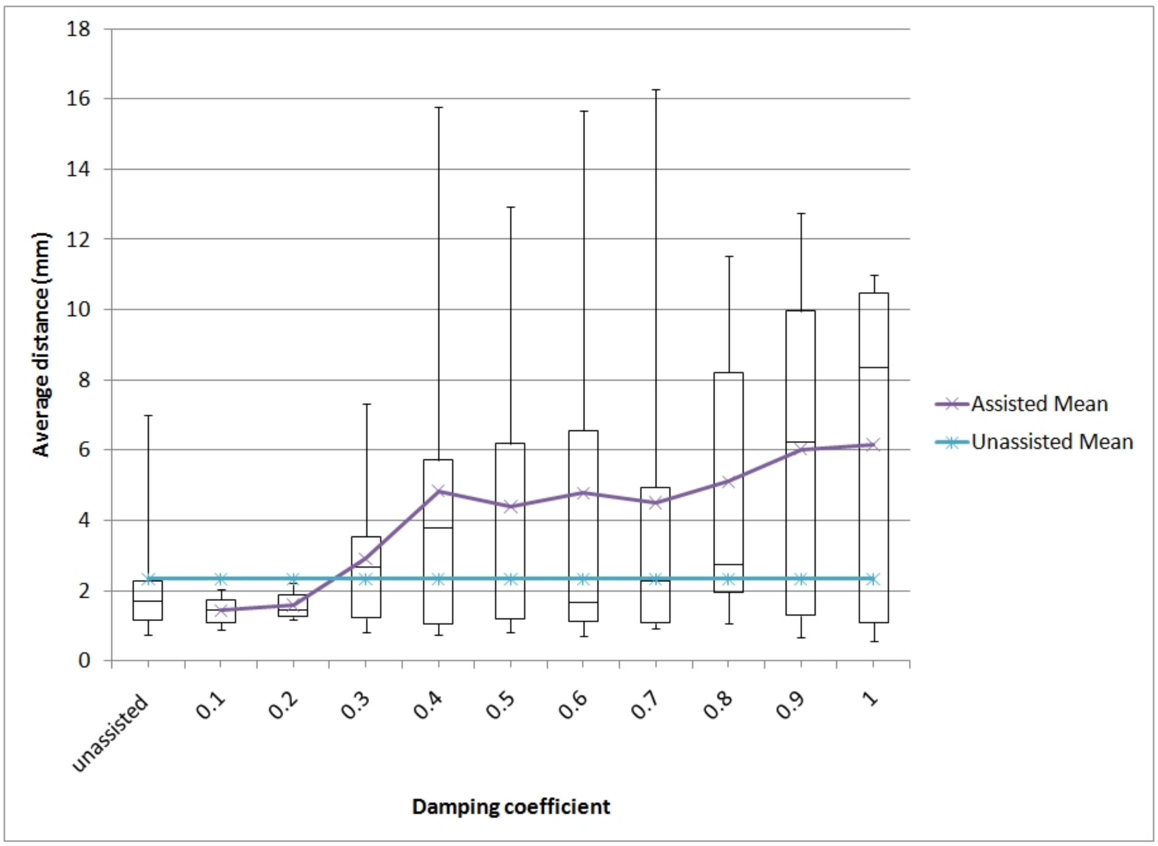

Figure 5.29: The average click-release displacement of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

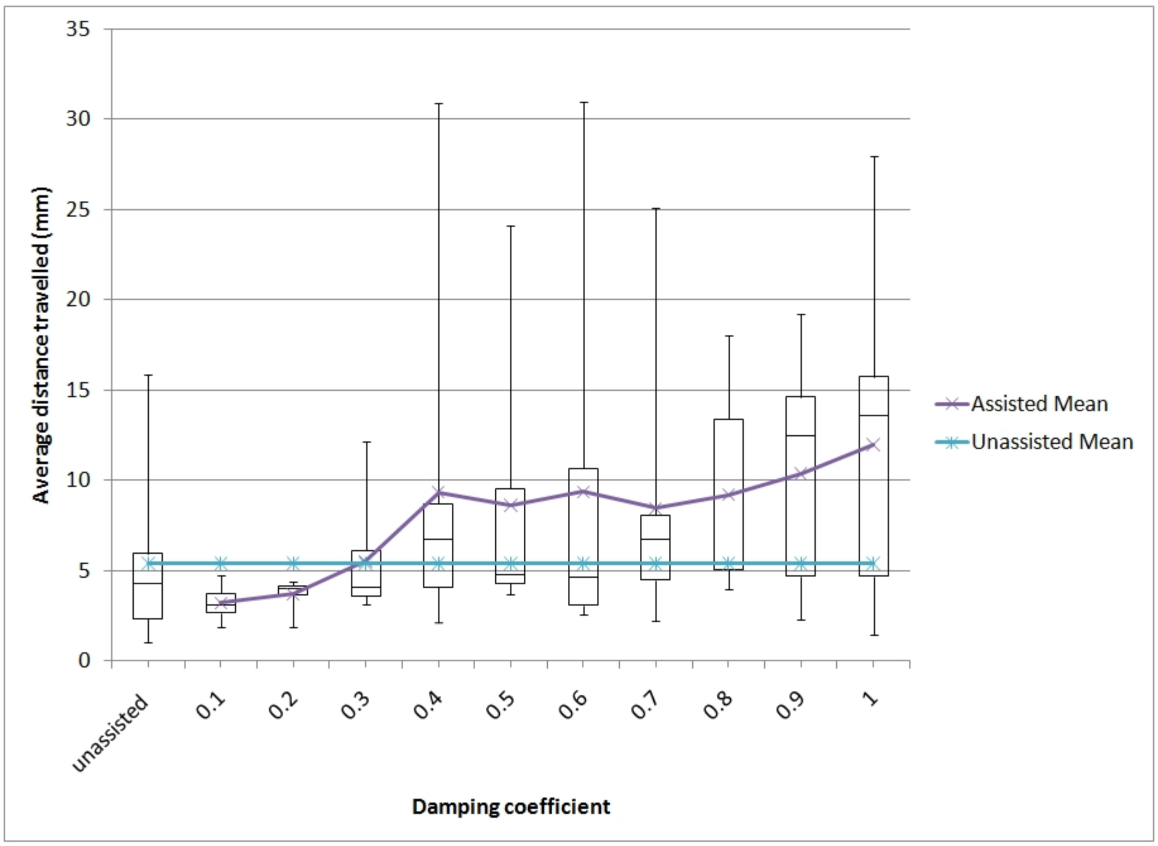

Figure 5.30: The average click-release distance travelled of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

performed a missed-click on release and as a result only the maximum whisker is visible.

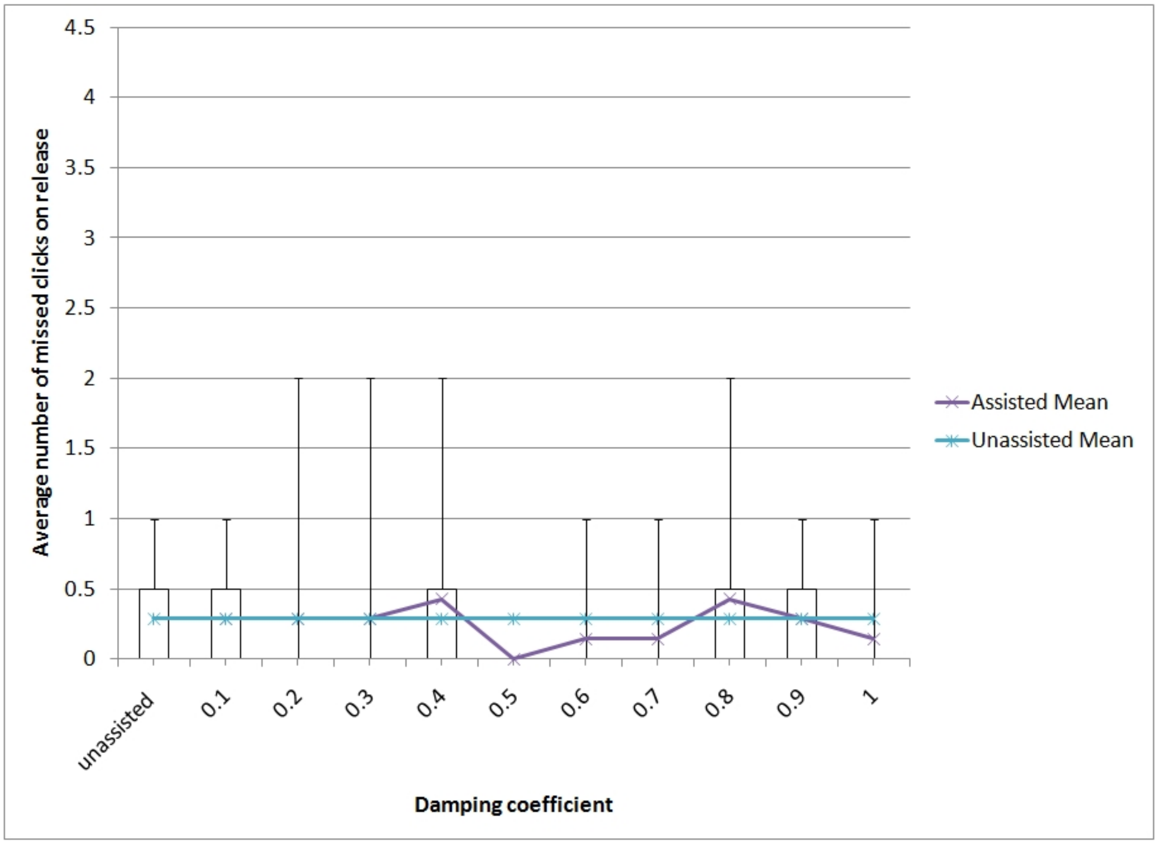

Figure 5.31: The average number of missed-clicks on release of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

Missed-Click on Click

It is apparent from the results shown in Figure 5.32 that an increase in the level of haptic damping can worsen the clicking performance of many users. The likely reason for this is that the increase in damping makes it more difficult to manipulate the device. As a result the operator is continually opposing a force which makes it more difficult to move the cursor to the desired location. For some damping levels the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph. For other damping levels only one operator performed a missed-click on click and as a result only the maximum whisker is visible.

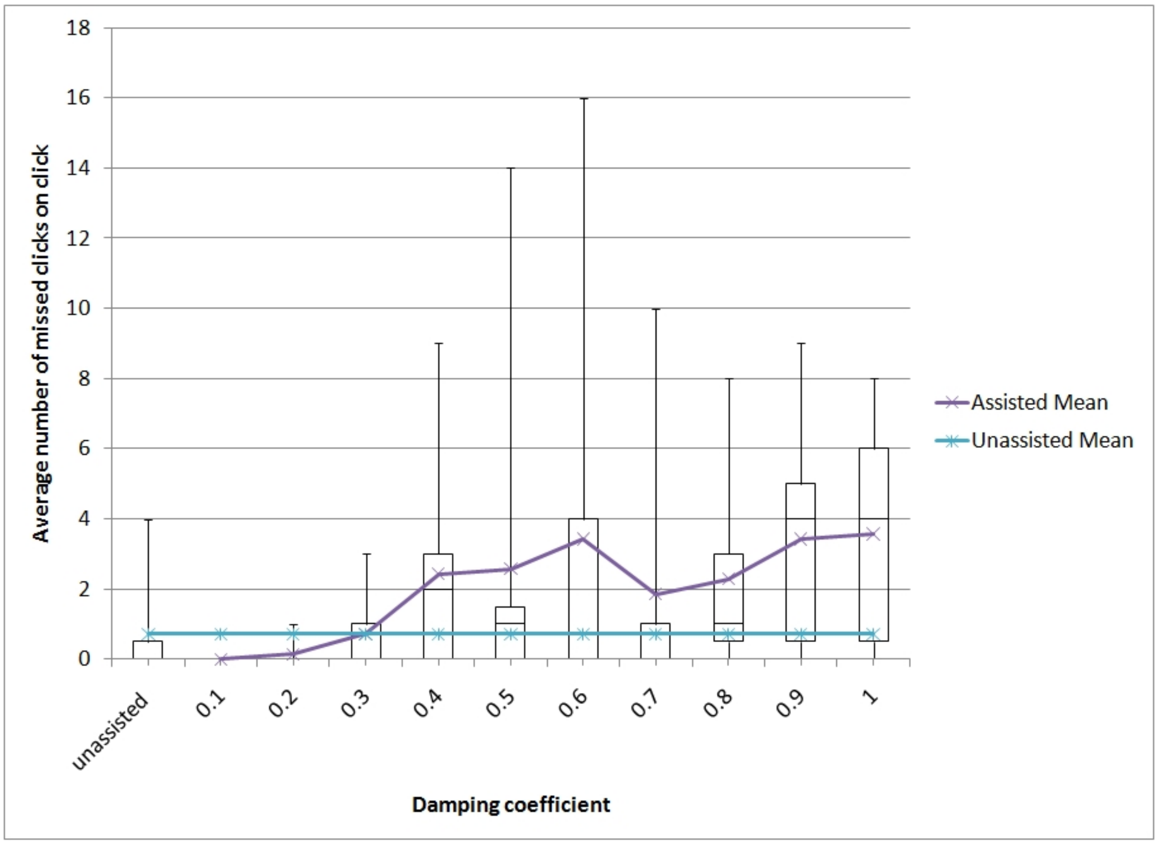

Figure 5.32: The average number of missed-clicks on click of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

Overshoot

It would be expected that damping would reduce the effect of overshoot as it should stabilise a person's movement towards a target. The results of Figure 5.33 show an improvement in average overshoot for the majority of damping levels when compared to the unassisted experiment. However, there are not any significant areas of correlation and so it is difficult to derive any conclusions that would be useful in the calibration of this technique.

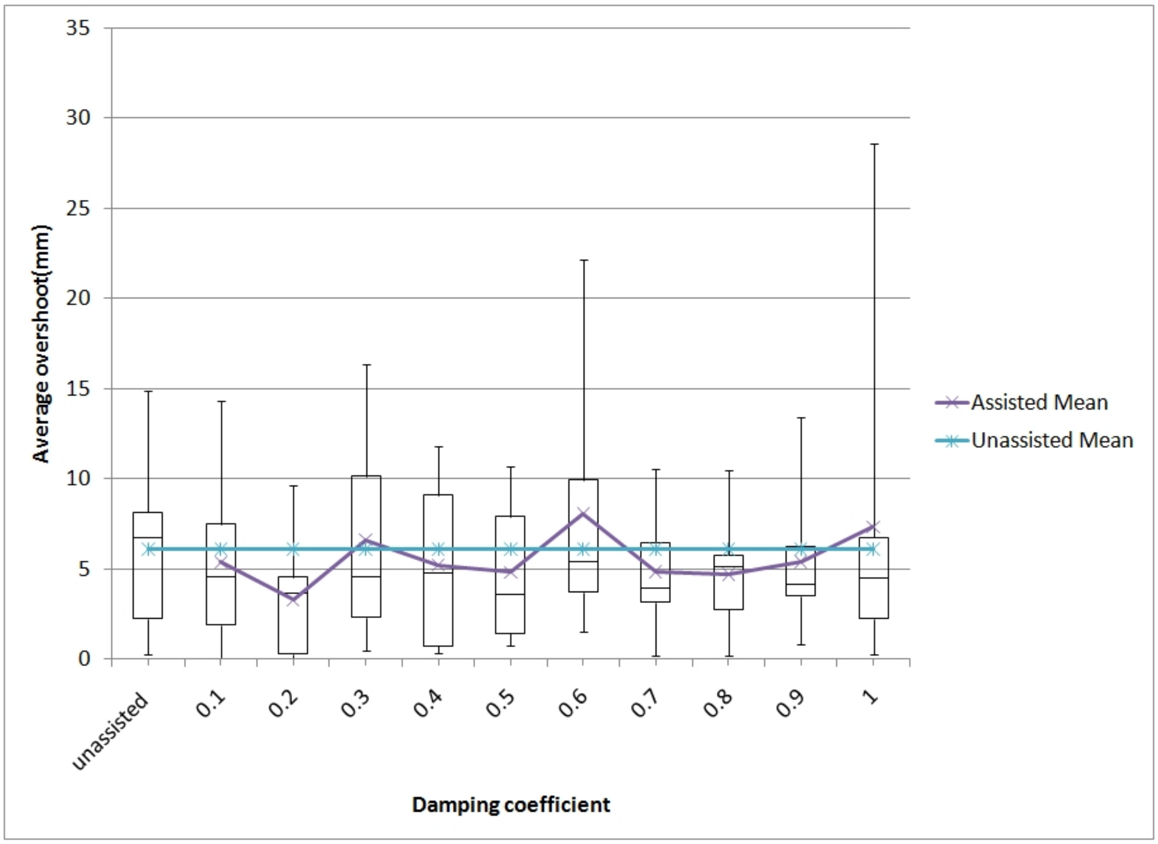

Figure 5.33: The average overshoot of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

Throughput

The average throughput levels produced at varying damping levels do not show any significant areas of correlation. At lower damping levels (up to 0.3) a small improvement in throughput is observed. At higher damping levels the throughput appears to deteriorate. The results are shown in Figure 5.34.

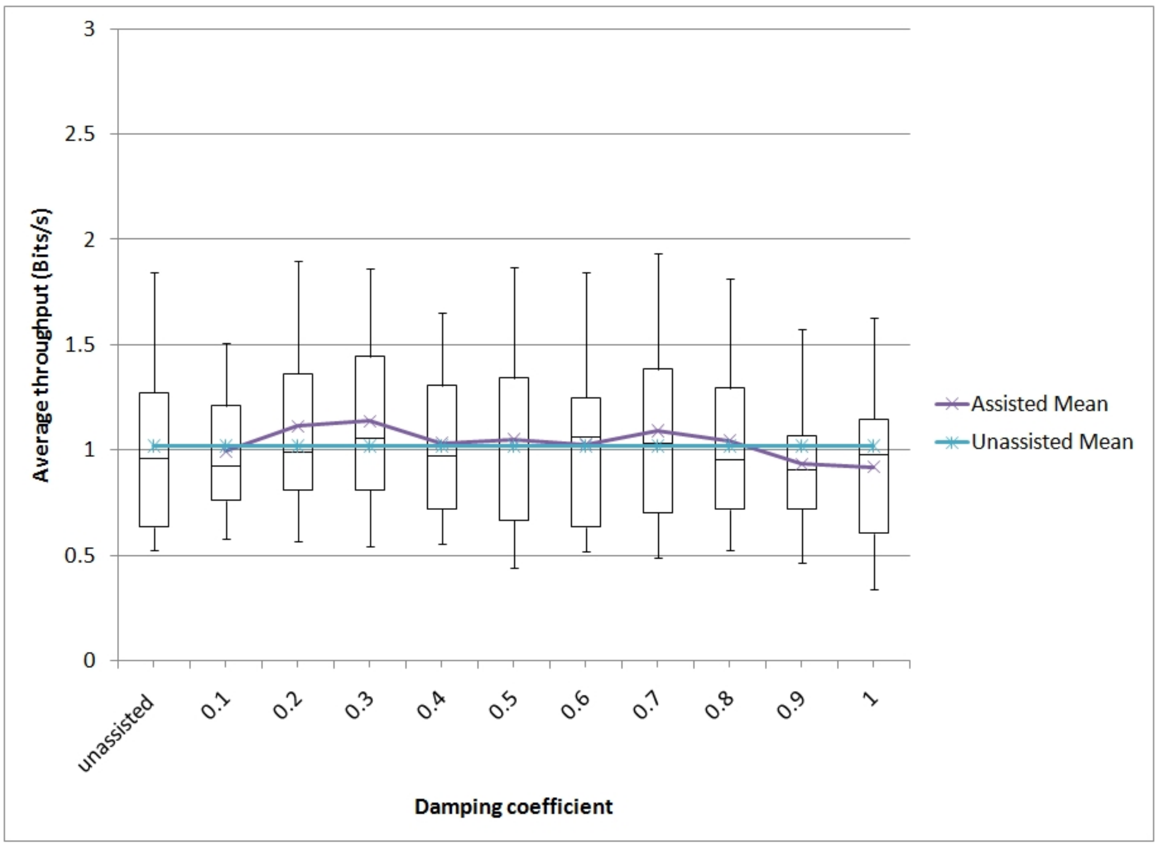

Figure 5.34: The average throughput of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

Movement Direction Change

One of the main aims of haptic damping is to filter out unwanted movements. The results in Figure 5.35 appear to show some improvement in the average number of movement direction changes compared to the unassisted experiment but not to any great extent. The level of damping does not appear to have a significant bearing on this measure.

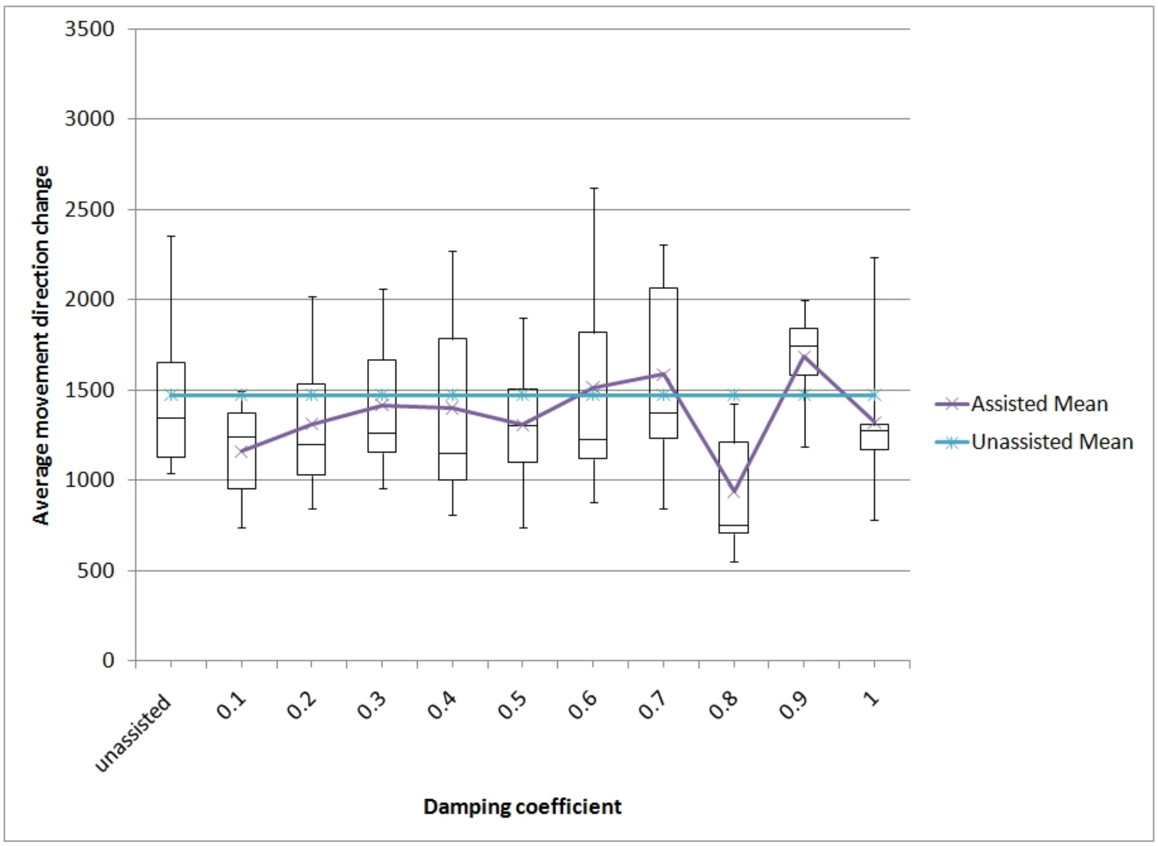

Figure 5.35: The average number of movement direction changes of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

Orthogonal Direction Change

Haptic damping appears to improve the measure for orthogonal direction changes, as shown in Figure 5.36. However, the results fluctuate significantly as the level of damping increases. This makes it difficult to produce any conclusions that would be useful in the calibration of haptic damping.

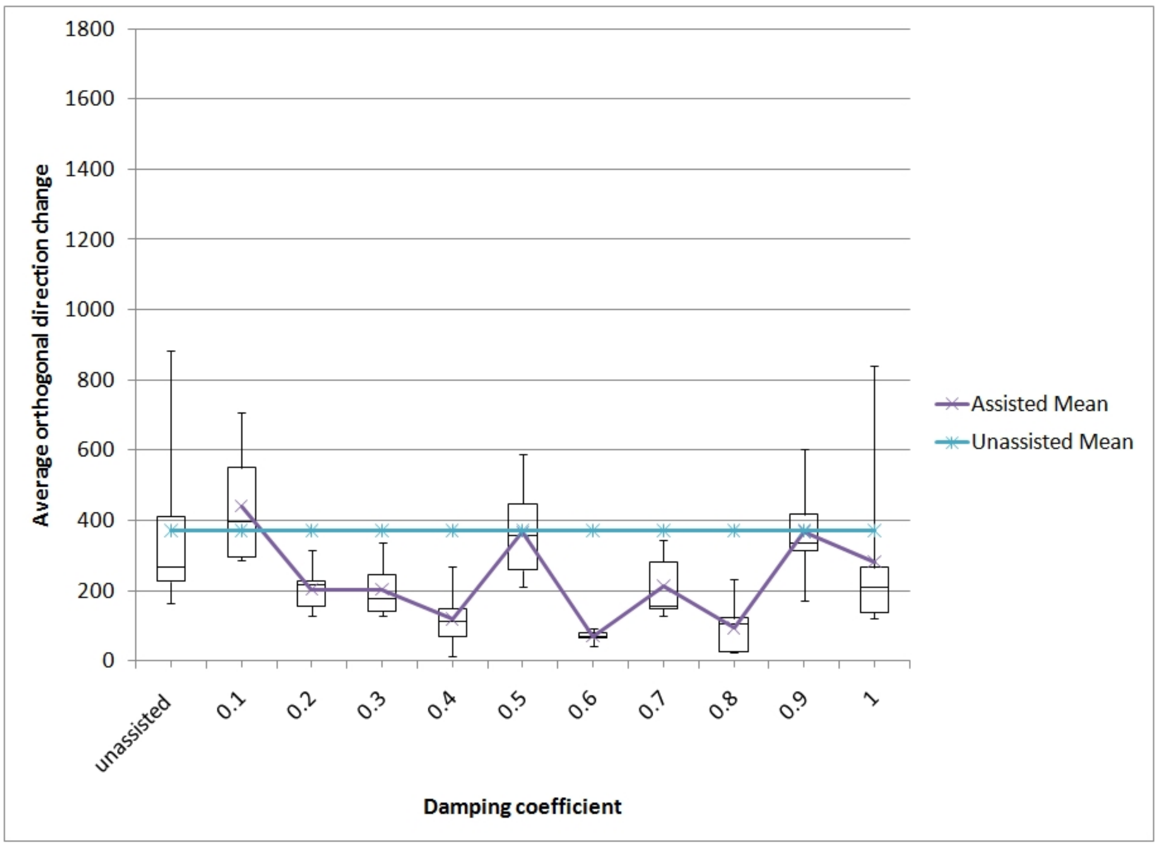

Figure 5.36: The average number of orthogonal direction changes of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

Movement Variability

The average movement variability seems to be improved by the introduction of haptic damping, as shown in Figure 5.37. The level of damping does not appear to have a significant influence on the level of improvement. Low levels of damping may help stabilise a free feeling device whilst greater damping levels may make the device more difficult to manipulate smoothly due to the increased motor workload.

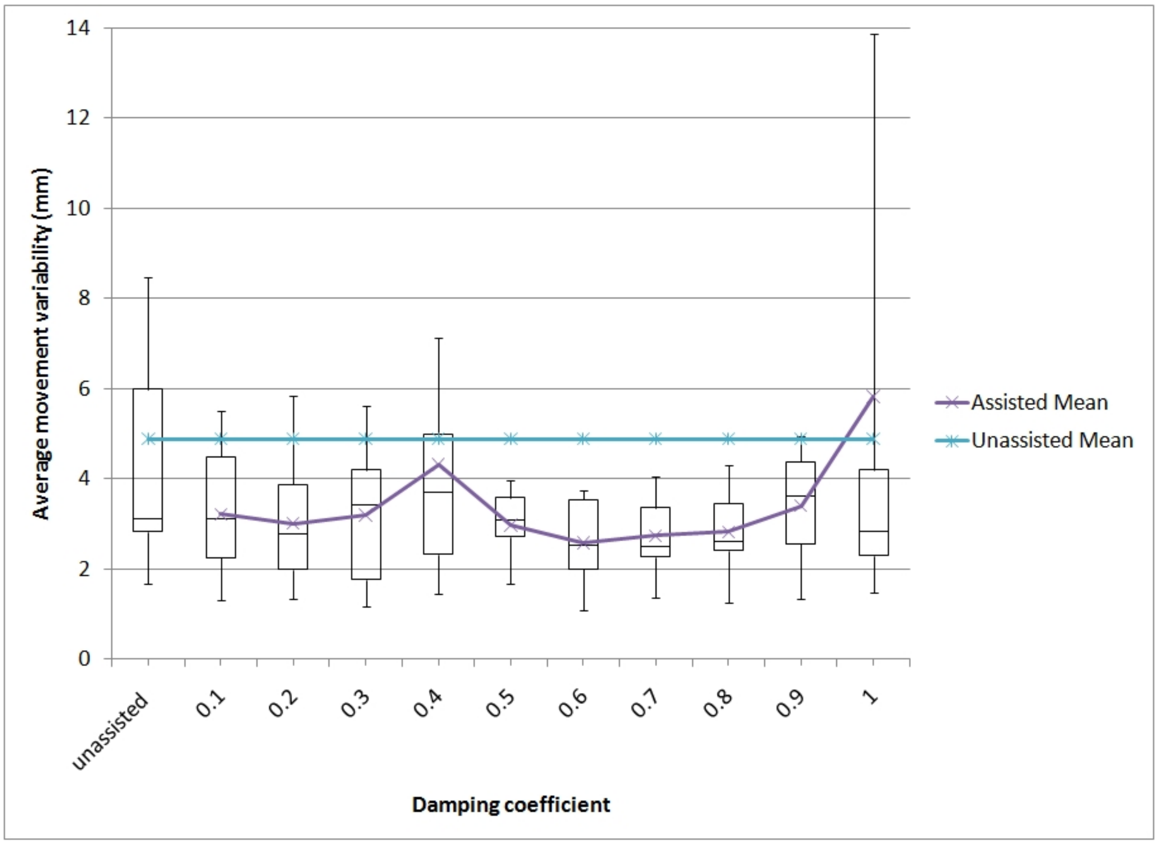

Figure 5.37: The average movement variability of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

Movement Error

The average movement error results in Figure 5.38 appear to show an improvement on the unassisted experiment. This suggests that damping reduces the movement away from the task axis. The level of damping does not appear to have a significant bearing on the result.

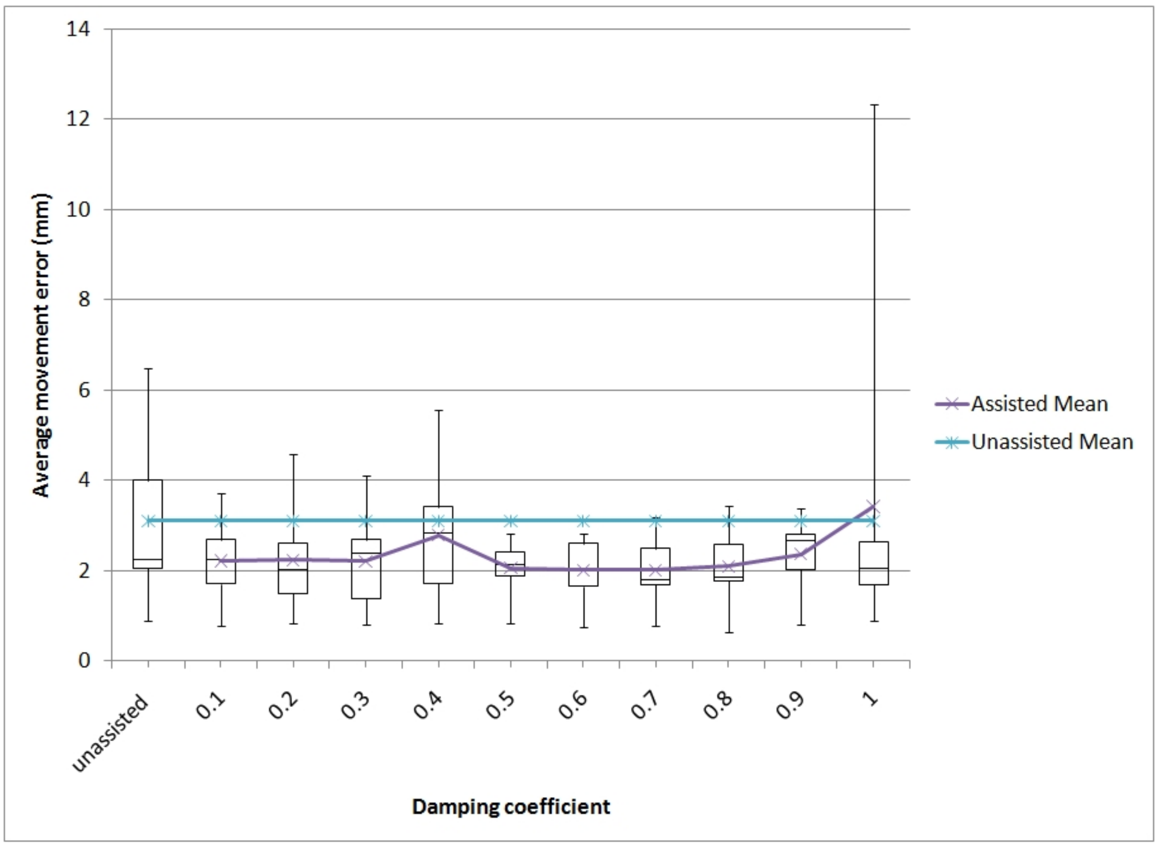

Figure 5.38: The average movement error of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

Movement Offset

The results produced in Figure 5.39 do not appear to provide any useful information on the movement offset. A motion impaired operator may produce many uncoordinated movements over the space of an experiment which could significantly distort this result.

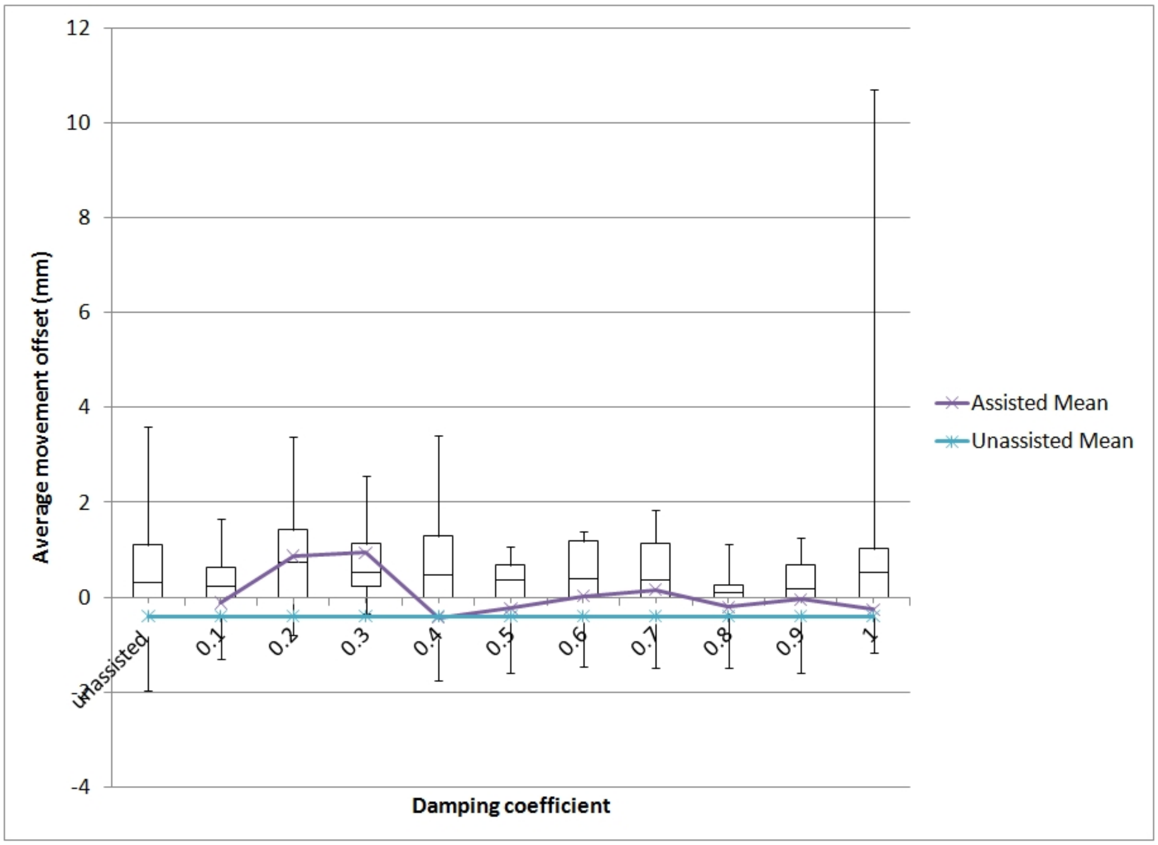

Figure 5.39: The average movement offset of seven motion impaired operators over fifteen successful selections is plotted against the varying level of damping.

5.8.2 Conclusions

Haptic damping does not appear to produce the same level of improvements as shown in previous studies [HLKC01]. Many measures seem to be worsened by the effects of haptic damping especially at higher viscosities. The likely reason for this is that the technique is intrusive so when the viscosity is increased it is more difficult to operate the device. By the end of the experiment some operators commented that they experienced arm ache due to the extra motor workload required to manipulate the device.

It appears that a low level of damping may assist the click-release displacement and distance travelled up until a damping level of 0.2. However, these measures were shown to significantly deteriorate after this damping level. Some improvements were found in the target homing measures but it is difficult to come to any strong conclusions from the results. There were not any strong areas of correlation and so it is difficult to identify any measures that would be useful in the calibration of this technique.

Non-intrusive filters may be more useful in reducing the effects of uncoordinated movements caused by spasm or tremor. The mouse adapter produced by Levine et al. [LS05] for people with hand tremor may be a better solution for disability in this area as it will assist without imposing a force on the operator.

5.9 Experiment 6 - Haptic Tunnels

Haptic tunnels clamp the operator to a set route from a starting location to the destination. A more direct path should improve the time to select between targets and reduce error rates. Previous studies [LHK+02b] have shown that this technique has produced the greatest improvement for operators with a higher severity of impairment. Haptic tunnels are designed to assist in target homing and so it will be these cursor measures that are the main concentration in the analysis.

5.9.1 Results

Movement Direction Change

The tunnel width did not have the expected results for the movement direction change. It was thought that thinner tunnels would produce more clamping and as a result reduce this measure. However, this is not shown in the results of Figure 5.40. The likely reason for this is that the thinner tunnels helped reduce the number of movement direction changes whilst the operator was navigating the tunnel but this had a trade off with the difficulty in actually selecting the desired channel. The operator may experience many additional movement direction changes just trying to select the desired tunnel.

Orthogonal Direction Change

The results in Figure 5.41 show that the average number of orthogonal direction changes is reduced by the introduction of haptic tunnels. The results fluctuate significantly and so it is difficult to identify areas of correlation that may be useful in the calibration of the tunnel width.

Movement Variability

The results in Figure 5.42 show an improvement in movement variability over the unassisted experiment. It was expected that the movement variability would be reduced by thinner tunnels due to the increased clamping. However, the opposite was observed in the results where there is a strong negative linear relationship between the movement variability and the increasing tunnel width (PMCC -0.826). It is more difficult to select the desired channel for thinner tunnels and so a higher error rate is recorded around the dead spot. As the tunnel width increases they still reduce excessive errors by clamping the proxy but are much easier to initially navigate.

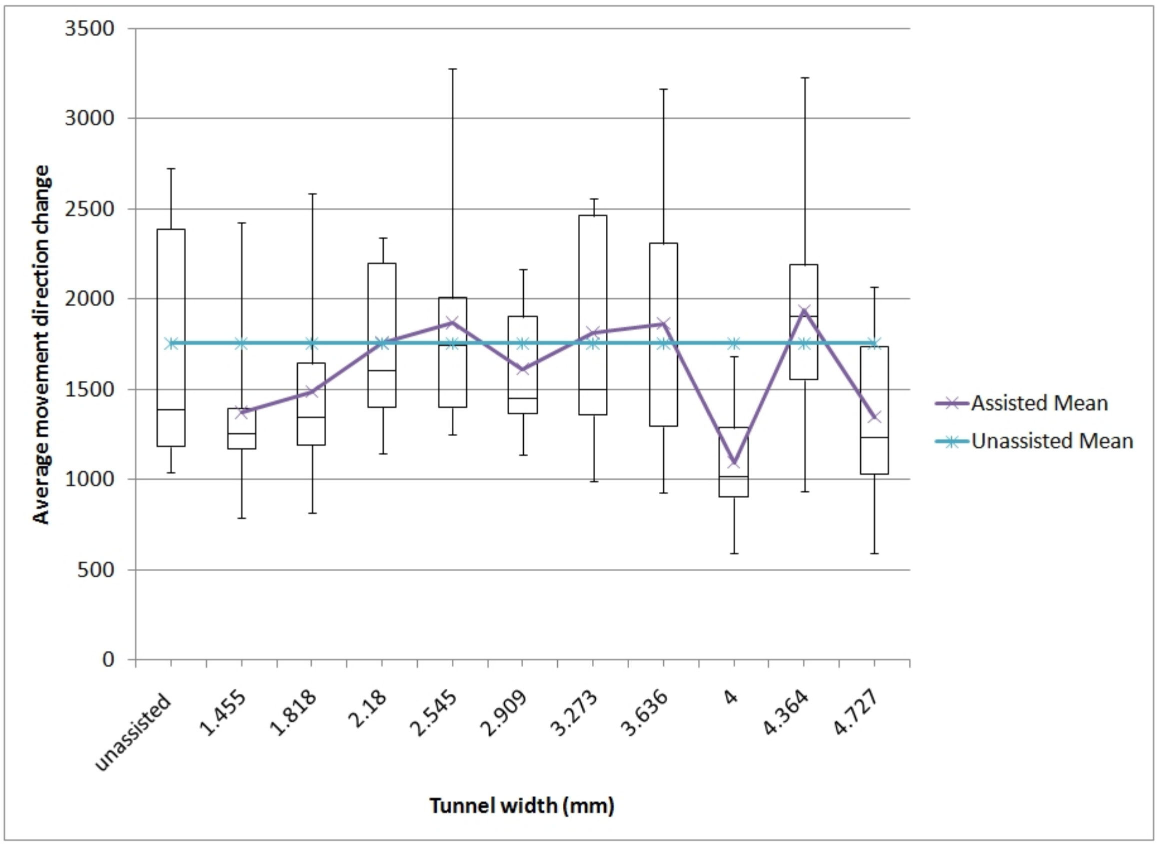

Figure 5.40: The average movement direction change of seven motion impaired operators over fifteen successful selections is plotted against the varying radius of haptic tunnels.

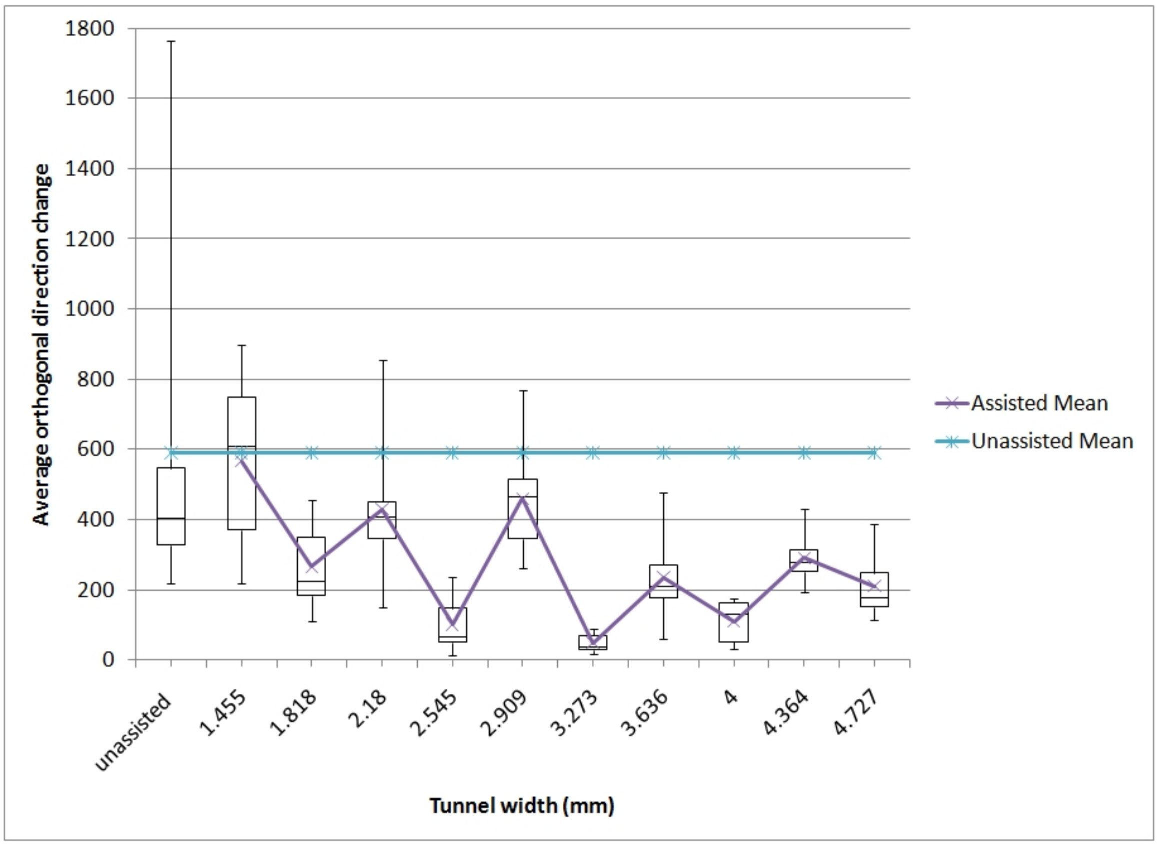

Figure 5.41: The average orthogonal direction change of seven motion impaired operators over fifteen successful selections is plotted against the varying radius of haptic tunnels.

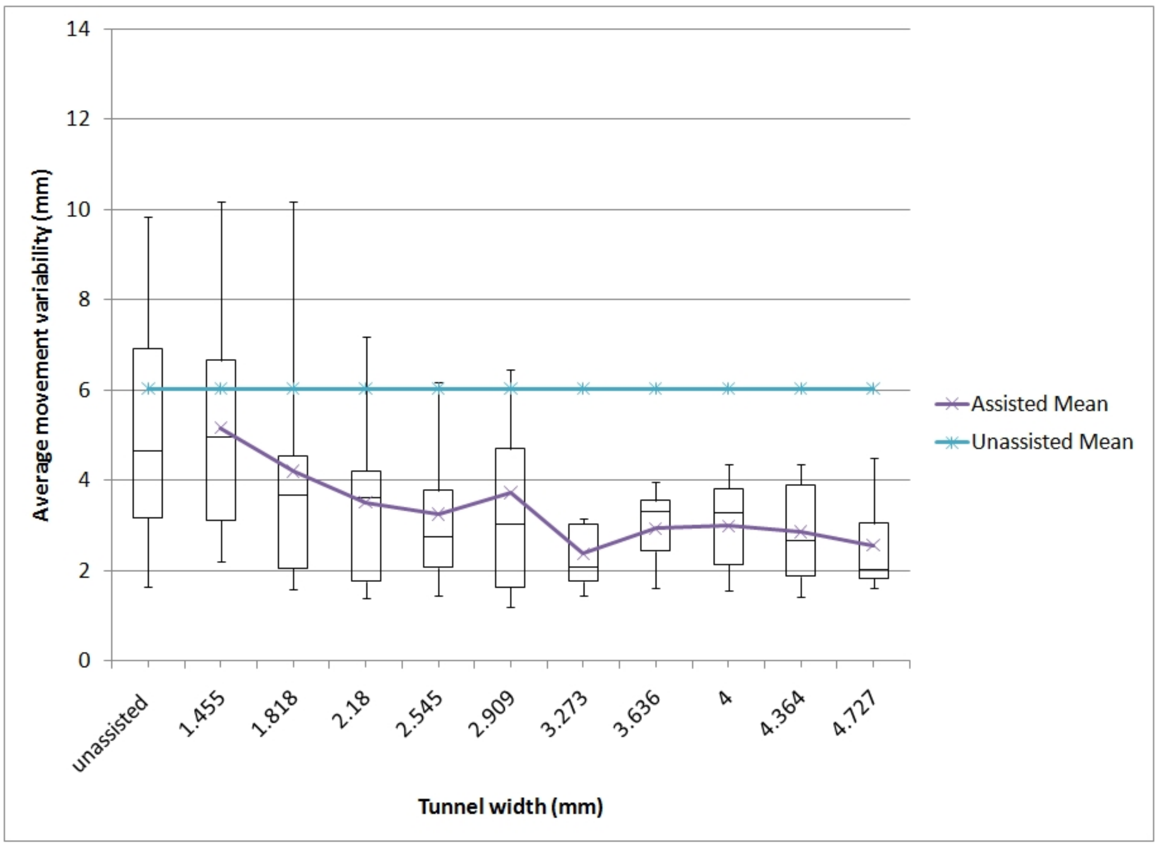

Figure 5.42: The average movement variability of seven motion impaired operators over fifteen successful selections is plotted against the varying radius of haptic tunnels.

Movement Error

The results from Figure 5.43 show that the movement error actually improves as the tunnels get wider. The reasons for this are that wider tunnels do not allow the operator to move excessively away from the task axis (which can distort the results) and the dead spot is wide enough so that the operator does not encounter problems when trying to select the desired channel. There was a strong negative correlation of -0.856 produced from the Pearson product-moment correlation coefficient (PPMCC).

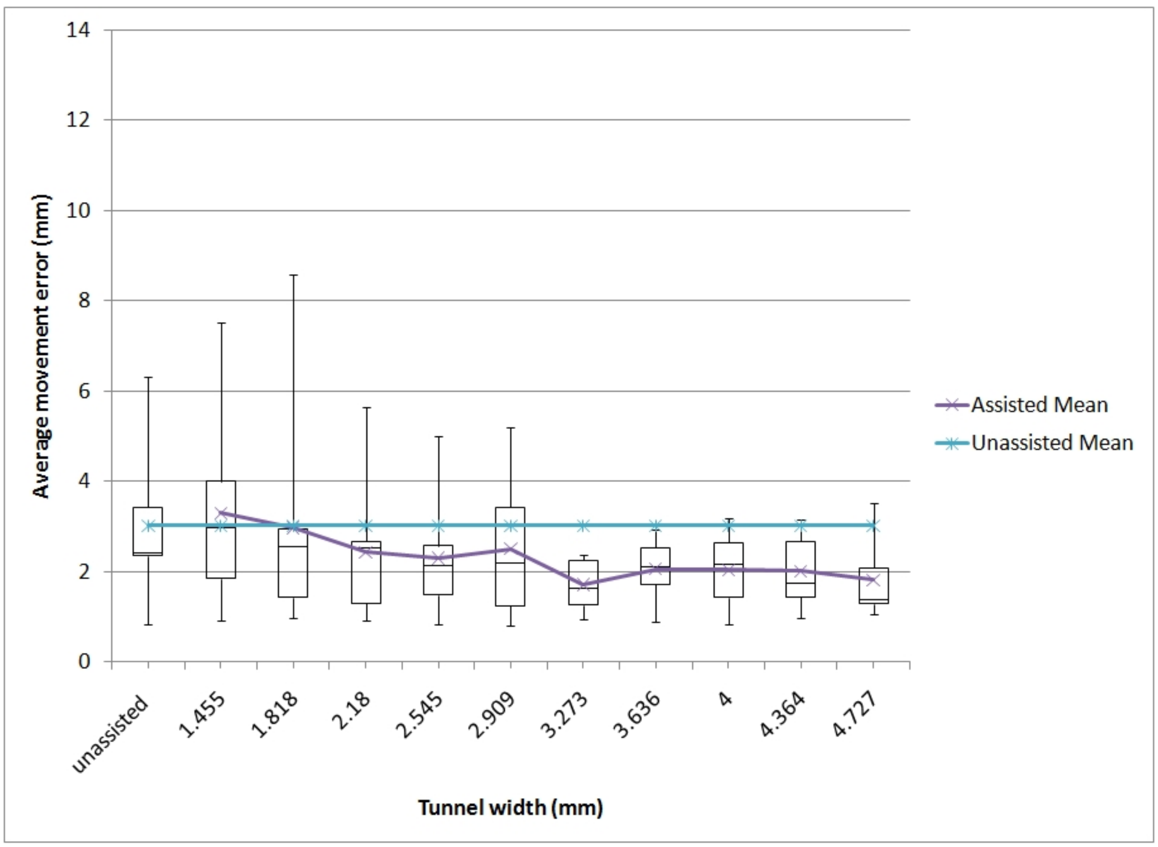

Figure 5.43: The average movement error of seven motion impaired operators over fifteen successful selections is plotted against the varying radius of haptic tunnels.

Movement Offset

The movement offset in Figure 5.44 shows an improvement on the unassisted experiment but does not provide any useful information on the effects of tunnel width.

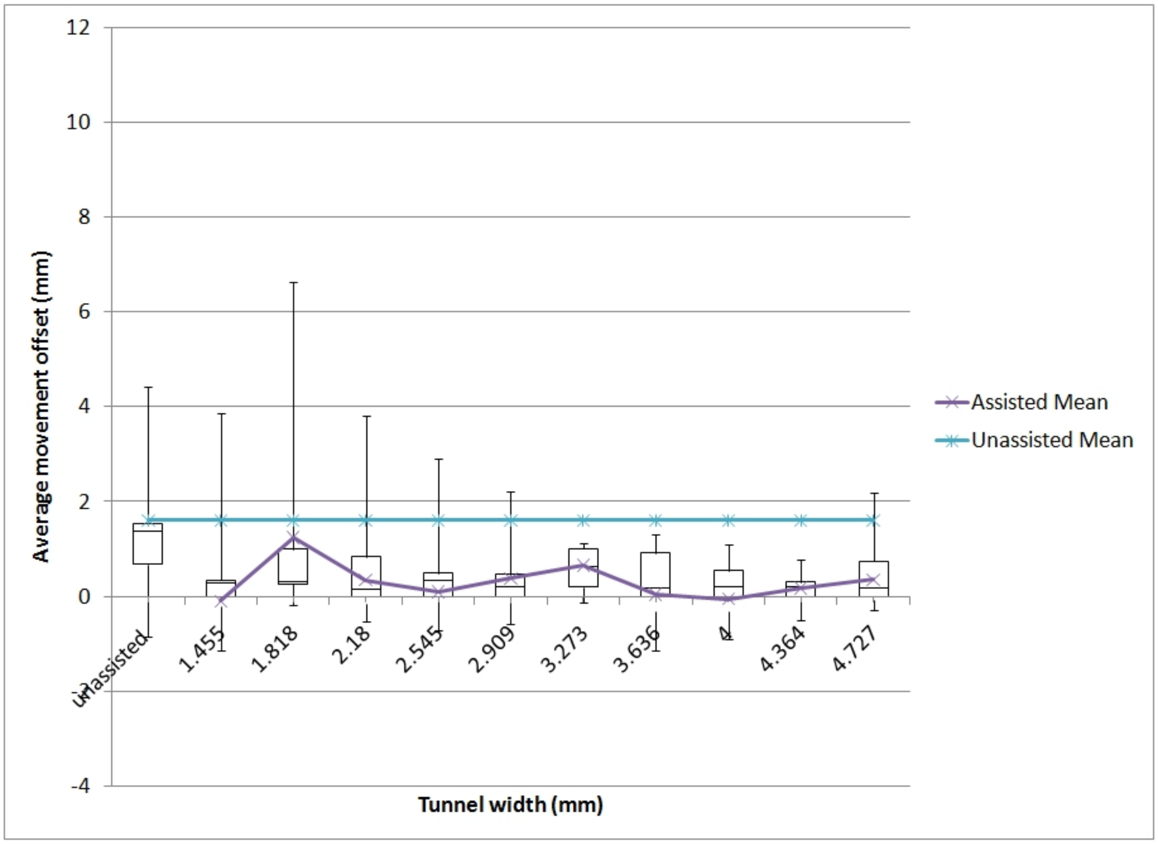

Figure 5.44: The average movement offset of seven motion impaired operators over fifteen successful selections is plotted against the varying radius of haptic tunnels.

Throughput

The difficulty of selecting the desired tunnel is shown by the assisted throughput measures in Figure 5.45. At lower tunnel widths the channels are much more difficult to select and so the navigation takes more time. It was observed in the experiment that an operator may begin navigating an undesired channel and then have to navigate back to the dead spot before continuing. As the tunnels become wider the operator will find it easier to select the desired channel and may benefit from a more direct route when compared to an unassisted interface.

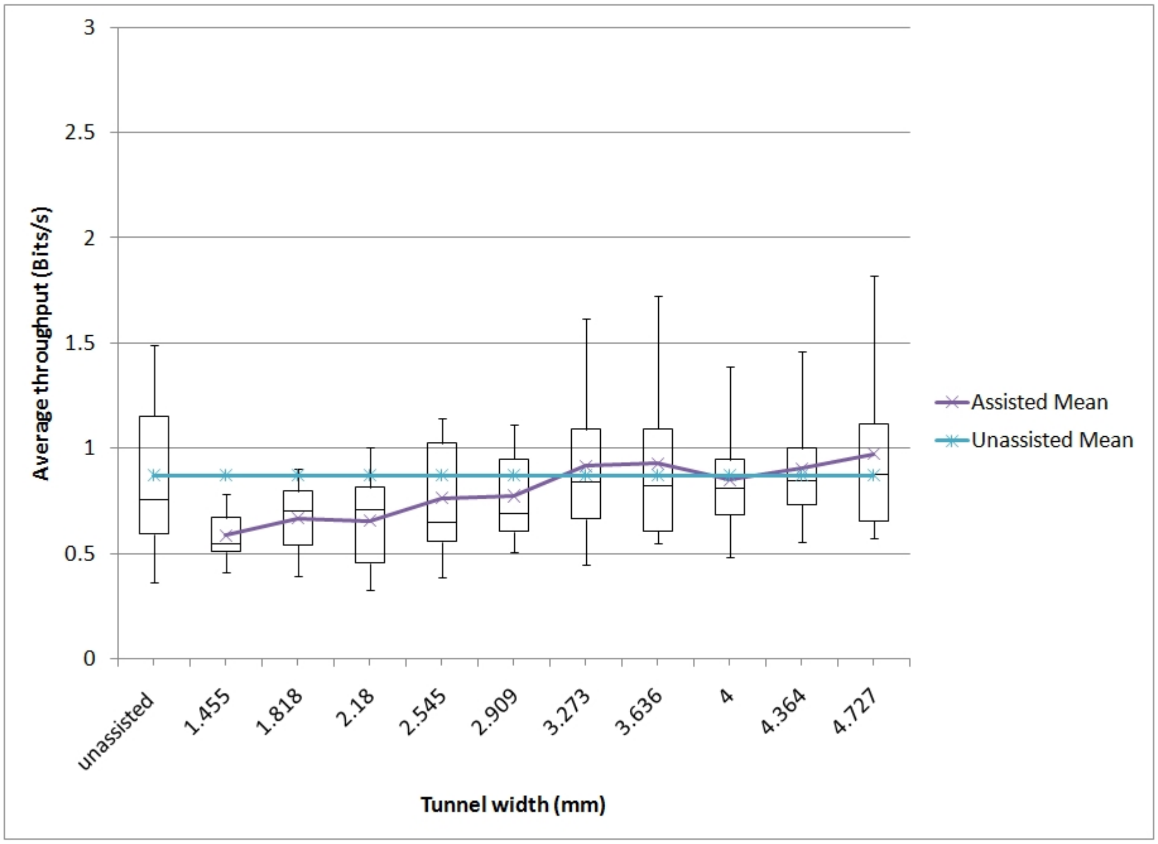

Figure 5.45: The average throughput of seven motion impaired operators over fifteen successful selections is plotted against the varying radius of haptic tunnels.

Conclusions

The results from the experiment show that the thinner tunnels may provide greater clamping but do not provide the best results. Measures such as movement variability, movement error and throughput actually improved as the tunnel width increased. A strong correlation was found between these measures and the increasing tunnel width. It is clear from the results and the experiment observations that each operator had difficulty selecting the desired channel when the tunnels were thinner. This meant that any benefits produced from the greater clamping were obscured by additional navigation errors.

The experiment layout will have a significant bearing on the effect of haptic tunnels. A central dead spot is convenient for navigating all four corners of the screen but the study has shown that many tunnels meeting at a single point can be detrimental to interaction. Alternative tunnel arrangements may cause navigation difficulties especially if the next path cannot be predicted.

This technique may benefit from having a set minimum tunnel width or a minimum sized dead spot. This would allow the operator to select the desired tunnel easily whilst receiving a suitable level of clamping. Further work would be required to determine the effect of the size of the dead spot.

In this experiment a tunnel was used with parallel walls. However, a funnel approach may be more suitable where the walls close in as the funnel approaches the target. This may benefit target acquisition as well as target homing by guiding the operator to the centre of the target. Further work is required to determine the effects a funnel would have on interaction.

5.10 Experiment Conclusions

Throughout the study a group of seven people provided the results for determining the effects of the type and level of assistance. One of the most noticeable results found in this study was that even on a weekly basis between analysis the habits of an individual can vary significantly. It was for this reason that the unassisted experiment was repeated for each experiment to give a fair comparison of the performance of the assisted techniques. The results confirm Koester's [KLS05] theory that the assistance must be dynamic to meet the needs of the individual during each session.

The results produced from the experiments show that the level of assistance can have a bearing on the performance of point and click tasks. For example, it was shown that increasing the spring stiffness of gravity wells and high-friction targets could significantly reduce the click-release displacement. Alternatively it was shown that higher levels of damping were detrimental to the click-release displacement and click-release distance travelled.

The results were very useful in identifying the key measures that were affected by each technique. It was also possible to identify areas of correlation in the clicking measures that will be useful in the calibration for each individual. It was shown that all the target acquisition techniques improved the click-release displacement. This was promising because it will be later shown in Section 6.1 that reducing the magnitude of this measure significantly reduces the chance of miss-clicking. It is for this reason that the click-release displacement is a good measure for determining if someone requires click assistance. There do not appear to be any significant detrimental effects of gravity wells, haptic cones, high-friction targets or haptic walls. One cursor measure that could be improved to provide more useful information is the missed-click on click. It would be useful to know if a target had already been entered before a miss-click on click is recorded to determine if the technique has been given a chance to assist.

The target homing techniques did not provide the level of performance expected. The likely reason for this is that haptic tunnels and haptic damping are very restricting to the operator. As a result any benefits that a technique may provide are obscured by other difficulties encountered. These would include the extra motor workload for haptic damping and the difficulties in navigating the correct channel for haptic tunnels. It was shown that high levels of damping could be significantly detrimental to interaction. As the expected performance increases were not observed in the homing techniques no further analysis will be taken at this stage. The results did not produce any significant areas of correlation that would be useful in the calibration of these techniques. The experiment layout is perhaps not appropriate for analysing the tunnel network as it would be unlikely to have sixteen tunnels meeting at a single point in an existing GUI. Further work is required to determine the effects of homing assistance. If someone does not have the range of motion to approximately locate the target then it may be the case that haptic assisted interfaces may not be the most appropriate solution. The following subsection provides a 'potential performance' comparison of the target acquisition techniques.

5.10.1 Potential Performance Comparisons - Target Acquisition Techniques

One of the most useful conclusions of the study would be to determine if certain techniques perform better than others. The measures most useful for comparing the target acquisition techniques are the click-release displacement and click-release distance travelled. The reason for this is that the levels of these measures were shown to be proportional to the number of missed-clicks, as shown in Figure 6.1 in the next chapter. The missed-click on release will be the best clicking measure to use as it guarantees that the operator has been provided with some assistance. Throughput will be useful for indicating which techniques improved the time to complete the task. Finally, many of the techniques were shown to reduce the effects of overshoot and so it will be useful to determine which one provides the best braking effect.

To compare the performance between techniques using a statistical method is difficult. The reason for this is that each experiment was taken on a different weekly session and the cursor habits of an individual can vary significantly in this time. This may have a bearing on the performance of the operator and the assistance. In addition to this there were ten experiments taken for the techniques that have calibration variables and just one experiment for the non-calibrating techniques.

One way to determine the performance increase of each technique is to divide the cursor measures of the unassisted experiments by the same measures of the assisted experiment. A result recorded that is higher than one will indicate a performance increase. To get some comparison of the potential performance benefits of each traditional technique the best recorded cursor results were taken from each individual across the whole range of assistance. The assumption made here is that the software will be able to perfectly calibrate each technique to produce the best results for each cursor measure. In practice this is unlikely but it will be useful in providing a 'potential performance' comparison between techniques. The results are shown in Table 5.2 and Figure 5.46.

	Gravity Wells	Haptic Cones	Friction Targets	Haptic Walls
missed-clicks on release	None recorded	None recorded	None recorded	1.000
Average successful Click-Release Distance travelled	2.087	2.611	10.673	1.007
Average successful Click-Release Displacement	2.048	3.178	6.499	1.281
Average Overshoot	None recorded	1.828	22.760	2.171
Throughput	1.383	0.806	1.614	1.109

Table 5.2: The best average potential performance ratio of seven operators for each cursor measure using each type of assistance. The potential performance ratio is calculated by taking the unassisted measure for each cursor measure and dividing it by the same best result across the range of assistance.

One thing that needs to be taken into consideration is that each calibrated technique is given ten opportunities to produce the best (or worst) result whereas the non-calibrating techniques are given just one opportunity. A more useful comparison will be made between the final calibrated traditional techniques and the new non-calibrated techniques in Chapter 6.

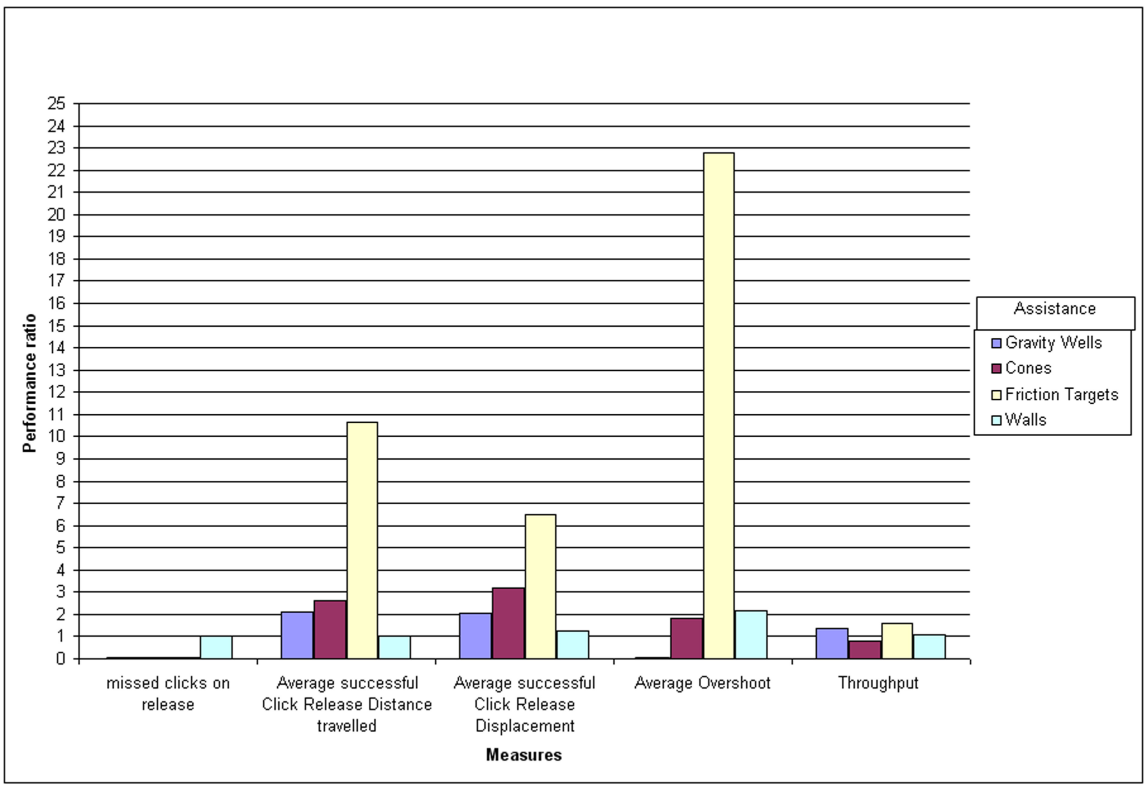

Figure 5.46: The best average potential performance ratio of seven operators for each cursor measure using each type of assistance. The potential performance ratio is calculated by taking the best result for each cursor measure across the range of assistance and dividing it by the same unassisted measure.

Click Measure Comparisons

High-friction targets seem to have the potential to produce the best results for the click-release displacement and distance travelled. It is unsurprising that no missed-clicks on release were observed if the technique is calibrated perfectly.

Haptic cones produced the next best performance increase in click-release displacement and distance travelled. This is because the proxy is clamped to the apex of the cone which provides good stability for clicking. As the apex is positioned at the centre of the target there is a much greater chance of selecting it successfully if the proxy moves slightly. This is supported by the fact that no missed-clicks on release were recorded by anyone in the cone assisted experiment.

Gravity wells produced the third best performance increase in click-release displacement and distance travelled. Although the measure is not as strong as high-friction targets it was shown that gravity wells have the potential to reduce the number of missed-clicks on release to zero. This supports the theory that providing assistance at the centre of a target can produce better results.

Very little performance difference was observed in the click-release displacement and distance travelled for haptic walls. This would explain why there were not any performance increases observed in the miss-clicks on release measure for this technique.

Overshoot Comparisons

Gravity wells provide a significant performance increase in overshoot. This will be credited to the braking effect gravity wells have on the operator. A low number of target re-entries were recorded for this experiment and so it is unsurprising that the resulting overshoot measure is low. The gravity well effect is enforced off the plane and this has shown to be significant in reducing the effects of overshoot. High-friction targets were shown to produce the next best levels followed by haptic walls and haptic cones. These improvements will be credited to each technique's unique braking effect.

Throughput Comparisons

The throughput comparisons of each technique are very similar. A small increase in throughput was observed by high-friction targets, gravity wells and haptic walls. The small decrease observed in haptic cones is very minimal and with increased practice of using the technique the throughput is likely to increase. There were no significant performance differences observed between techniques.

Having established the key performance differences between techniques the following chapter identifies the key measures used for the appropriate selection and calibration of targeting based haptic assistance.

Chapter 6

Experiments - Haptic Assistance Selection and Calibration

The results of the previous chapter have been useful in identifying the effects of each haptic technique and the bearing the level of assistance has on interaction. The key calibration variables have been established and will be used to select an appropriate level of assistance for the individual. Wall et al. [WPS+02] place emphasis on achieving a suitable level of assistance without constraining the operator too much. The success of the calibration will be governed by the improvement over the unassisted experiments and how closely the results compare to those of an average able bodied person. If it is possible to improve the results of a motion impaired operator to the level of an able bodied person then the calibration will have been hugely successful. A final performance comparison between techniques will be made at the end of the chapter.

6.1 Target Acquisition Techniques

The analysis of each haptic technique has been useful in identifying key areas of improvement in target acquisition. By analysing the unassisted experiments it was shown that users with a low click-release displacement and low click-release distance travelled were less prone to miss-clicking. A strong correlation was found between the number of missed-clicks and the click-release displacement with the PPMCC producing a value of 0.797. A strong correlation was also found between the number of missed-clicks and the click-release distance travelled, with the PPMCC producing a value of 0.929. These correlations were found over the fifteen successful selections of the ISO 9241-9 based task. The results of this are shown graphically in Figure 6.1. It should be noted that no missed-clicks were recorded for a frequency of 9 or 11 and so there is a gap for these values.

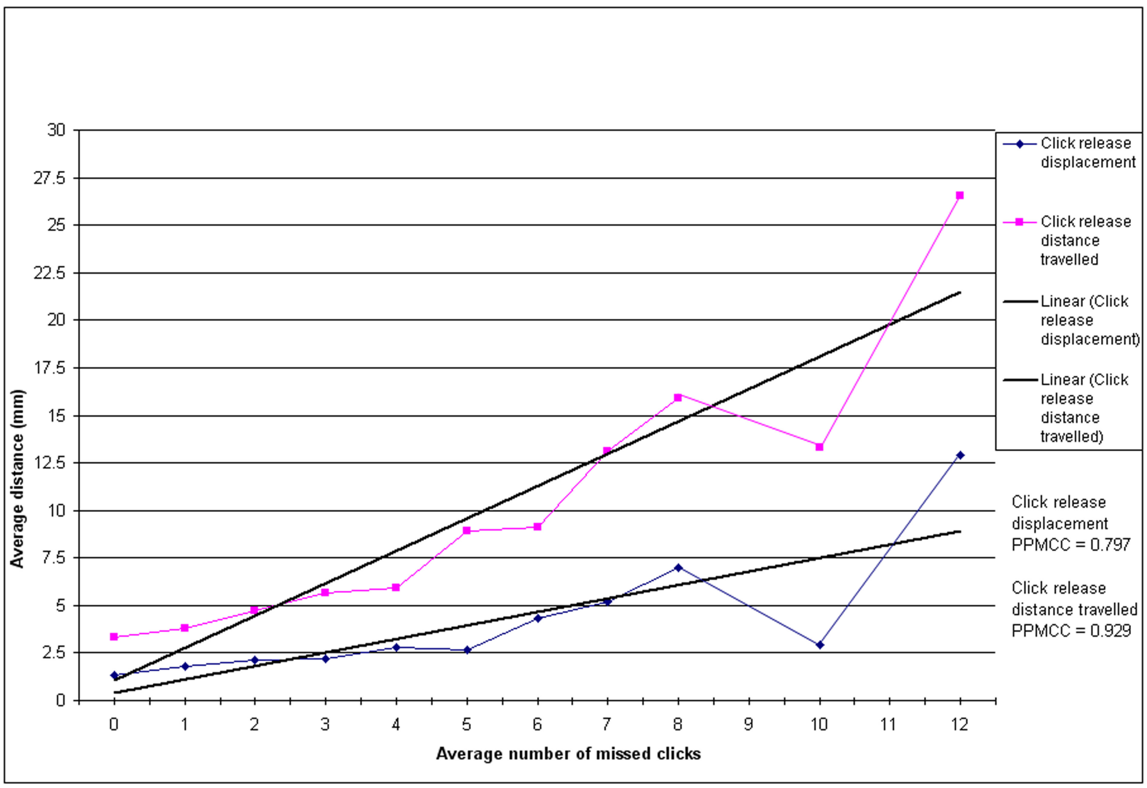

Figure 6.1: The average number of missed-clicks is plotted against the corresponding average click-release displacement and distance travelled.

Seven able bodied operators were asked to perform the same ISO 9241-9 based task without assistance. The results from the able bodied operators produced an average click-release displacement of less than 0.7mm with a very low number of missed-clicks, as shown further on in Table 6.1. This click-release displacement will be used as the benchmark to determine if an operator requires click assistance. If an operator has a click-release displacement less than or equal to 0.7mm then their performance will be similar to an able bodied operator and they will not require click assistance because they already have a steady click.

Koester et al. [KLS05] discuss the importance of a dynamic system that will adjust to a person's ability in both the long term and the short term. The dynamic calibration of each technique that requires tuning will be governed by the average click-release displacement. For example, if a person's click-release displacement continues to rise above 0.7mm then the level of assistance will be increased to provide greater clamping. The click release distance travelled was not chosen because it can be distorted by certain haptic techniques such as gravity wells and high-friction targets.

6.1.1 High-Friction Targets - Calibration

To fully utilise high-friction targets it will be necessary to calibrate them to meet the needs of the individual. It was observed in previous experiments that some operators could have difficultly navigating to the centre of a target if the friction level was too high. The results from the study on high-friction targets, in Section 5.5, indicate that the key measures are the click-release displacement and the missed-click measures. Increases in dynamic friction were shown to improve the click-release displacement and therefore should reduce the number of missed-clicks.

Stage 1 - Initial Unassisted Analysis

The first stage of the proposed method for calibrating high-friction targets is to ask the user to perform a full stage of the point and click task (15 successful clicks) without assistance. Once this stage has been completed the person's average successful click-release displacement can be evaluated. If the click-release displacement is equal to or below the average able bodied result then the operator will not require assistance.

Stage 2 - Initial Dynamic Friction Calibration

If the successful click-release displacement is above the able bodied average (0.7mm) then an estimate of the dynamic friction level required will be made for the first stage of calibration. This will be based on the graph in Figure 6.2. The graph shows the average click-release displacement of six operators with an unassisted click-release displacement above 0.7mm against the lowest corresponding dynamic friction level that provided a click-release displacement less than or nearest to 0.7mm. (The seventh operator was below the 0.7mm threshold).

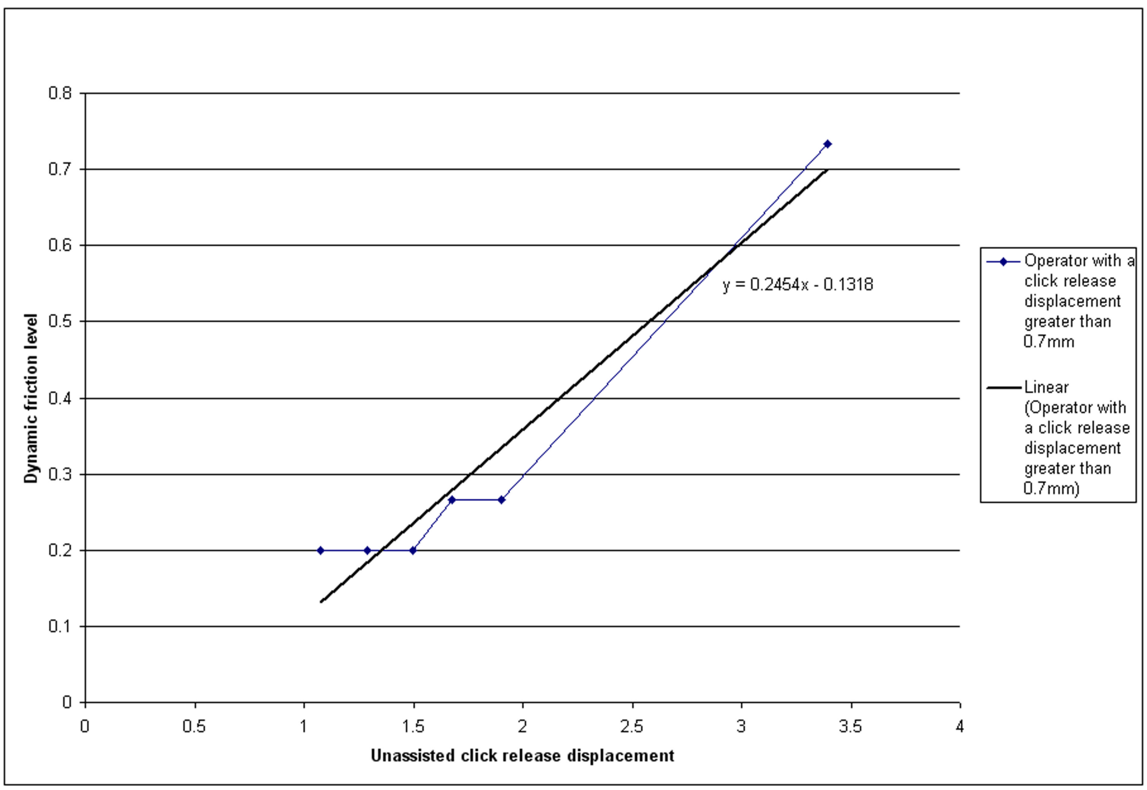

Figure 6.2: The lowest dynamic friction level for each individual to produce an average click-release displacement less than or approximately 0.7mm.

These results will be used to approximate a suitable level of assistance for the first stage of selections. Any inappropriate levels of assistance will be rectified in the following calibration stage. The equation of the line can be used to estimate this initial dynamic friction level which is given in the form of y = mx + c.

y = 0.2454x - 0.1318

Stage 3 - Further Dynamic Friction Calibration

Once the initial dynamic friction level has been selected the user will be asked to perform the task again with the high-friction targets enabled. At the end of this stage (15 successful clicks) the click-release displacement will be re-evaluated as follows.

- if the average successful click-release displacement lies in a range of 10% (0.63mm) below and 25% (0.875mm) above the able bodied 0.7mm threshold then maintain the current friction level.
- if the average successful click-release displacement is greater than 25% (0.875mm) of the able bodied 0.7mm threshold then increase the dynamic friction level by 10% (0.08) of the maximum stable friction level (0.8).
- if the average successful click-release displacement is less than 10% (0.63mm) of the able bodied 0.7mm threshold then decrease the dynamic friction level by 10% (0.08) of the maximum stable friction level (0.8).

Ten percent was chosen for the lower threshold limit to ensure that the dynamic friction level would reduce if the level of assistance was too high. Twenty five percent was chosen for the upper threshold limit to ensure that the level of dynamic friction would only be increased if the operator definitely requires stronger assistance. The process will be repeated a total of 10 times to evaluate the results of the calibration.

6.1.2 Results

Successful Click-release Displacement

The results produced in Figure 6.3 show that the calibrated high-friction targets can reduce the click-release displacement. All of the average calibrated measures are below that of the unassisted experiment. It is also clear from these results that the initial level of dynamic friction is appropriate as it is not dissimilar to the results that follow it.

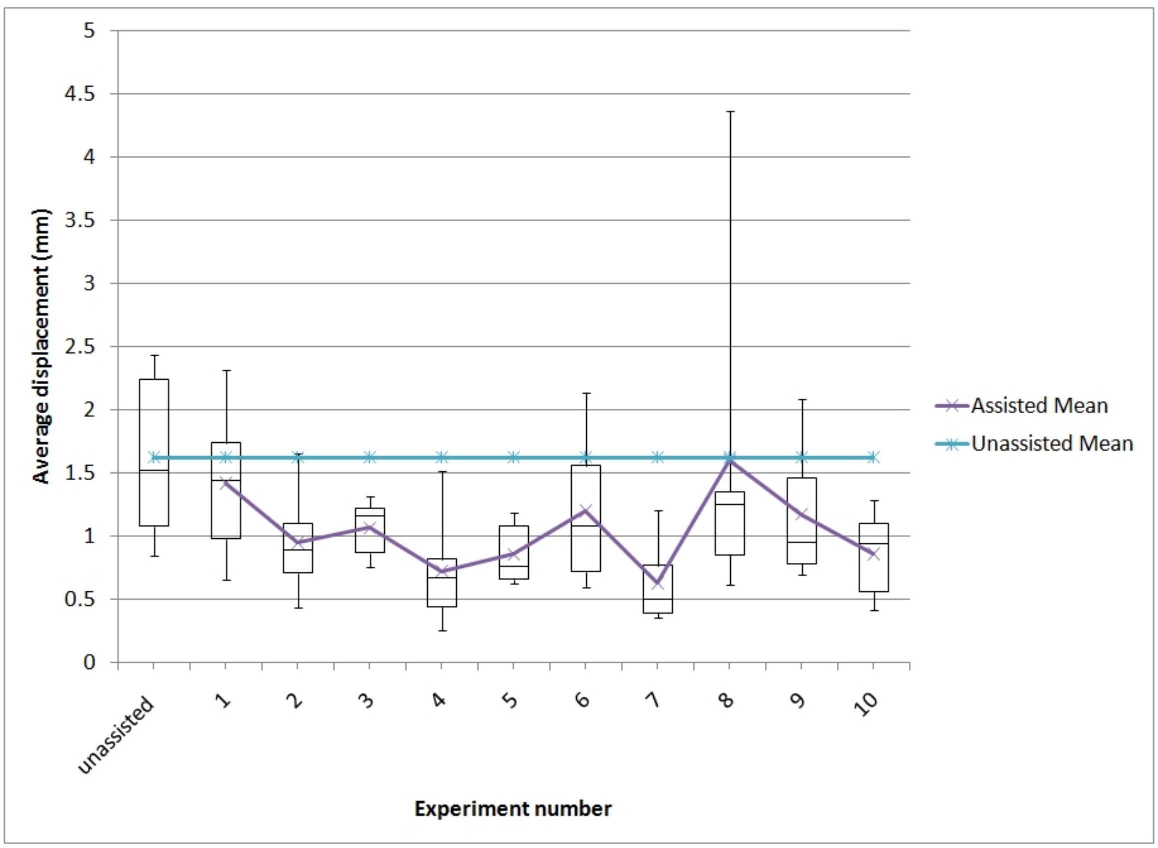

Figure 6.3: The average successful click-release displacement of seven motion impaired operators over fifteen successful selections using calibrated high-friction targets.

Successful Click-release Distance Travelled

The average click-release distance travelled measure shows a significant improvement with calibrated high-friction targets when compared to the unassisted experiment. The results are shown in Figure 6.4. All average assisted results are over halved when compared to the unassisted experiment.

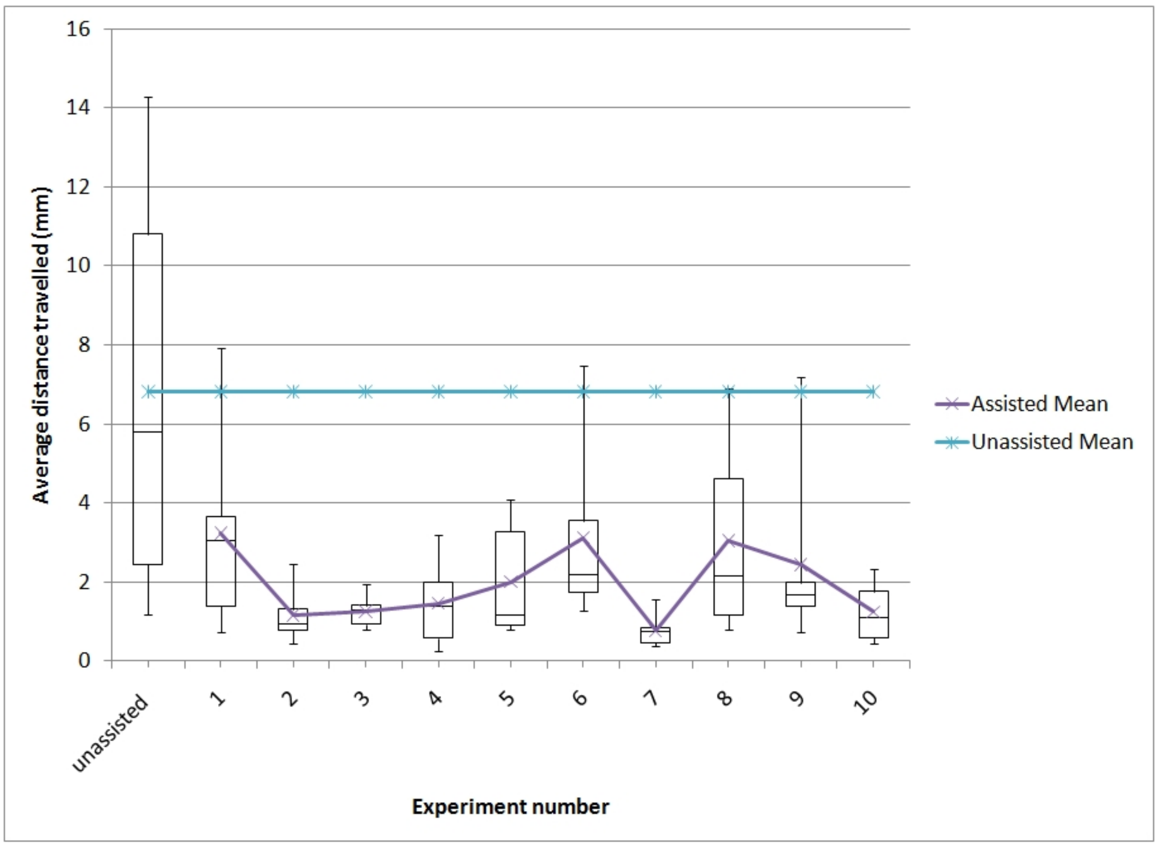

Figure 6.4: The average successful click-release distance travelled of seven motion impaired operators over fifteen successful selections using calibrated high-friction targets.

Missed-Click on Release

The number of missed-clicks on release appears to fluctuate between experiments, as shown in Figure 6.5. One result produced the same number of average missed-clicks on release as the unassisted experiment but all the other results lie below that line. No missed-clicks on release are recorded for any operator on four occasions. For some experiments the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph. For other experiments only one operator performed a missed-click on release and as a result only the maximum whisker is visible.

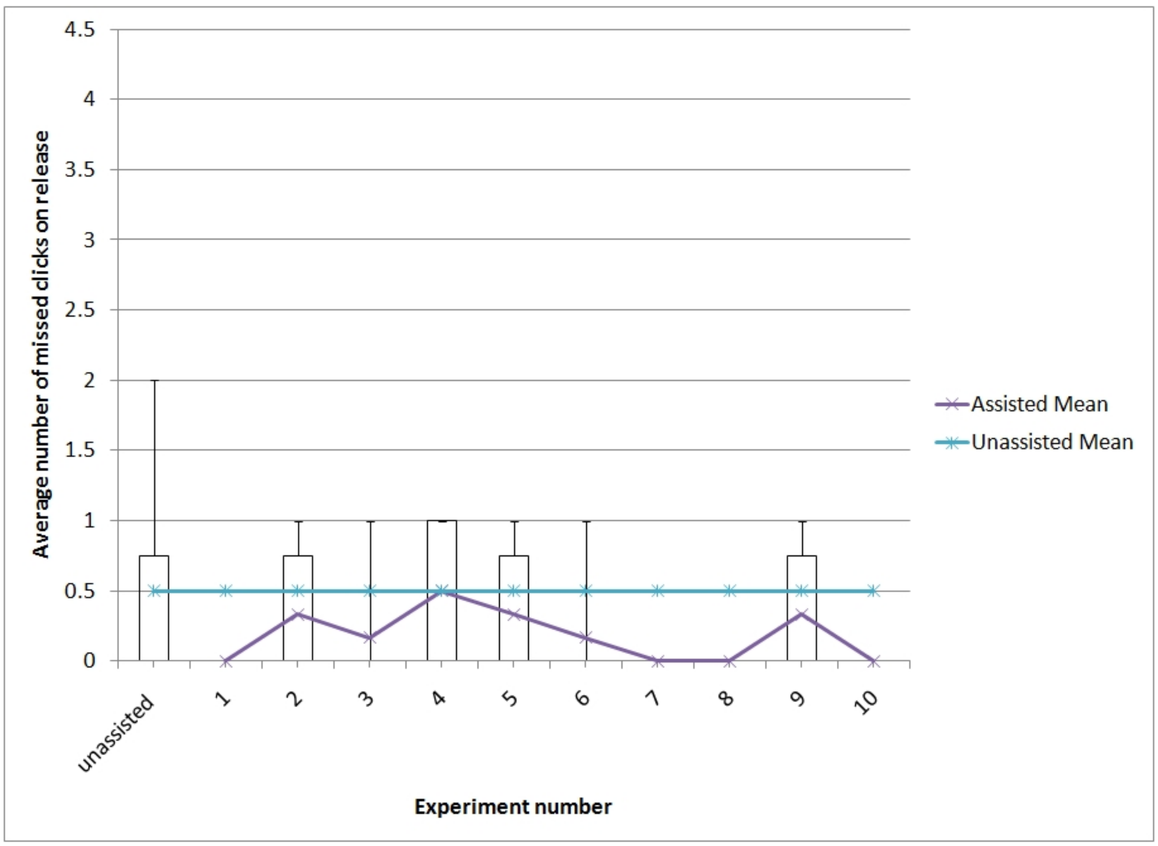

Figure 6.5: The average number of missed-clicks on release of seven motion impaired operators over fifteen successful selections using calibrated high-friction targets.

Missed-Click on Click

High-friction targets do not appear to benefit the missed-click on click measure when compared to the unassisted experiment, as shown in Figure 6.6. This was also recorded for the previous experiment in Section 5.5. It has been observed in the experiments that some operators have difficulty navigating to the centre of a target due to the friction force. Many operators attempted to acquire the target at its edge and so a slight movement may draw the proxy off the target and result in a missed-click. There may be valid reasons to only execute the operation on the click release if high-friction targets are in use. For some experiments the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph.

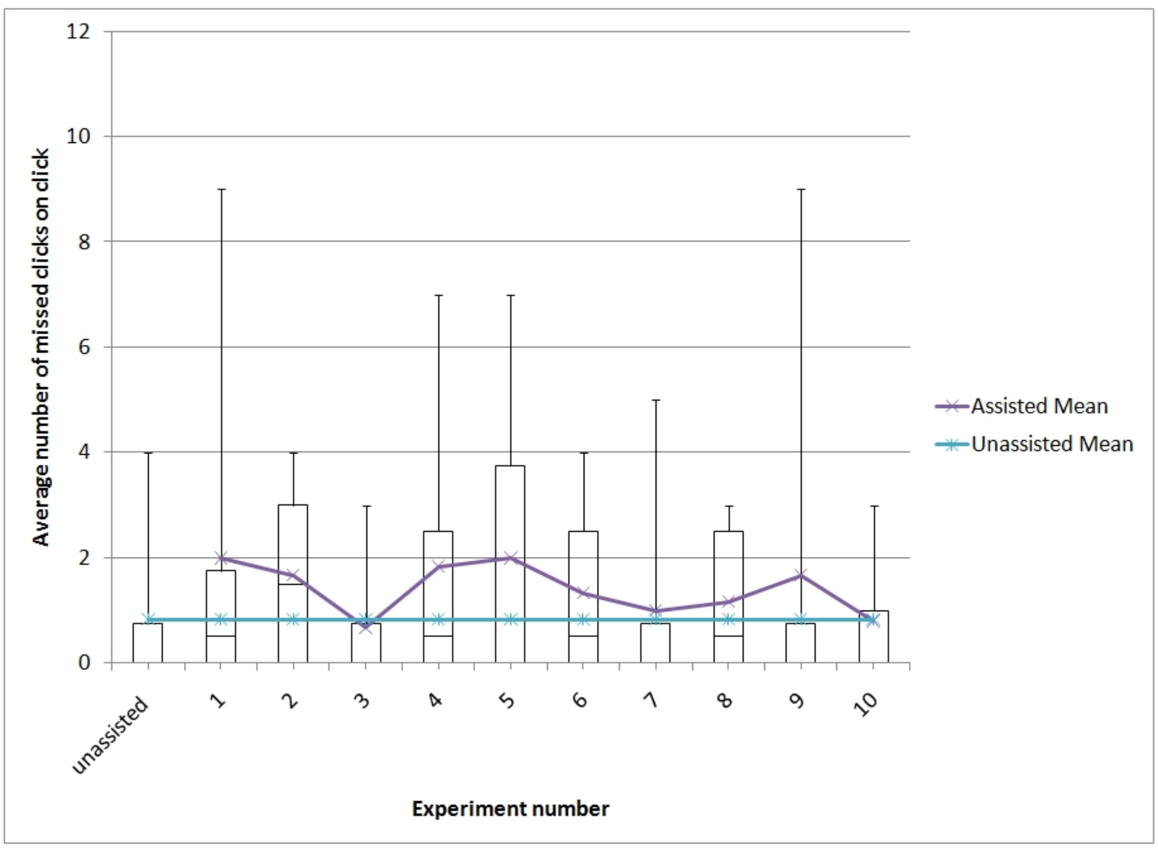

Figure 6.6: The average number of missed-clicks on click of seven motion impaired operators over fifteen successful selections using calibrated high-friction targets.

Overshoot

The results from Figure 6.7 show that calibrated high-friction targets provide an improvement for each average overshoot measure when compared to the unassisted experiment.

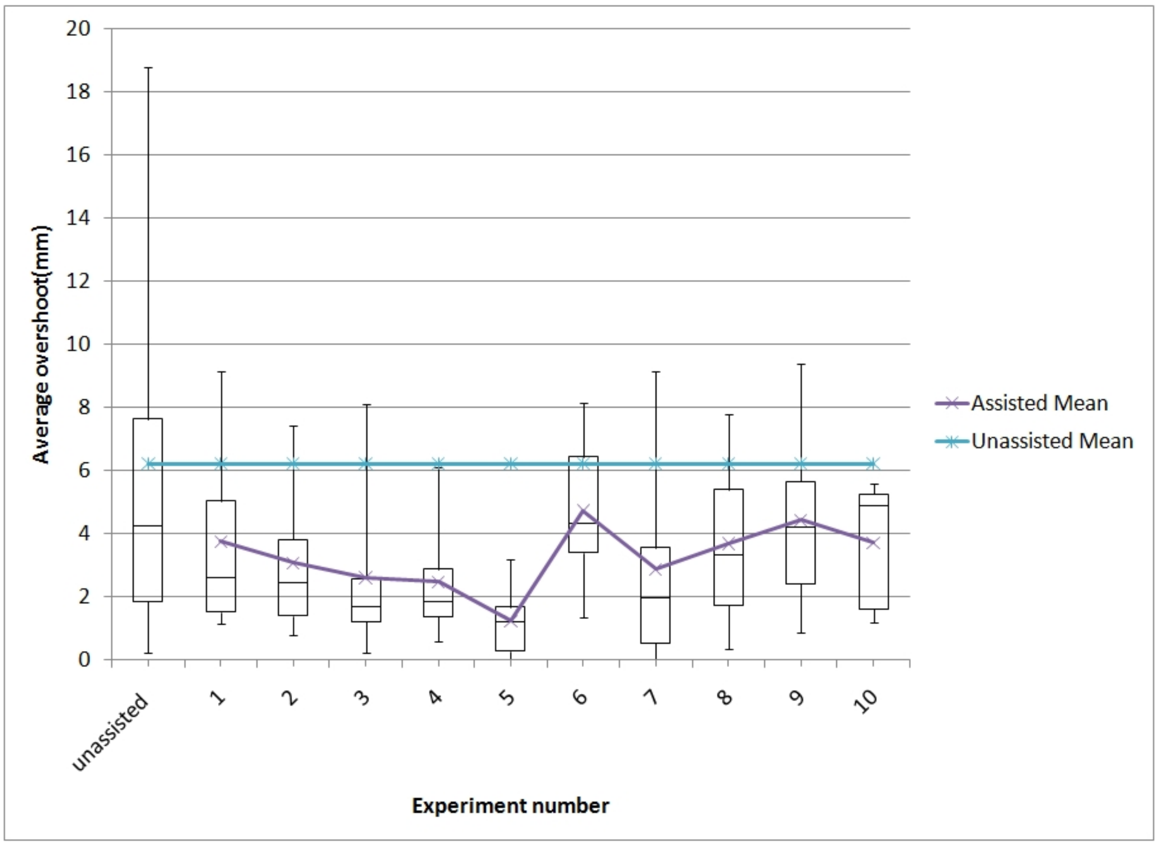

Figure 6.7: The average overshoot of seven motion impaired operators over fifteen successful selections using calibrated high-friction targets.

Throughput

All but one of the average throughput levels in Figure 6.8 show an improvement on the unassisted experiment but not to a large extent. This confirms that high-friction targets do not hinder the time between selections or the difficulty of the task.

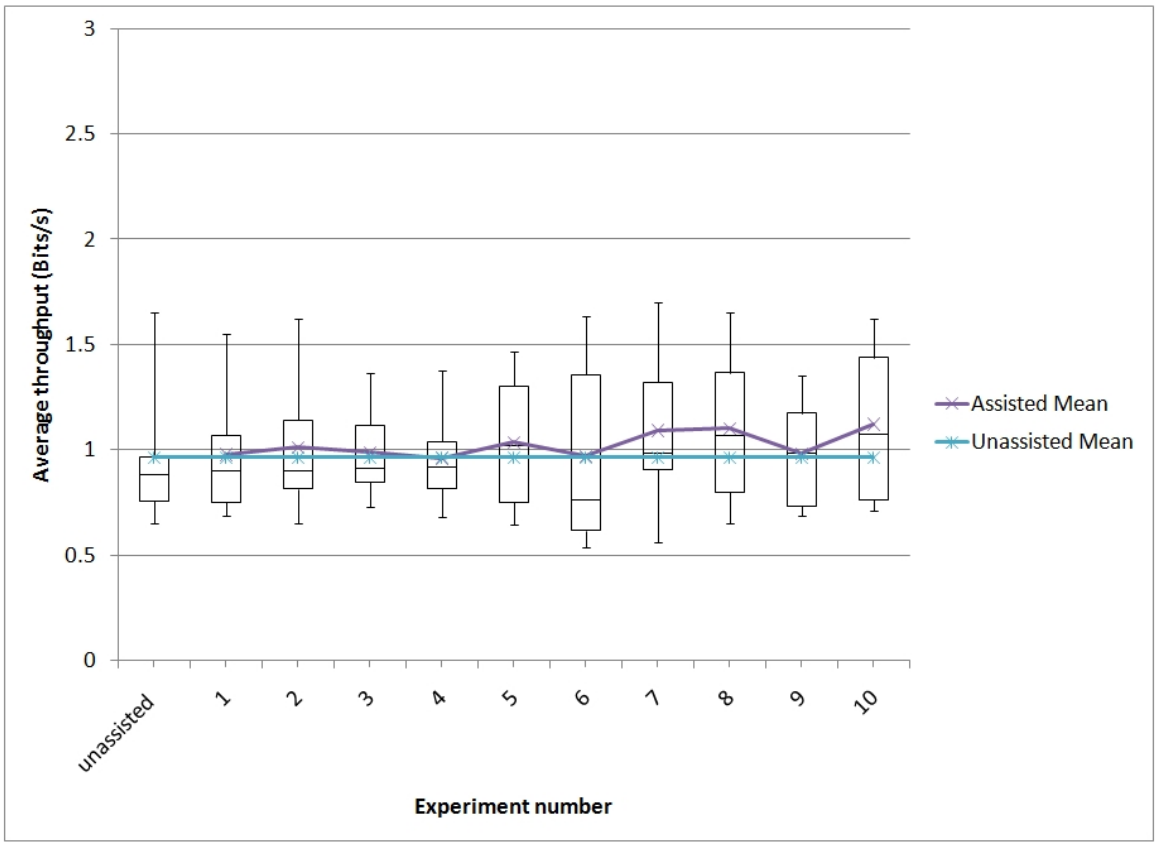

Figure 6.8: The average throughput of seven motion impaired operators over fifteen successful selections using calibrated friction targets.

6.1.3 Gravity Wells - Calibration

Some operators may prefer not to use the haptic virtual plane or may not understand the concept of it. As a result it is necessary to have an alternative method that can be used. The imposing force of gravity wells may be helpful in this instance because the operator does not require a detailed understanding of the technique to use it successfully. The ideal result of a gravity well is to assist to a suitable level without being excessive. Gravity wells can be intrusive on an interface and so the level of assistance needs to be carefully selected.

Stage 1 - Initial Unassisted Analysis

The first stage of the proposed method for calibrating gravity wells is to ask the operator to perform a full stage of the point and click task (15 successful clicks) without assistance. Once this stage is complete the person's average successful click-release displacement can be evaluated. If the click-release displacement is equal to or below the average able bodied result then the operator will not require assistance.

Stage 2 - Initial Spring Stiffness Calibration

If the successful click-release displacement is above the able bodied average (0.7mm) then an estimate of the stiffness required will be made for the first stage of calibration. This will be based on the graph in Figure 6.9. The graph shows the average unassisted click-release displacement of seven operators against the corresponding lowest spring stiffness that provided a click-release displacement less than or nearest to 0.7mm.

These results will be used to approximate a suitable level of assistance for the first calibration stage. Any inappropriately selected levels of assistance will be rectified in the next calibration stage. The equation of the line can be used to estimate the initial stiffness level and is given in the form of $y = mx + c$.

$y = 0.031x + 0.0647$

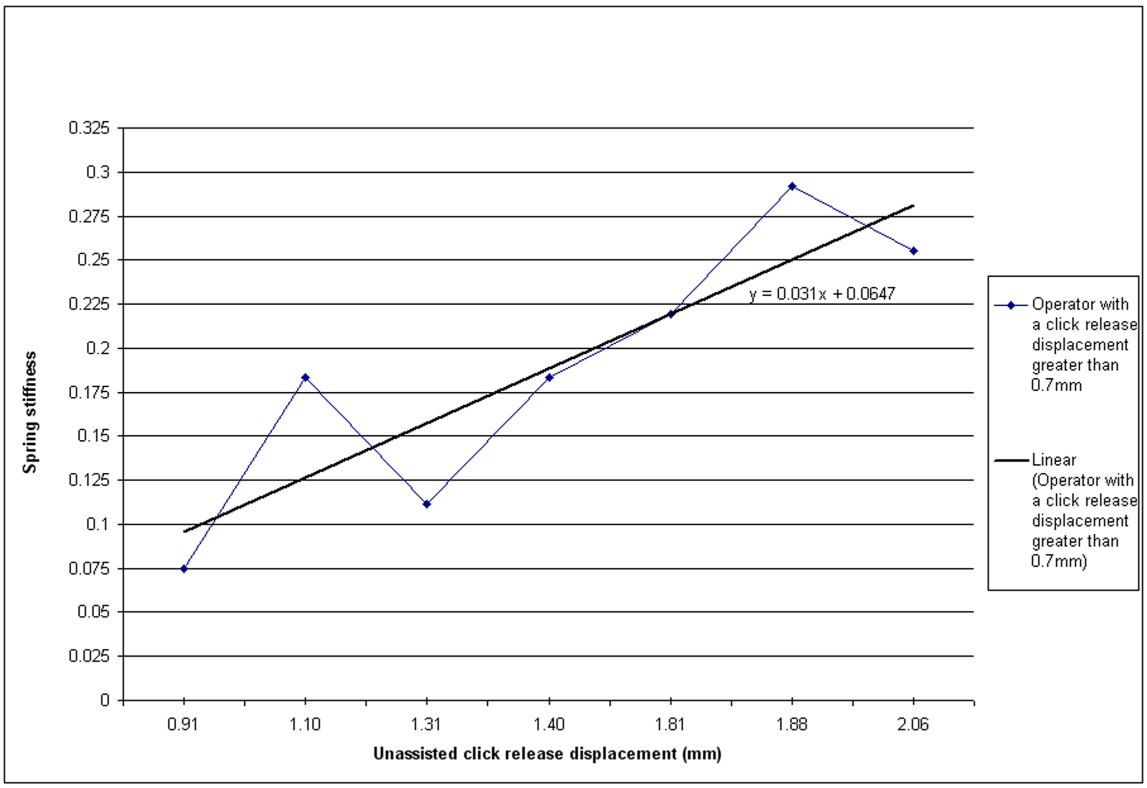

Figure 6.9: The lowest gravity well spring stiffness for each individual to produce an average click-release displacement less than or approximately 0.7mm.

Stage 3 - Further Spring Stiffness Calibration

Once the initial spring stiffness has been selected the user will be asked to repeat the task again with gravity wells enabled. At the end of the stage (15 successful clicks) the click-release displacement will be re-evaluated as follows.

- if the average successful click-release displacement lies in a range of 10% (0.63mm) below and 25% (0.875mm) above the able bodied 0.7mm threshold then maintain the current stiffness level.

- if the average successful click-release displacement is greater than 25% (0.875mm) of the able bodied 0.7mm threshold then increase the spring stiffness by 10% (0.04) of the maximum stable stiffness (0.4).

- if the average successful click-release displacement is less than 10% (0.63mm) of the able bodied 0.7mm threshold then decrease the stiffness by 10% (0.04) of the maximum stable stiffness (0.4).

Ten percent was chosen for the lower threshold limit to ensure that the stiffness level would reduce if the level of assistance was too high. Twenty five percent was chosen for the upper threshold limit to ensure that the stiffness level would only be increased if the operator definitely requires stronger assistance. This process will then be repeated a total of 10 times to evaluate the results of the calibration.

6.1.4 Results

Successful Click-release Displacement

The positive effects of calibrated gravity wells on the click-release displacement are shown in Figure 6.10. It is clear from these results that the calibrated gravity wells produce a consistent reduction in the average click-release displacement. Each operator produced a click-release displacement below the unassisted average. The results also confirm that the initial level of stiffness choice is appropriate as it is not dissimilar to the results that follow it.

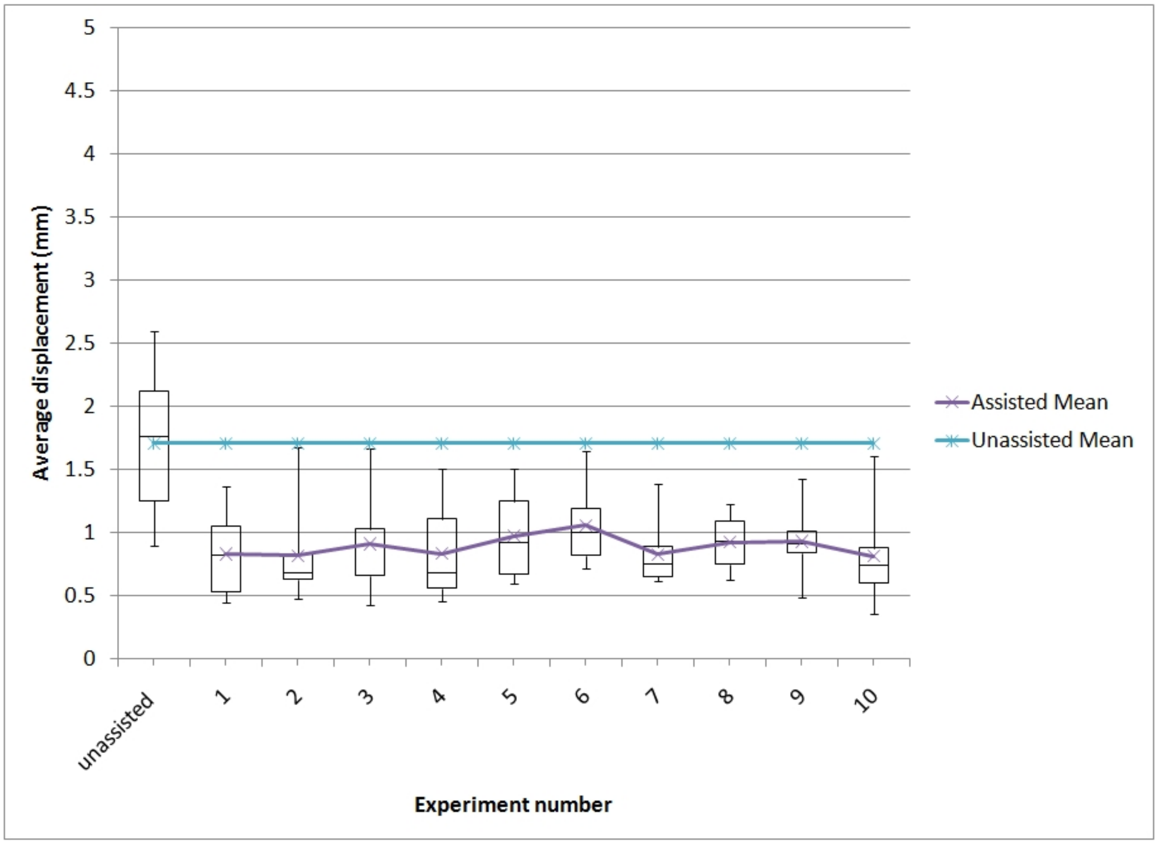

Figure 6.10: The average successful click-release displacement of seven motion impaired operators over fifteen successful selections using calibrated gravity wells.

Successful Click-release Distance Travelled

The click-release distance travelled measure also shows a significant improvement on the unassisted experiment. All average calibrated levels lie below the unassisted experiment. The results are shown in Figure 6.11.

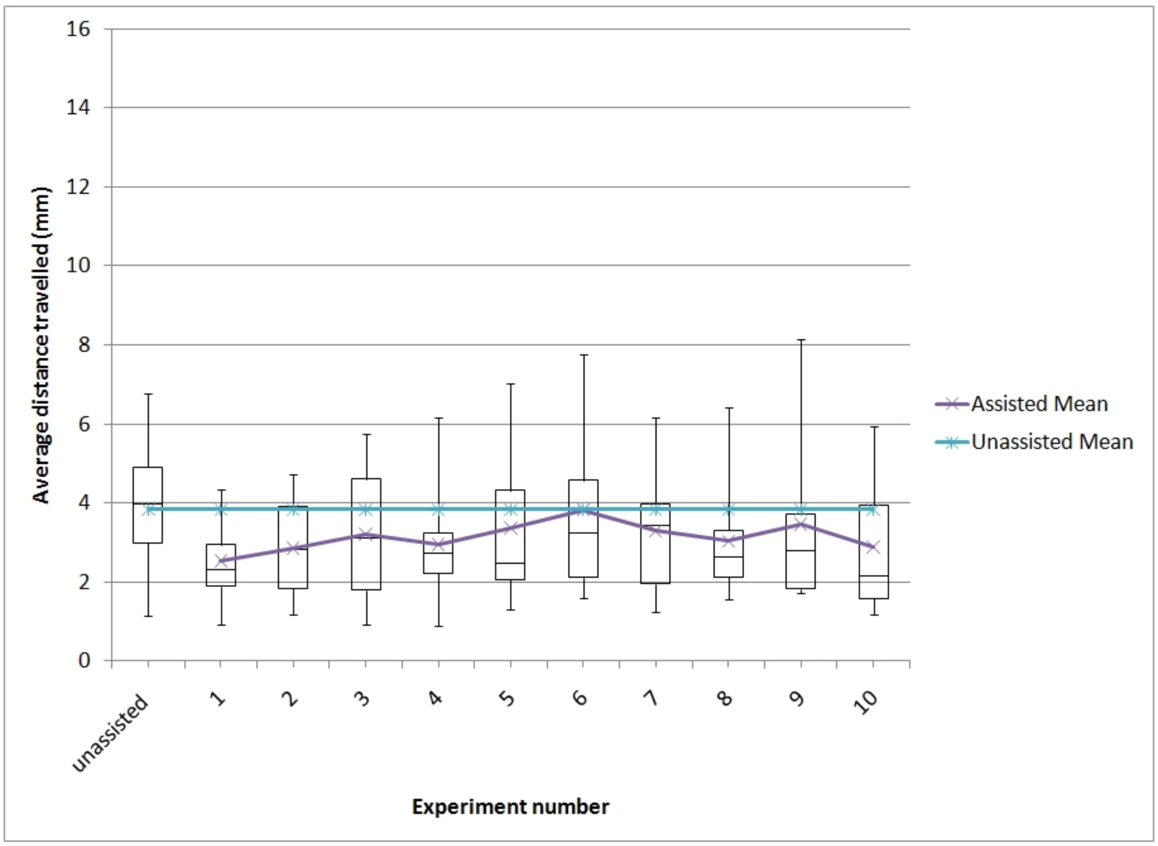

Figure 6.11: The average successful click-release distance travelled for ten experiments using calibrated gravity wells.

Missed-Click on Release

The effects of improving the click-release displacement and the click-release distance travelled are confirmed by the fact that all the assisted missed-click on release measures were below those recorded in the unassisted experiment. This is shown in Figure 6.12. No missed-clicks on release were recorded by any operator on two occasions. For some experiments the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph. For other experiments only one operator performed a missed-click on release and as a result only the maximum whisker is visible.

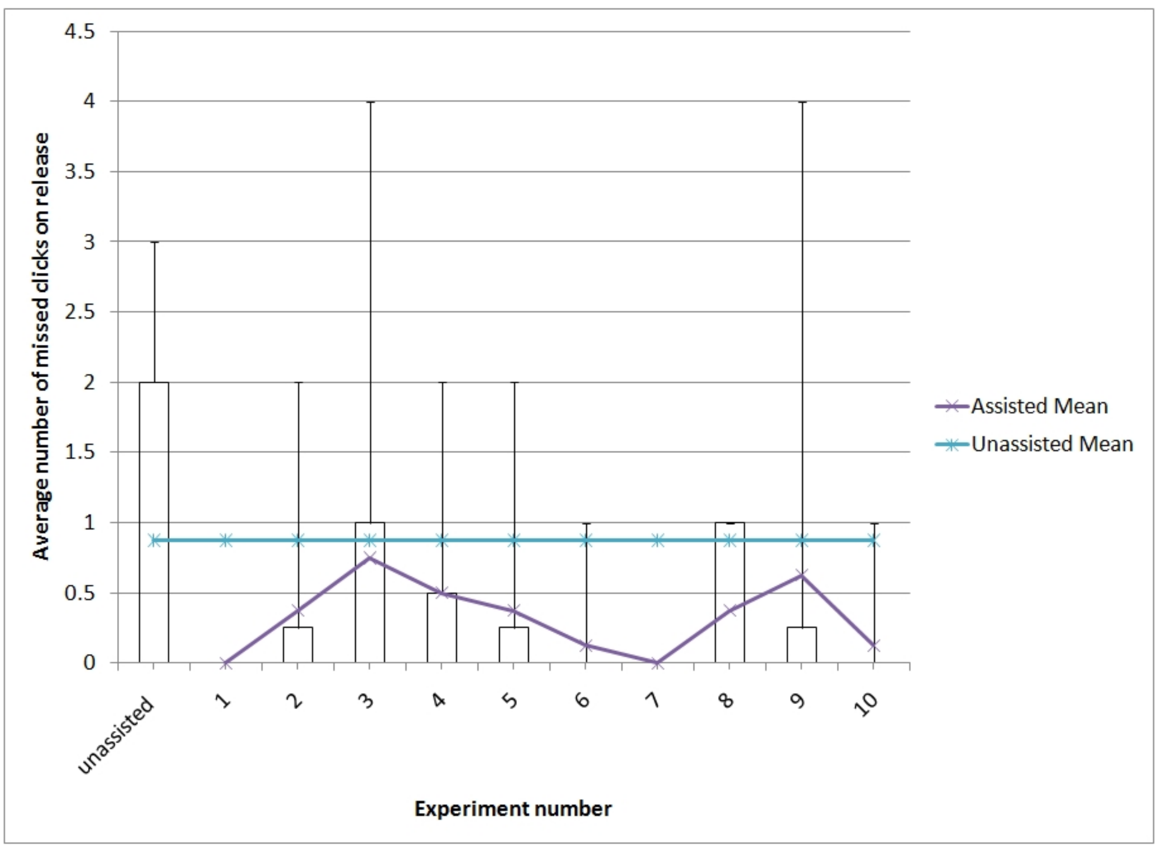

Figure 6.12: The average number of missed-clicks on release of seven motion impaired operators over fifteen successful selections using calibrated gravity wells.

Missed-Click on Click

It is difficult to determine what effects assistance has on the missed-click on click measure. If the target region has not been entered before the missed-click occurs then the technique is not given an opportunity to assist. The current measure does not indicate whether the missed-click occurred before the target had been entered or not. The calibrated results of Figure 6.13 are not significantly different to the unassisted experiment and half the results lie below the unassisted line. For some experiments the minimum whisker, lower quartile and the median are zero and as a result it is only the upper quartile and the maximum whisker that are visible on the graph. For other experiments only one operator performed a missed-click on click and as a result only the maximum whisker is visible.

Overshoot

Gravity wells provided the greatest performance increase of all assistance for the overshoot measure in the previous experiments. It appears, from the results in Figure 6.14, that calibrated gravity wells also provide a substantial improvement for this measure. All average overshoot measures are significantly reduced when compared to the unassisted experiment.

Throughput

All of the average throughput levels of the calibrated gravity wells improved when compared to the unassisted experiment. This confirms that calibrated gravity wells improve the time to target and reduce the difficulty of the task.

6.2 Conclusions

The results produced from the calibrated techniques are promising. The key measures appear to show significant improvement over the unassisted experiments. The main

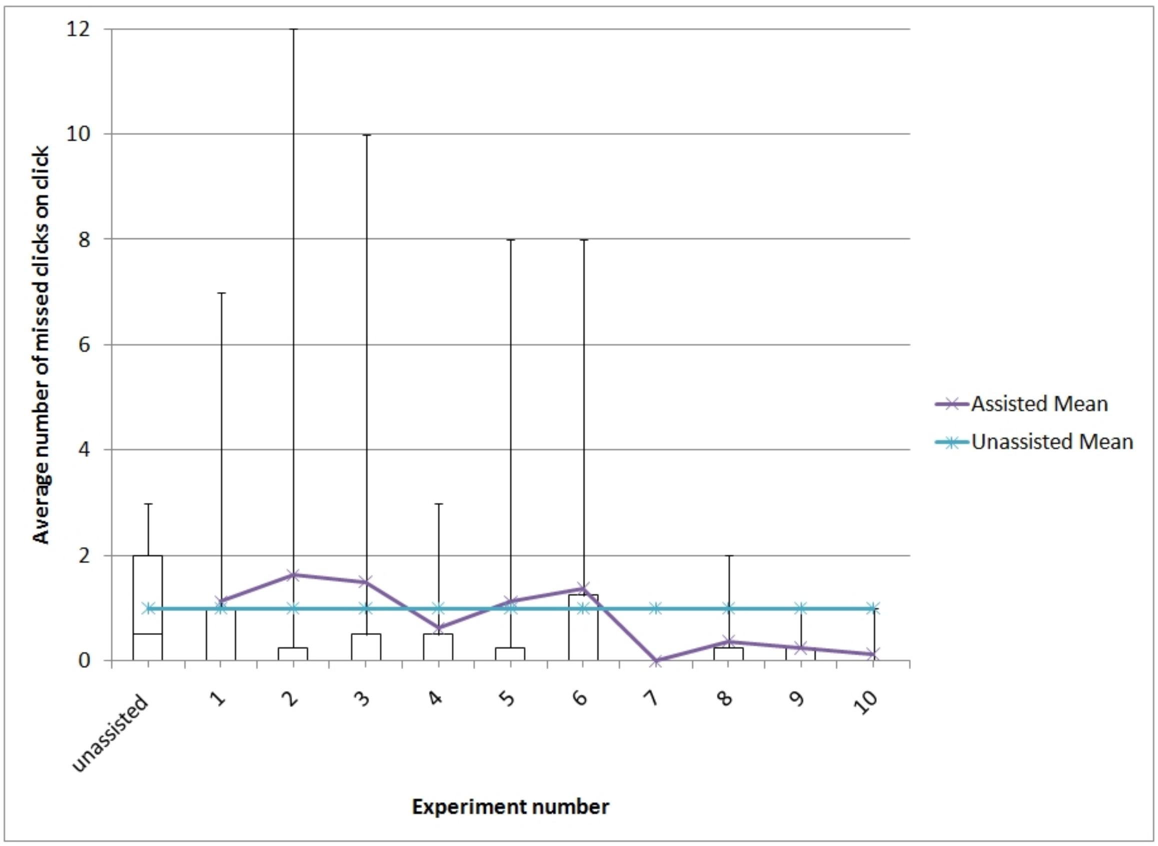

Figure 6.13: The average number of missed-clicks on click of seven motion impaired operators over fifteen successful selections using calibrated gravity wells.

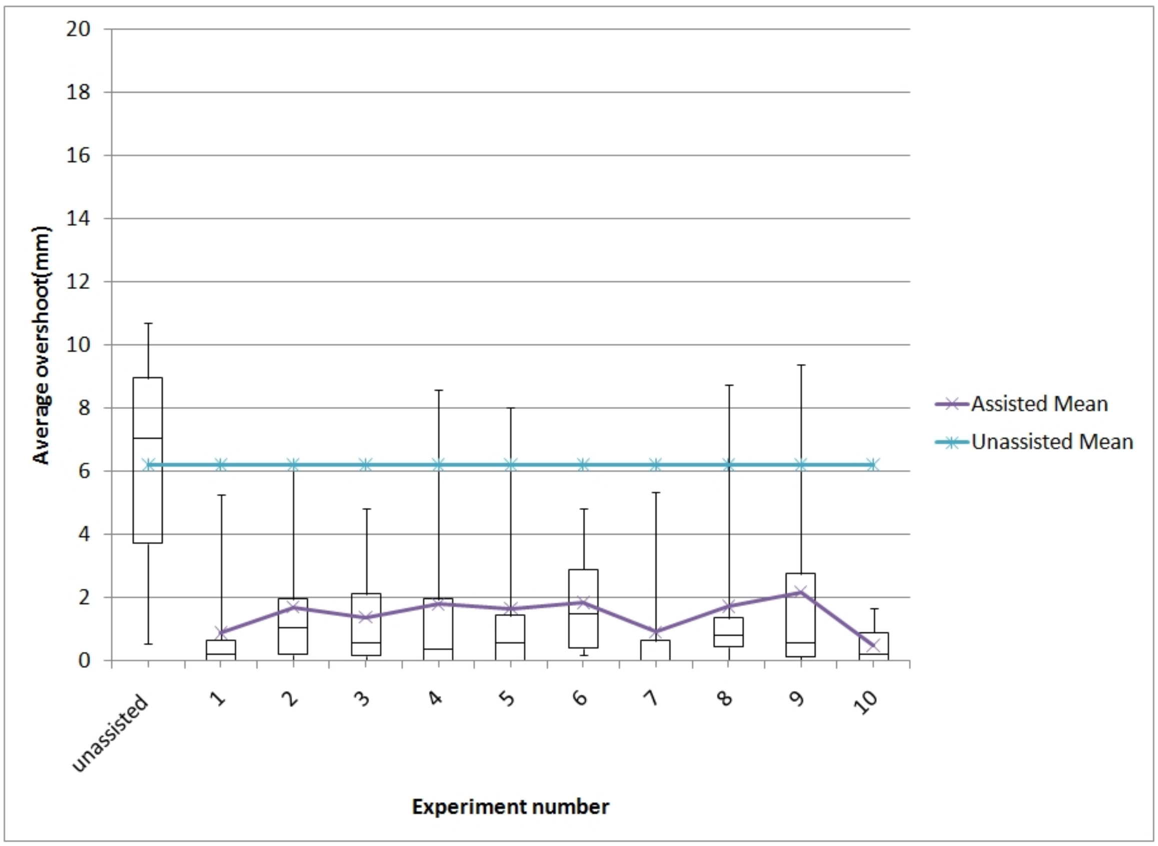

Figure 6.14: The average overshoot of seven motion impaired operators over fifteen successful selections using calibrated gravity wells.

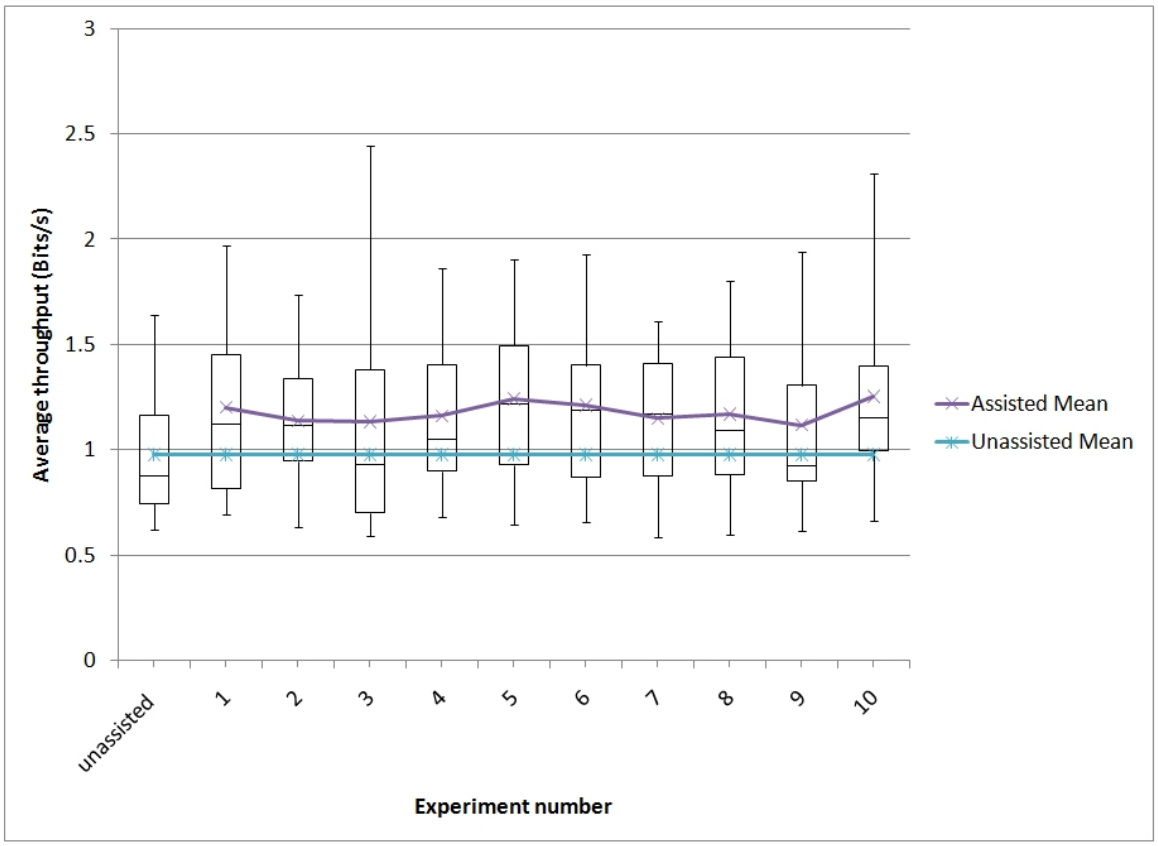

Figure 6.15: The average throughput of seven motion impaired operators over fifteen successful selections using calibrated gravity wells.

advantage of these calibration methods is that they are dynamic and will alter according to the individuals needs. This also ensures that if any anomalies occur during the first stage of analysis the operator will not be clamped to a level of assistance that they may not require. The method for both high-friction targets and gravity wells could be easily automated into existing software packages given the GUI layout. A queue containing the previous 15 clicking properties could be evaluated to produce the suitable level of assistance. The following subsections provide useful information for measuring the effectiveness of each technique.

6.2.1 Technique Comparison to Able Bodied Operators

Seven able bodied operators were asked to perform the same ISO 9241-9 based task. The average of the fifteen successful selections are shown in Table 6.1. The task was completed by each able bodied operator without assistance. Each operator had previous experience of performing the task and using the haptic device.

These results have been used in Table 6.2 to give a comparison between an assisted motion impaired operator and an unassisted able bodied operator. It should be noted that the experiments were taken on different weekly sessions and a motion impaired operator's clicking abilities can vary in this time. Another consideration is that the average of the ten experiments is taken for the calibrated techniques whereas the results from the non-calibrating techniques and the able bodied operators are taken from a single experiment. Both of these factors may have a bearing on the results but it will be useful to have an approximate comparison of each assistive technique to an able bodied operator.

Average missed-clicks

The average number of missed-clicks has previously been discarded because it does not provide any useful information on the effect of calibration on haptic assistance.

Measure	Result
missed-clicks	0.143
missed-clicks on click	0.000
missed-clicks on release	0.000
target re-entry	1.286
movement time (s)	1.449
task axis crossing	51.429
Movement error	2.193
Movement offset	0.151
Movement variability	3.030
Throughput	1.990
Movement Direction change	588.286
Orthogonal Direction change	80.143
Average Pre-Click Distance travelled	49.515
Average During-Click Distance travelled	1.079
Average Click Release Distance	0.648
Average successful Pre-Click Distance travelled	49.614
Average successful During-Click Distance travelled	1.064
Average successful Click Release Distance	0.651
Average Overshoot	1.681

Table 6.1: The average cursor measure results produced from the unassisted ISO 9241-9 based task for seven able bodied operators

Cursor Measure	Able Bodied	Calibrated Gravity Wells	Haptic Cones	Calibrated Friction Targets	Haptic Walls
Average missed-clicks	0.143	2.15	1.286	2.45	2.429
Average missed-clicks on click	0.000	0.813	0.571	1.413	0.857
Average missed-clicks on release	0.000	0.325	0.000	0.183	0.571
Average successful Click-Release Distance travelled	1.064	3.138	1.430	1.975	4.554
Average successful Click-Release Displacement	0.651	0.893	0.521	1.049	1.301
Average Overshoot	1.681	1.458	3.770	3.257	3.922
Average Throughput	1.990	1.178	0.792	1.024	1.090

Table 6.2: The average recorded measures of seven motion impaired operators over fifteen successful selections for each type of assistance.

However, it is important to show that the haptic techniques can benefit this measure in a final interface. Haptic cones produced an averaged missed-click value of 1.286 which was the closest value to an able bodied operator (0.143). The three other techniques all produced an average between 2.1 - 2.5 missed-clicks over 15 successful selections.

Average missed-clicks on click

For the missed-click on click measure haptic cones produced an average result of 0.571 which was the closest to the able bodied average of 0. Calibrated gravity wells produced the next best result of (0.8125) followed by haptic walls (0.857) and calibrated high-friction targets (1.413).

Average missed-clicks on release

The results of Table 6.2 show that haptic cones can reduce the number of missed-clicks to zero which is the same value recorded for able bodied operators. High-friction targets produced the next best result of 0.183 which is also very low. Gravity wells also produced a low level of missed-clicks on release with an average of 0.325 over the fifteen selections. Haptic walls were the least effective in reducing the number of missed-clicks on release.

Average Successful Click-Release Distance Travelled

Haptic cones produced a value of 1.430mm for the successful click release distance travelled which was the closest result to the able bodied average (1.064mm). High-friction targets produced the next best results with a value of 1.975mm. Gravity wells are less useful in reducing this measure due to the device oscillation discussed in Subsection 5.4.1. Haptic walls had the least effect in reducing the click release distance travelled.

Average successful Click-Release Displacement

The results in Table 6.2 show that haptic cones have the capability to reduce the average click-release displacement to 0.521mm which is below that of an average able bodied operator (0.651mm). Gravity wells were also shown to significantly reduce this measure to 0.893mm. The positive results of these techniques are promising as it has been shown that reducing the click-release displacement can significantly reduce the chance of miss-clicking. Each technique is within an acceptable range of an able bodied operator. Haptic walls were the least effective in reducing the click release displacement.

Average Overshoot

Gravity wells have proven to be the most effective technique in reducing overshoot. The results in Table 6.2 show that gravity wells can produce better results (1.458) than the average able bodied operators (1.681). Calibrated high-friction targets, haptic cones and haptic walls were less effective in reducing this measure.

6.2.2 Target Acquisition Technique Performance Comparisons

Another useful measure would be to determine if certain techniques produce better performance than others. The performance has been calculated using the same method that was used in Subsection 5.10.1 where the cursor measures of the unassisted experiments are divided by the same measures of the assisted experiment. A result recorded that is higher than one will indicate a performance increase. The results differ from those in Table 5.2 because in reality it is unlikely that the software will be able to tune the device perfectly to meet all the needs of the operator. Improvements are still observed for the calibrated techniques when compared to an unassisted interface.

The average of the ten results were taken for the calibrated techniques to compare the performance to the techniques that did not require calibration. It should be noted that the results from the non-calibrating techniques were taken from a single experiment and so this may have a bearing on the results when compared to the average of the calibrated techniques. The results are shown in Table 6.3 and Figure 6.16.

	Gravity Wells	Haptic Cones	Friction Targets	Haptic Walls
Average missed-clicks	1.744	1.111	1.156	1.417
Average missed-clicks on click	1.231	0.750	0.590	1.500
Average missed-clicks on release	2.692	None recorded	2.727	1.000
Average successful Click-Release Distance Travelled	1.221	2.611	3.449	1.007
Average successful Click-Release Displacement	1.913	3.178	1.495	1.281
Average Overshoot	4.256	1.828	1.909	2.171
Throughput	1.205	0.806	1.063	1.109

Table 6.3: The average performance ratio of seven motion impaired operators for each cursor measure using each type of assistance. The performance ratio is calculated by taking the unassisted measure for each cursor measure and dividing it by the same measure for each type of assistance.

Average missed-clicks

Each technique has produced a performance value greater than one which confirms that they are all useful in reducing the average number of missed-clicks. The greatest performance increase was produced by calibrated gravity wells. Haptic walls produced the second best performance increase followed by calibrated high-friction targets and haptic cones.

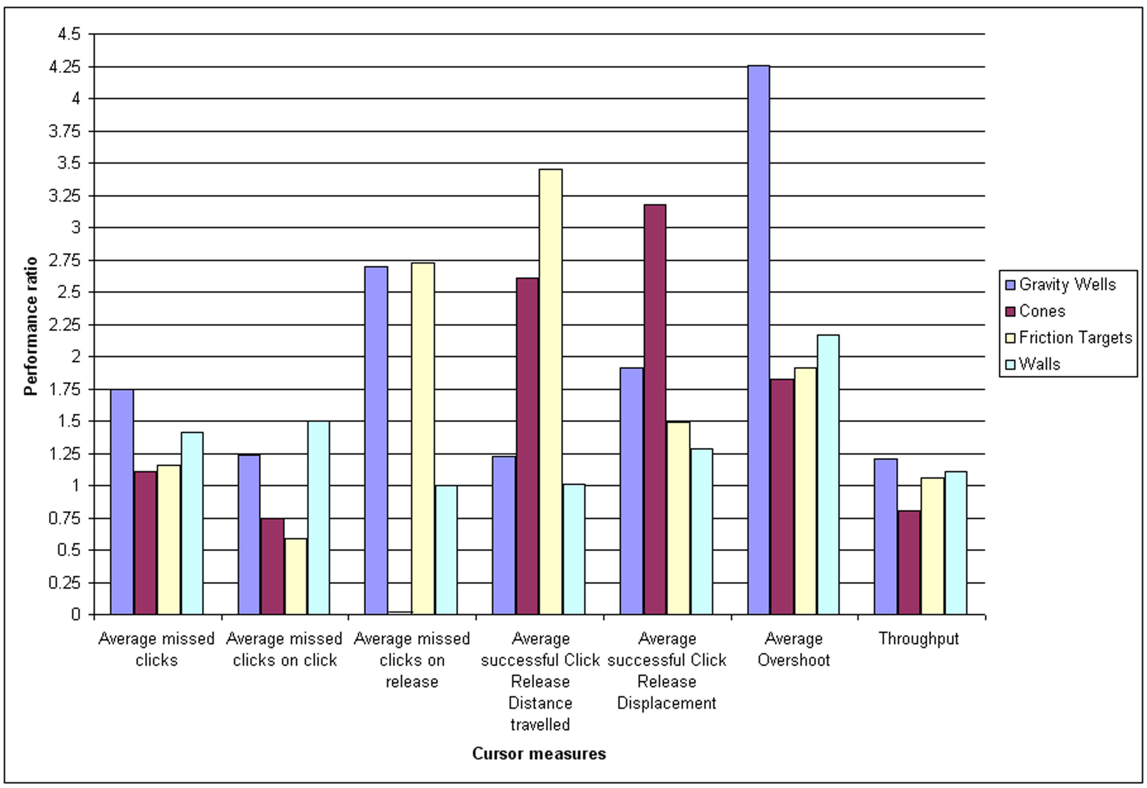

Figure 6.16: The average performance ratio of seven motion impaired operators for each cursor measure using each type of assistance. The performance ratio is calculated by taking the unassisted measure for each cursor measure and dividing it by the same measure for each type of assistance.

Average missed-clicks on Click

A performance increase in the number of missed-clicks on click has only been observed for haptic walls and gravity wells. If an operator does not enter a target region then the technique is not given a chance to assist them. The main concern is that the overall number of missed-clicks has improved for each technique.

Average missed-clicks on Release

Haptic cones produced the best performance increase with no missed-clicks on release recorded. Calibrated gravity wells and calibrated high-friction targets produced the next best performance increase. Haptic walls did not provide any performance increase for this measure.

Average successful Click-Release Distance Travelled

The missed-click measures are useful in showing improvements but they do not help explain why they occur. The click-release distance travelled helps give a measure of the stability that a technique provides. High-friction targets produced the best performance increase for the click-release distance travelled. Haptic cones produced the next best performance increase followed by calibrated gravity wells. Very little performance difference was observed in the click-release distance travelled for haptic walls.

Average successful Click-Release Displacement

The click-release displacement also helps give a measure of the stability that a technique provides. Haptic cones produced the greatest performance increase in click release displacement which will be credited to the proxy clamping at the cone apex. Calibrated gravity wells produced the next best performance increase followed by calibrated high-friction targets and haptic walls.

Average Overshoot

Gravity wells appear to provide a significant performance increase in overshoot. This will be credited to the braking effect gravity wells have on the operator. It should be noted that a very low level of target re-entries were recorded for this experiment and so it is unsurprising that the resulting overshoot measure is low. The gravity well effect is enforced off the plane and this has shown to be significant in reducing the effects of overshoot. Throughout the study, gravity wells have proven to be the best haptic assistive technique in reducing the overshoot measure. Although haptic walls were not as effective as gravity wells they did produce the next best performance increase for this measure. It will be necessary to have an alternative non-intrusive technique to assist in this area in case a user has joint problems that could be aggravated by the pull of gravity wells. As a result haptic walls will be used as the reserve technique for this measure. Both calibrated high-friction targets and haptic cones produced a performance increase in overshoot.

Throughput Comparisons

The throughput comparisons of each technique are very similar. A small increase in throughput performance was observed for calibrated gravity wells, calibrated high-friction targets and haptic walls. The small decrease in performance was observed for haptic cones but this level was very minimal and with increased practice using this technique it is likely to increase. Gravity wells appear to be the most effective in producing a performance increase in throughput.

6.2.3 Target Acquisition Technique Improvement Frequency

Some techniques may also be better suited in assisting a wider range of disabilities. It is also important to determine the number of people that improved, remained similar or worsened on each measure for each type of assistance. The ranking was obtained as follows:

- A technique was said to improve the performance of a cursor measure for an individual if the average assisted value is less than 10% of the unassisted experiment.
- A technique was said to worsen the performance of a cursor measure for an individual if the average assisted value is greater than 10% of the unassisted experiment.
- A technique was said to produce similar performance for an individual if the assisted value is within a 10% range of the unassisted experiment.

The results produced from this ranking system are shown in Table 6.4.

Assistance	Gravity Wells			Haptic cones			Friction targets			Haptic wall		
Frequency	I	S	W	I	S	W	I	S	W	I	S	W
Average successful Click-Release Distance travelled	4	1	2	6	1	0	5	2	0	6	0	1
Average successful Click-Release Displacement	6	1	0	7	0	0	5	1	1	6	0	1
Average Overshoot	7	0	0	6	1	0	4	1	2	7	0	0
Throughput	4	3	0	0	2	5	2	4	1	3	3	1

Table 6.4: The number of Improved (I), Similar(S) and Worsened (W) measures based on the average of each type of assistance.

The missed-click measures were not included in this table because if an operator did not miss-click in the unassisted experiment and then miss-clicked just once in one of the ten experiments for the calibrated techniques then this would be regarded as a worsened result, which is not true. The fact that the average successful click release displacement and average successful click release distance travelled has improved for the majority of operators using each technique would suggest that the number of missed-clicks will have improved too. This statement is based on the results shown in Figure 6.1. The improvements in the missed-click measures have been shown in the previous subsections.

6.3 Summary

The results from this chapter prove that non-calibrating techniques can produce similar if not better performance levels than traditional techniques if implemented carefully. Haptic cones produced significant improvements across the key clicking measures. They were also shown to improve the greatest number of operators for clicking operations. This is shown by the fact that haptic cones improved 6/7 people in click-release displacement and 7/7 in click-release distance travelled. Additionally, haptic walls were shown to improve the overshoot of all participants (7/7) but not to the same performance level as calibrated gravity wells. If the operator understands the concept of a haptic technique that does not require force calibrations then this will allow the designer to concentrate on other areas that need to be tuned for a motion impaired operator.

If the non-calibrating techniques cannot be used then the results produced from the calibrated assistance were also promising. Significant improvements were shown in the key clicking measures for calibrated gravity wells and calibrated friction targets. The calibration techniques were shown to provide a suitable level of assistance without constraining the operator too much. The majority of operators were shown to produce improvements of more than 10% for the key cursor measures when using the assistance. This is confirmed by the results shown in Table 6.4.

Haptic cones have been chosen as the primary assistance for target acquistion in the final system implementation because they have produced positive results for a wide range of operators. This technique has other benefits that techniques such as gravity wells do not have, such as providing assistance for double clicks whereas the gravity well effect would not be felt after the first click. Another benefit is not having to oppose a spring force to exit an undesired target or when drag and dropping. The problem of target distracters is less of a hindrance for haptic cones as the user can work off the plane when required and enter a cone by pushing into the z-axis when targeting. This allows operators to ignore the assistance easily if they wish, which was emphasised by Gunn et al. [GMD09]. Haptic cones should also be suitable for a much greater range of disabilities as they do not impose a force that could potentially cause discomfort for some users.

If the operator does not understand the concept of haptic cones or would prefer an alternative technique then they will be given the opportunity to use calibrated gravity wells or calibrated high-friction targets. If overshoot is a concern then gravity wells may be better suited in assisting the individual. Appendix A discusses how these results have been used to give greater accessibility to a computer by automating existing interfaces with haptic assistance.

Chapter 7

Conclusions

7.1 Introduction

Exploiting the sense of touch in GUI's has become an important factor in assisting operators with a variety of disabilities. It has proven to be beneficial to the successful completion of a variety of point and click tasks. In this thesis, techniques have been developed to extend the types of assistance that can be simulated with haptic feedback. The focus has been on appropriately calibrating existing haptic techniques to meet the needs of the individual and utilising the 3D capabilities of the Phantom Omni to produce assistance that will accommodate a wider range of disability. Some adaptable user interfaces are not always useful because operators get to know where components are located and how the system reacts. This has not been a problem with the techniques proposed in this thesis because the way that the task is presented does not change. The haptic feedback experienced by the operator remains the same; it is just the force levels that are adjusted.

The results have been useful in providing a performance comparison between techniques that require calibration and techniques that do not. There is very limited research in this area particularly due to the requirement of participants for data collection. Previous processing limitations of computer hardware were also a limiting factor. Incorporating haptic assistance into interface design has proven to benefit interaction rates in terms of targeting times and error rates for people with disabilities associated with cerebral palsy.

Ideally all user interfaces would be designed to meet the needs of a motion impaired operator. This may include elements such as the GUI layout, button sizes etc. However, software companies will rarely implement this type of system because it is not commercially viable. Most user interfaces are designed to meet the requirements of the mass market. As a result, it is more useful to adapt existing user interfaces for motion impaired operators to improve access to commonly used software. Greater access to existing software, such as the Windows on-screen keyboard and Microsoft Word, has been achieved by automating the GUI with haptic assistance.

The following section discusses the key findings produced in each chapter of this thesis. Section 7.3 indentifies the future work that could follow this research.

7.2 Discussion and Conclusions

Before work can commence in developing haptic assistance a detailed background is required in the area. Chapter 1 discussed the motivations and research objectives of the thesis. It provided a relevant understanding that is important to any developer when designing haptic assistance for disabled computer users. In this thesis the Phantom Omni was employed to provide the force feedback.

Chapter 2 discussed the problems encountered with traditional pointing devices and the difficulties that are associated with cerebral palsy. It then went on to cover areas in which haptic technology has been developed and how force feedback has been used to assist a wide range of disabled computer users.

Section 2.7 discussed the design of pointing device interfaces. It identified the reasons why traditional assistance, with a static configuration, may not assist everyone. This is because each individual's disability is unique. When developing haptic assistance for users with motor difficulties it is essential that the techniques will benefit areas of weakness and not impair other areas. The findings of previous work in device calibration strengthen the argument that haptic assistance must address an individual's specific needs dynamically.

The chapter also discussed why non-intrusive haptic techniques may be better suited in assisting a wider range of disability. If non-calibrating haptic assistance could provide similar performance to tuned traditional assistance then this would eliminate one of the many calibration variables for a motion impaired operator. The end of the chapter takes into consideration the safety of the user when using a haptic device. A number of safety measures are suggested for haptic applications.

Chapter 3 demonstrated methods for implementing traditional haptic assistive techniques along with a number of improvements. The key calibration variables have been identified for tuning each technique to the needs of the operator. The chapter also produced a number of new haptic techniques that were designed to be non-intrusive and should therefore assist a greater range of disability. All the techniques have been implemented in such a way that they can be easily automated in existing interfaces.

Chapter 4 investigated the cursor measures often used to record performance in point and click tasks. One of the greatest difficulties was determining appropriate cursor measures that would be useful in identifying areas of strength and weakness. A series of new measures have been created that attempt to provide greater knowledge of a person's clicking habits. These measures were useful in identifying the stability of a person in the targeting phase and provided a greater knowledge of why errors occur.

In Chapter 5 a series of experiments were reported to determine what effects each technique has on user performance in a point and click task. The levels of assistance were adjusted for techniques with calibration variables to determine their effects. It was shown that the level of assistance could have a significant influence on the operator's performance. Many techniques were shown to reduce the number of errors and improve the time taken to complete the task. Improvements, however small, can be a huge benefit to the operator and significantly improve interaction. One of the crucial elements of this study was having direct access to volunteers for data collection. Data recording can be a long process due to factors such as varying abilities, mistakes, distractions, limitation of one device etc.

The new clicking measures were useful in identifying areas of correlation that are key to the calibration of each click assistive technique for the individual. The stability that a technique provides was shown to be important for reducing the click-release displacement and distance travelled. This was promising as it was shown that higher levels of these measures can significantly increase the chances of miss-clicking.

The results produced from haptic cones confirm that increasing the degrees of freedom can improve interaction when implemented carefully. A consistent improvement was observed when haptic cones were in operation. The non-intrusive clamping effect was shown to be as effective as the traditional haptic techniques.

The results of the homing assistance did not seem to produce significant levels of improvement. The reason for this could be that the participants in the study did not require homing assistance. Langdon et al. [LHK+02b] discuss that only severely impaired users gained from haptic tunnels. It was felt that haptic tunnels and haptic damping were intrusive on interaction and so any benefits that they provided were obscured by other difficulties. Many participants were fighting the assistance rather then allowing it to help interaction. There were not any areas of correlation recorded that would be useful in the calibration of these techniques. Gunn et al. [GMD09] also suggest that there may be valid reasons for a skilled user to want to ignore the advice provided by a computer system. They go on to argue that force feedback might limit this ability to ignore the advice and therefore be less effective as an aid. Non-intrusive techniques such as haptic cones were shown to benefit the clicking phase and so similar techniques may be more useful in improving the homing phase. Another theory is that if the operator does not have the range of motion to physically move the device around the workspace then haptic assistance may not be as effective. This appeared to be the case for one participant in the group who had a very limited range of movement. Even with the various types of assistance and adjusting the gain settings it was not possible to provide enough assistance for the operator to complete the targeting task.

Chapter 6 used the analysis of the results to identify areas of correlation that would be useful in the selection and calibration of target acquisition techniques to meet the needs of the individual. The two calibrated techniques investigated in the study were high-friction targets and gravity wells. An initial level of assistance was estimated for the spring stiffness and dynamic friction level using the previous results from Chapter 5. The assistance levels that followed were automatically adjusted depending on the results produced from the click-release displacement. Techniques such as gravity wells can be intrusive on interaction and so it was necessary to calibrate the spring stiffness so that they clamp sufficiently without being excessive. The results were promising as significant improvements were observed in the key cursor measures when compared to an unassisted interface. If a suitable cursor measure can be identified then self calibrating techniques appear to work well as they are dynamic and will adapt to the operator's needs.

Haptic cones produced the best results in terms of the clicking measures. The results were promising in that the clicking stability was improved to a level similar to able bodied users. This has shown to significantly reduce the probability of miss-clicking. The results confirm that non-calibrating assistance can produce similar if not better results than traditional calibrated techniques. Haptic cones should assist a greater range of disabilities as the force levels do not require tuning to optimise interaction rates. The technique also has many benefits that gravity wells do not have. One of these is that once a gravity well has been clicked it will not reinitialise again until the well has been exited. If the task requires a double click then on the second click there will not be any assistance provided by the well. Haptic cones do not suffer from this shortcoming. Additionally, if a drag and drop operation is required when gravity wells are in operation then the user will have to oppose the spring force to exit the target. This is because the well will only disable once a click and release has been completed. When haptic cones are in use the operator can simply exit the cone in the z-axis and drag the object to the desired destination.

For the results to benefit an end user they need to be applied to existing interfaces. Appendix A investigated automating Microsoft Word and the Windows on Screen Keyboard with haptic assistance. The system uses an initial experiment to identify if the user requires click or overshoot assistance. Once the correct assistance has been chosen based on the system in Chapter 6 it will be applied directly to the interface. The system has be deployed at the NANSA day centre to provide greater access to word processing applications.

7.3 Future Work

There are four main areas that could form the continuation of the work presented in this thesis. The first would be the further development of the calibration of traditional haptic techniques. The implementation of the dynamic calibration for gravity wells and high-friction targets was to provide a suitable level of assistance without constraining the operator too much. Further work is required to evaluate if the operator has the motor control to operate these techniques successfully. There may be other conditions that need to be addressed in the calibration stage. For example, if a technique is not improving the interaction rates then it would be useful to address this and provide the operator with an alternative solution.

One area in which work could be continued is the development of homing techniques. The desired results were not observed for the traditional homing techniques. Further work needs to address whether a less intrusive technique may provide better results. For example, if a V-Shaped channel [1] were to be embedded into the haptic virtual plane then this may produce better results than haptic tunnels. The reason for this is that the operator can choose to use the assistance if they wish and they are not just constricted to within the channel. An example of two V-shaped channels is given in Figure 7.1.

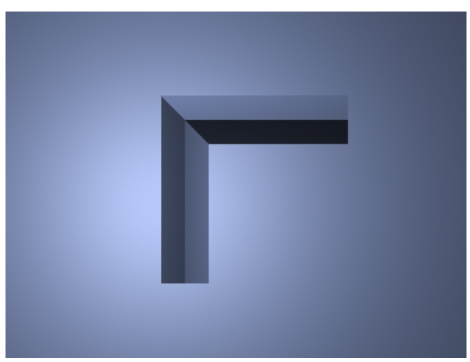

Figure 7.1: Two V-shaped channels are embedded into the haptic virtual plane.

The technique will be less prone to the difficulties in navigating the desired channel when many channels meet at the same point. A similar concept worked well for target acquisition by embedding cones into the haptic virtual plane.

[1] Note the cross-section of the channel is V-shaped

Some operators may have the motor control to operate the cursor but have difficulties with the button press on the device. It was observed that some operators had difficulty locating the button on the stylus. A possible area to research could be to provide the operator with a simulated haptic button on the plane. This would allow the operator to push into the plane, feel the simulated button, and acquire the desired target. It would be useful to investigate the effect that haptic assistance has on a haptic button and compare the results to a traditional device button.

One of the difficulties that arise when using haptic assistance in existing interfaces is understanding the concept of a haptic technique. Describing the sense of touch can be difficult without actually experiencing it in person. It is not possible to use a visual cue directly on an existing interface. One possible solution is to use modern day graphics cards capabilities of dual screens. One screen could be used on the interface whilst the other is used as a visual cue for the haptic assistance.

Appendix A

Haptic Assisted Applications

For the results produced in this study to be of any great benefit to an end user it will be necessary to apply them to an application. The configuration produced from the experiments could be applied to existing interfaces and significantly improve a disabled person's access to a computer and software applications. Manually designing and mapping an interface for haptic assistance would be too time consuming due to the fact that many interfaces have tens if not hundreds of buttons. In addition to this the toolbars may be moved or resized which will result in the mapping becoming inaccurate. As Windows based applications dominate the market it will be these that are the main concentration for mapping with haptic assistance. The aim of this section is to develop a system to run a haptic thread in the background of the operating system that can be applied to an open application. A previous concern of using haptic interfaces with existing software packages was the processing power required in the haptic thread. To provide stable forces to a haptic device a refresh rate of over 1000Hz is required. This previously would have required expensive dual processor architectures where the haptic thread could be performed on one processor leaving the second free for application processing. The growing popularity of multi-core architectures has ensured that this is no longer an issue and provides affordable consumer level hardware. Advances in haptic rendering algorithms have also contributed in making this possible.

A.1 Using the Phantom Omni to operate the Windows Cursor

SensAble Technologies do not provide drivers for using the Phantom Omni as a pointing device in a Windows application. As a result is was necessary to create a system to handle cursor events using the haptic device. This has been achieved by using the `winuser.h` header, which provides a series of functions for dealing with the on screen cursor and associated events.

A.1.1 Cursor Positioning

The position of the proxy can be projected onto the 2D plane of the GUI to give the correct mapping of the cursor on screen. The `winuser.h` header provides the `SetCursorPos(int X,int Y)` function for positioning the cursor in screen coordinates. The position of the proxy is stored by CHAI3D in the OpenGL coordinate system and so a projection is required to map it correctly to the on screen cursor. This is achieved using the OpenGL function `gluProject()`.

A.1.2 Button Events

The button events such as button up and button down are handled by the `mouse_event()` function by passing the appropriate button flag. This corresponds to which button has been pressed on the device and its status. The key events that have been used are shown in Table A.1.

A.2 Interface Automation

The Microsoft Office suite has been the dominant software package for word-processing, spreadsheet, and presentation tools since the early 1990's. Suitable access to these

Event	Action
MOUSEEVENTF_LEFTDOWN	Specifies that the left button is down.
MOUSEEVENTF_LEFTUP	Specifies that the left button is up.
MOUSEEVENTF_RIGHTDOWN	Specifies that the right button is down.
MOUSEEVENTF_RIGHTUP	Specifies that the right button is up.

Table A.1: Mouse Events

applications could give disabled computer users much greater opportunities in the areas previously discussed. Automating and integrating haptic assistance into Office applications has not previously been attempted and it was unknown whether it would be possible to implement. Further investigation into the area suggested that it would be possible. The following section describes how automating haptic assistance for Office applications has been achieved.

A.2.1 Microsoft Word

Microsoft Word is considered one of the main applications in the Office suite and so it was decided that this would be the first application to be automated. Research in the area produced a MSDN article titled "How To Handle Events for Word by Using Visual C# .NET" [HS]. This article provides a template on how to identify key events in a Microsoft Word application. Some of these included in the template were events such as:

- DocumentBeforeClose
- DocumentBeforeSave
- DocumentChange
- WindowBeforeDoubleClick
- WindowBeforeRightClick

Before the features of a Microsoft Office application can be used, the "primary interop" assembly for that application needs to be installed. The interop assemblies enable managed code to interact with a Microsoft Office application's COM-based object model.

One of the key elements required from the Word interface is the button coordinates and button width. With this information it will be possible to create and position the haptic assistance accordingly. To gain access to these attributes it is necessary to study the window contents of an Office application. Each window hosts a series of Commandbars which may be a toolbar or menubar. Additionally every CommandBar plays host to controls such as buttons, drop-downs, and so on. The hierarchy of this is shown in Figure A.1 adapted from [Micb].

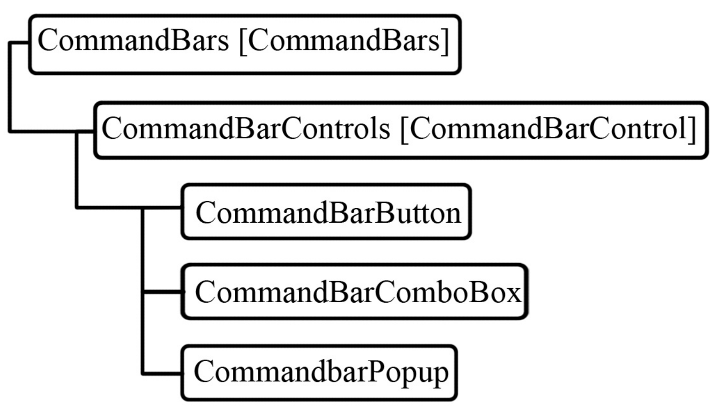

Figure A.1: The Commandbar object hierarchy for Microsoft Office applications.

There are many CommandBarControl types, as shown in Table A.2. This also shows each control's corresponding integer index. A full list and details can be found at [Micc].

Each CommandBarControl within the interface has its own unique ID. The ID has many uses such as updating and searching for a control. The `FindControl()`

mso Control Type	**Index**
msoControlCustom	0
msoControlButton	1
msoControlEdit	2
msoControlDropdown	3
msoControlComboBox	4
msoControlButtonDropdown	5
msoControlSplitDropdown	6
msoControlOCXDropdown	7
msoControlGenericDropdown	8
msoControlGraphicDropdown	9
msoControlPopup	10
msoControlGraphicPopup	11
msoControlButtonPopup	12
msoControlSplitButtonPopup	13
msoControlSplitButtonMRUPopup	14
msoControlLabel	15
msoControlExpandingGrid	16
msoControlSplitExpandingGrid	17
msoControlGrid	18
msoControlGauge	19
msoControlGraphicCombo	20
msoControlPane	21
msoControlActiveX	22
msoControlSpinner	23
msoControlLabelEx	24
msoControlWorkPane	25
msoControlAutoCompleteCombo	26

Table A.2: The MSO Control types with the corresponding index.

function retrieves a reference to a control hosted by the CommandBar that meets the specified search criteria. Once the CommandBarControl has been located it is then possible to access its attributes such as its position, width, visibility etc. Figure A.2 shows the ID's of each icon in a typical Microsoft Word toolbar.

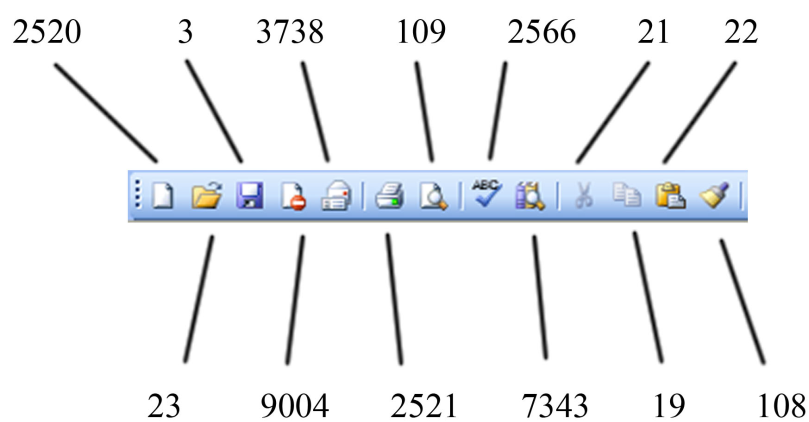

Figure A.2: Toolbar ID's for a traditional Microsoft Word interface.

An extensive list of all the CommandBar ID's can be found at [Micd]. Having extracted the key features from the GUI the next stage was to handle the events related to the position of the window and toolbars. If the window is resized or moved then the mapping of the buttons will change. These events need to be handled so that the positioning of the haptic assistance can be updated. The event handler used for window movement or resizing is the `ApplicationEvents3_WindowSizeEventHandler`. The same update is required when a commandbar is moved or resized. The commandbar event is handled by the `_CommandBarsEvents_OnUpdateEventHandler`.

Although this article was written in C# it was decided that the interface extraction would be continued in this environment due to the ease of development and greater available literature. One of the major benefits of using Microsoft .NET is that it provides a language-independent development system [DiL02]. Classes and libraries can be written in Visual Basic, C++, C# and used in other languages. It is also possible to derive from classes in a different language. A dynamic link library (.dll) will be created in C# to extract the key interface information and then used in the C++ applications for haptic assistance. A typical C# application template is shown in the following code snippet.

```
using System.Data;
using System.Drawing;
using System.Text;
using System.Windows.Forms;
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Diagnostics;
using Word = Microsoft.Office.Interop.Word;
using test = Microsoft.Office.Core;
using System.Runtime.InteropServices;


namespace WindowsApplication1
{
    public class Program
    {
        [STAThread]
        public static void Main()
        {
            //Insert code for interface extraction
        }
    }
}
```

Once the C# .dll had been created the next stage of development was to link that into the C++ haptic project. Loading the .dll is straightforward in C++, as shown in the following code snippet. In this example the main() function from the C# .dll is called and executed in a C++ application.

```
#using <mscorlib.dll>
#using <myfirstcsharpdll.dll>
using namespace WindowsApplication1;
```

```
int main
{
    Program p;
    p.Main();
}
```

With the necessary interface information extracted in the C# .dll the next stage was to use that to configure the haptic assistance correctly in the C++ application. The position and width of each control is stored in an array that can be accessed easily in C++. When the events regarding the window and toolbar positioning are fired, each control is updated in the array and the haptic assistance repositioned. The successful mapping of haptic assistance in a Microsoft Word application can be observed in Figure A.3. This figure shows a transparent Word interface with the white squares mapped correctly in the OpenGL window behind. The transparency is achieved using WinTrans v1.1 [Ivo].

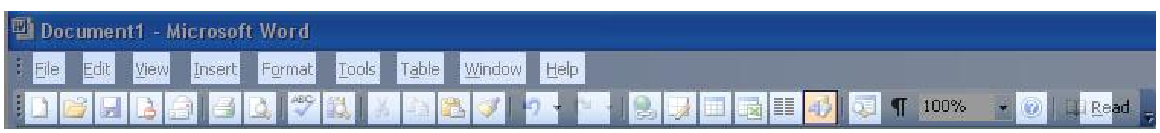

Figure A.3: The automated haptic mapping of a Word interface. Each white square represents the mapping of haptic assistance for the corresponding Microsoft Word icon.

A.2.2 Windows On-Screen Keyboard

The mapping of the Windows on-screen keyboard will also be important for motion impaired operators that have difficulty using a standard keyboard. To locate the on screen position of each key is straightforward using the Windows API. The Windows API provides a function called `FindWindowEx()` that can be used to search for a window matching a specified class name and/or window name. The class name or window name of each key was extracted using the Visual Studio Tool named Spy++.

A C# .dll has been created and used in the C++ application using the same method discussed in Subsection A.2.1. The correct mapping of haptic assistance for the on-screen keyboard is shown in Figure A.4. This figure shows the transparent keyboard with the black squares mapped correctly in the OpenGL window behind.

Figure A.4: The automated haptic mapping of the Windows On-Screen Keyboard. Each black square represents the mapping of haptic assistance for the corresponding key.

A.3 Summary

Both the Word and on-screen keyboard interfaces have been tested with gravity wells, high-friction targets, haptic cones and haptic walls. Each operator was able to produce coherent sentences in Microsoft Word using the haptic techniques applied to the on screen keyboard. Although data analysis was not performed at this stage it was clear by observing the participants that target selection was much easier and took less time when haptic assistance was enabled. The techniques that appeared to improve target acquisition the most were gravity wells and haptic cones.

Bibliography

[Ass] The Stroke Association. Stroke rehabilitation. http://www.stroke.org.uk/information/stroke_rehabilitation/index.html.

[BCRB03] S. Baillie, A. Crossan, S. Reid, and S. Brewster. Preliminary development and evaluation of a bovine rectal palpation simulator for training veterinary students. *Cattle Practice.*, 11:101–106, 2003.

[BCS] F. Barbagli, F. Conti, and K. Salisbury. Overview of haptic rendering techniques. http://www.stanford.edu/class/cs277/slides/CS_277

[Bre98] S. Brewster. The design of sonically enhanced widgets. *Interacting with Computers*, 11(2):211–235, 1998.

[BSR07] J. Broeren, K. Sunnerhagen, and M. Rydmark. A kinematic analysis of a haptic handheld stylus in a virtual environment: a study in healthy subjects. *Journal of NeuroEngineering and Rehabilitation*, 4(1):13, 2007.

[CB05] A. Cockburn and S. Brewster. Multimodal feedback for the acquisition of small targets. *Ergonomics*, 48:1129–1150, 2005.

[CBM+] F. Conti, F. Barbagli, D. Morris, C. Sewell, and S. Grange. CHAI3D open source haptic API. http://www.chai3d.org/.

[Cen] The NHS Technology Adoption Centre. Technology implementation projects. http://www.technologyadoptionhub.nhs.uk/517/518/522/our-projects.html.

[CJ68] W.R. Corliss and E.G. Johnson. Teleoperator controls. *AEC-NASA Technology Survey*, page 170, 1968.

[Cora] Immersion Corporation. Consumer study shows video game console purchasing behavior may be influenced by vibration feedback technology. http://ir.immersion.com/ReleaseDetail.cfm?ReleaseID=212029.

[Corb] Immersion Corporation. What is haptics? http://www.immersion.com/corporate/press_room/what_is_haptics.php.

[CS07] S.V.G Cobb and P.M. Sharkey. A decade of research and development in disability. *The International Journal of Virtual Reality*, 6(2):51–68, 2007.

[DiL02] Paul DiLascia. Call unmanaged dlls from C#, killing processes cleanly. *MSDN Magazine 2002*, 2002.

[EPP] Enhanced pointer precision. http://support.microsoft.com/default.aspx ?scid=kb;en-us;895550.

[GI05] Z. Gao and I.Gibson. Haptic b-spline surface sculpting with a shaped tool of implicit surface. *Computer-Aided Design and Applications*, 2:263–272, 2005.

[GMD09] C. Gunn, W. Muller, and A. Datta. Performance improvement with haptic assistance: A quantitative assessment. In *Proc. of the World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 511–516, Washington, DC, USA, 2009.

[GSK07] V. Gourishankar, G. Srimathveeravalli, and T. Kesavadas. Hapstick: A high fidelity haptic simulation for billiards. In *Proc. of the Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 494–500, 2007.

[GWW08] K. Gajos, J. Wobbrock, and D. Weld. Improving ther performance of motor-impaired users with automatically-generated, ability-based interfaces. In *Proceeding of the twenty-sixth annual SIGCHI conference on Human factors in computing systems*, pages 1257–1266, New York, NY, USA, April 5-10 2008.

[Hapa] UK Haptics. http://www.ukhaptics.co.uk/Default.aspx.

[Hapb] UK Haptics. Virtual veins system. http://www.ukhaptics.co.uk/VirtualVeins.aspx.

[Har07] Simon Harper. Is there design-for-all? *Univ Access Inf Soc*, 6(1):6:111–113, 2007.

[HKLC05] F. Hwang, S. Keates, P. Langdon, and P.J. Clarkson. Movement time for motion-impaired users assisted by force feedback: effects of movement amplitude, target width, and gravity well width. *Univ Access Inf Soc*, 4:85–95, 2005.

[HLKC01] F. Hwang, P. Langdon, S. Keates, and J. Clarkson. Haptic assistance to improve computer access for motion-impaired users. In *Eurohaptics 2001 Conference Proceedings*, pages 176–178, 2001.

[HLKC03] F. Hwang, P. Langdon, S. Keates, and J. Clarkson. The effect of multiple haptic distractors on the performance of motion-impaired users. In *6th ERCIM Workshop "User Interfaces for All"*, pages 14–25, Alghero, Italy, September 2003.

[HM07] V. Hayward and K. MacLean. Do it yourself haptics, part I. *IEEE Robotics and Automation Magazine*, 15(1):104–119, 2007.

[HS] Microsoft Help and Support. How to handle events in word by using visual C# .net. http://support.microsoft.com/kb/824022.

[Ivo] Ivory. Window transparency. http://wintrans.en.softonic.com/.

[JT66] L. Jones and J. Thousand. Servo controlled manipulator device. 1966. US Patent 3,263,824 Northrop Corporation.

[Kan] *The Oxford English Dictionary Second Edition.*

[KHL+02] S. Keates, F. Hwang, P. Langdon, P.J. Clarkson, and P. Robinson. The use of cursor measures for motion-impaired computer users. *Universal Access in the Information Society*, 2(1):18–29, 2002.

[KLA+03] H. Koester, E. LoPresti, G. Ashlock, W. McMillan, P. Moore, and R Simpson. Compass: Software for computer skills assessment. In *Proc. of CSUN 2003 International Conference on Technology and Persons with Disabilities*, Los Angeles, CA, March 2003.

[KLCR00] S. Keates, P. Langdon, J. Clarkson, and P. Robinson. Investigating the use of force feedback for motion-impaired users. In *Proc. of the 6th ERCIM Workshop*, pages 207–212, Florence, Italy, 2000.

[KLS05] H. Koester, E. LoPresti, and R Simpson. Toward goldilocks' pointing device: Determining a "just right" gain setting for users with physical impairments. In *Proc. of the 7th international ACM SIGACCESS conference on Computers and accessibility*, pages 84–89, Baltimore, MD, USA, 2005.

[KLS06] H. Koester, E. LoPresti, and R Simpson. Factors influencing user performance with pointing devices. *Proc. of RESNA 29th International Annual Conference*, 2006.

[KYS+05] R. Kuber, W. Yu, P. Strain, E. Murphy, and G. McAllister. Assistive multimodal interfaces for improving web accessibility. *CHI Haptic Workshop*, 6(2-3):133–148, 2005.

[LBA00] E. LoPresti, D. Brienza, and J. Angelo. Evaluation of computer head control software to compensate for neck movement limitations. In *Proc.*

on the 2000 conference on Universal Usability, pages 147–148, Arlington, Virginia, United States, 2000.

[LD03a] S. D. Laycock and A. M. Day. The haptic rendering of polygonal models involving deformable tools. *Proc. of EuroHaptics*, pages 176–192, 2003.

[LD03b] S. D. Laycock and A. M. Day. Recent developments and applications of haptic devices. *Computer Graphics Forum*, 22(2):117–132, 2003.

[LD06] E. Lövquist and U. Dreifaldt. The design of a haptic exercise for post-stroke arm rehabilitation. In *Proc. of 6th Intl Conference on Disability, Virtual Reality & Associated Technology*, Esbjerg, Denmark, 2006.

[LD07] S.D. Laycock and A.M. Day. A survey of haptic rendering techniques. *Computer Graphics Forum*, 26:50–65, 2007.

[LHK+02a] P. Langdon, F. Hwang, S. Keates, J. Clarkson, and P. Robinson. Developing assistive interfaces for motion-impaired users using cursor movement analysis in conjunction with haptic feedback. In *Proc. ICDVRAT '02.*, pages 223–230, Reading, UK, 2002.

[LHK+02b] P. Langdon, F. Hwang, S. Keates, P.J. Clarkson, and P. Robinson. Investigating haptic assistive interfaces for motion-impaired users: Force-channels and competitive attractive-basins. In *Proc. of Eurohaptics 2002*, pages 122–127, Edinburgh UK, 2002.

[LHK+02c] P.M. Langdon, F. Hwang, S. Keates, P.J. Clarkson, and P. Robinson. Developing assistive interfaces for motion-impaired users using cursor movement analysis in conjunction with haptic feedback. In *Proc. ICDVRAT '02*, pages 223–230, Reading UK, 2002.

[LKCR00] P. Langdon, S. Keates, J. Clarkson, and P. Robinson. Using haptic feedback to enhance computer interaction for motion-impaired users. In *Proceedings of ICDVRAT'00*, pages 25–32, Alghero, Italy, September 2000.

[LS05] J. Levine and M. Schappert. A mouse adapter for people with hand tremor. *IBM Syst. J.*, 44(3):621–628, 2005.

[Mac98] R. L. Mace. A perspective on universal design. In *Proc. of Designing for the 21st Century: An International Conference on Universal Design.*, Retrieved from http://www.design.ncsu.edu/cud/about_us/usronmacespeech.htm, 1998.

[MC95] P.A. Millman and J.E. Colgate. Effects of non-uniform environment damping on haptic perception and performance of aimed movements. In *Proceedings of Eurohaptics Conference*, pages 703–712, 1995.

[MC01] P.A. Millman and J.E. Colgate. Using haptics technology to deliver motivational therapies in stroke patients: Concepts and initial pilot studies. In *Proceedings of the ASME Dynamic Systems and Control Division*, pages 1–6, 2001.

[McG90] R. McGill. A blackboard knowledge-based approach towards implementing an adaptive force joystick computer input device for persons with tremor disability. In *Proc. of the RESNA Annual Conference*, pages 431–432, 1990.

[MG07] C. Mauri and T. Granollers. On the assessment of the interaction quality of users with cerebral palsy. In *Proc. of the The Second International Conference on Availability, Reliability and Security*, pages 799–805, 10-13 April 2007.

[MH08] T. Macnair and R. Hicks. Cerebral palsy, January 2008. http://www.bbc.co.uk/health/conditions/cerebralpalsy1.shtml.

[Mica] GW Micro. Window-eyes. http://www.gwmicro.com/Window-Eyes/.

[Micb] Microsoft. Commandbars collection object. http://msdn.microsoft.com/en-us/library/aa190804(office.10).aspx.

[Micc] Microsoft. How to customize menus and menu bars in excel. http://support.microsoft.com/kb/830502.

[Micd] Microsoft. Microsoft word and excel commandbar id's. http://www.microsoft.com/downloads/details.aspx?FamilyID=6c2a221e-e77e-4e3c-8320-36583cdbe0a2&DisplayLang=en.

[MKS01] I. MacKenzie, T. Kauppinen, and M. Silfverberg. Accuracy measures for evaluating computer pointing devices. In *Proc. of the ACM Conference on Human Factors in Computing Systems - CHI 2001*, pages 9–16, Seattle, Washington, United States, 2001.

[MMS+90] M. Minsky, O. Ming, O. Steele, Jr. F. Brooks, and M. Behensky. Feeling and seeing: issues in force display. In *Proc. of the 1990 symposium on Interactive 3D graphics*, pages 235–241, Snowbird, Utah, United States, 1990.

[MW05] B. Myers and J. Wobbrock. Feeling and seeing: issues in force display. In *Proc. of the 11th Int'l Conference on Human-Computer Interaction*, pages 1962–1970, Snowbird, Utah, United States, July 22-27 2005.

[MZ98] T. Miller and R. Zeleznik. An insidious haptic invasion: adding force feedback to the X desktop. In *Proc. of the 11th annual ACM symposium on User interface software and technology*, pages 59–64, San Francisco, California, United States, 1998.

[NHSa] NHS. Cerebral palsy. http://www.nhs.uk/Conditions/Cerebral-palsy/Pages/Introduction.aspx.

[NHSb] NHS. The nhs technology adoption centre. http://www.technologyadoptionhub.nhs.uk/.

[NSF] Nintendo 64 games console. http://www.nintendo.co.uk/NOE/en_GB/systems/nintendo_64_1152.html.

[NWI] Nintendo wii games console. http://www.nintendo.co.uk/NOE/en_GB/wii_54.html.

[OABG02] I. Oakley, A. Adams, S. Brewster, and P. Gray. Guidelines for the design of haptic widgets. In *Proc. of British HCI 2002. British Computer Society*, pages 195–212, London, UK, 2002.

[OMBG00] I. Oakley, M. McGee, S. Brewster, and P. Gray. Putting the feel in 'look and feel'. In *Proc. of the SIGCHI conference on Human factors in computing systems*, pages 415–422, The Hague, The Netherlands, 2000.

[PCBB08] B. Plimmer, A. Crossan, S. Brewster, and R. Blagojevic. Multimodal collaborative handwriting training for visually-impaired people. In *Proc. Eurohaptics 2001*, pages 393–402, Florence, Italy, 2008.

[PDE98] ISO ISO/TC 159/SC4/WG3 N147: Ergonomic requirements for office work with visual display terminals (VDTs). *Part 9 - Requirements for non-keyboard input devices, International Organisation for Standardisation*, 1998.

[PL04] X. Peng and W. Zhangand M. C. Leu. Interactive solid modeling in a virtual environment with haptic interface. In *Proc. of Virtual and Augmented Reality Applications in Manufacturing.*, pages 43–61, 2004.

[Ram95] C. Ramstein. A multimodal user interface system with force feedback and physical models. In *Proc. of IFIP INTERACT'95: Human-Computer Interaction*, pages 157–162, Lillehammer, Norway, 1995.

[RDLT06] G. Robles-De-La-Torre. The importance of the sense of touch in virtual and real environments. *In IEEE Multimedia, Special issue on Haptic User Interfaces for Multimedia Systems*, 13(3):24–30, 2006.

[Res90] J.B. Reswick. The moon over Dubrovnik - a tale of worldwide impact on persons with disabilities. *Proc. of Advances in external control of human extremities*, pages 123–135, 1990.

[RHDK08] P. Rhienmora, P. Haddawy, M. Dailey, and P. Khanal. Development of a dental skills training simulator using virtual reality and haptic device. *NECTEC Technical Journal*, 8:140–147, 2008.

[RP] Nintendo 64 rumble pack. http://www.nintendo.co.uk/NOE/en_GB/systems/accessories_1225.html.

[SBM+95] K. Salisbury, D. Brock, T. Massie, N. Swarup, and C. Zilles. Haptic rendering: Programming touch interaction with virtual objects. In *Proc. of the Symp. on Interactive 3D Graphics*, pages 123–130, 1995.

[Sci] Freedom Scientific. Jaws for windows screen reading software. http://www.freedomscientific.com/about/about.asp.

[Sco] Scope. Introduction to scope. http://www.scope.org.uk/home/scope.shtml.

[She96] J. R. Shewchuk. Triangle: Engineering a 2D quality mesh generator and Delaunay triangulator. In *Proc. of FCRC '96/WACG '96: Selected papers from the Workshop on Applied Computational Geormetry, Towards Geometric Engineering*, pages 203–222, London, UK, 1996.

[Sjö01] S. Sjöstrom. Designing haptic computer interfaces for blind people. In *Proc. of Sixth International Symposium on Signal Processing and its Applications*, pages 68–71, 2001.

[Sun] D. Sunday. Geometry algorithms - point to a segment distance. http://softsurfer.com/Archive/algorithm_0102/algorithm_0102.htm #dist_Point_to_Segment().

[Sut65] I. Sutherland. The ultimate display. *IFIP*, 2:506, 1965.

[Teca] SensAble Technologies. Openhaptics toolkit version 3.0 programmers guide. http://www.sensable.com/documents/documents/OpenHaptics_ProgGuide.pdf.

[Tecb] SensAble Technologies. Phantom desktop haptic device. http://www.sensable.com/haptic-phantom-desktop.htm.

[Tecc] SensAble Technologies. Phantom omni haptic device. http://www.sensable.com/haptic-phantom-omni.htm.

[Tecd] SensAble Technologies. Product overview. http://www.sensable.com/products-sensable-overview.htm.

[Tel] Telegraph. Nintendo wii 'may help cerebral palsy children'. http://www.telegraph.co.uk/news/uknews/2276616/Nintendo-Wii-'may-help-cerebral-palsy-children'.html.

[UPK06] D. Ulrika, G. Paul, and Z. Kulcsar. Exploring haptics as a tool to improve training of medical doctors in the procedure of spinal anaesthetics. *Proc. of EuroHaptics*, pages 176–192, 2006.

[Van00] G. Vanderheiden. Fundamental principles and priority setting for universal usability. In *CUU '00: Proceedings on the 2000 conference on Universal Usability*, pages 32–37, Arlington, Virginia, United States, 2000.

[WFL09] J. Wobbrock, J. Fogarty, and S. Liu. The angle mouse: Target-agnostic dynamic gain adjustment based on angular deviation. In *Proc. of the 27th international conference on Human factors in computing systems*, pages 1401–1410, Boston, MA, USA, April 4-9 2009.

[WG07] J. Wobbrock and K. Gajos. A comparison of area pointing and goal crossing for people with and without motor impairments. In *Proc. of the 9th international ACM SIGACCESS conference on Computers and accessibility*, pages 3–10, Tempe, Arizona, USA, 2007.

[WH01] S.A. Wall and W.S. Harwin. Design of a multiple contact point haptic interface. In *Proc. of Eurohaptics 2001*, pages 146–148, University of Birmingham, July 1-4th 2001.

[WPS+02] S. Wall, K. Paynter, A. Shillito, M. Wright, and S. Scali. The effect of haptic feedback and stereo graphics in a 3D target acquisition task. In *Proc. of Eurohaptics 2002*, pages 23–29, University of Edinburgh, July 8-10th 2002.

[YGB01] W. Yu, K. Guffie, and S. Brewster. Image to haptic data conversion: A first step to improving blind people's accessibility to printed graphs. In *Proc. Eurohaptics 2001*, pages 87–89, Birmingham, UK, 2001.

[YTT06] H.T. Yau, L.S. Tsou, and M.J. Tsai. Octree-based virtual dental training system with a haptic device. *Computer-Aided Design and Applications*, 3:415–424, 2006.

[ZS95] C.B. Zilles and J.K. Salisbury. A constraint based god-object method for haptic display. In *Proc. of the IEEE Conference on Intelligent Robots and Systems*, pages 146–151, 1995.