Developing assistive interfaces for motion-impaired users using cursor movement analysis in conjunction with haptic feedback

P M Langdon[1], F Hwang[1], S Keates[1], P J Clarkson[1] and P Robinson[2]

[1]Dept. of Engineering, [2]Computer Laboratory, University of Cambridge, Cambridge, UK

{pml24, fh220, lsk12, pjc10}@eng.cam.ac.uk, *Peter.Robinson@cl.cam.ac.uk*

ABSTRACT

Following a pilot study that suggested that haptic force-feedback could, under certain conditions, lead to 20-50% improvements in time to target in a selection task, a series of experiments further investigated the use of haptic feedback modulated on the basis of cursor position. Improvement in times were obtained for specific haptic assistance techniques, particularly for the more impaired users. Cursor path data was simultaneously collected and found to identify particular features or properties of the motion-impaired cursor movement that can be specifically addressed using modulated haptic force-feedback. This suggests that parameters obtained from temporal and curvature analysis of cursor movements for haptic tasks could be used to set or adapt force-feedback in user interfaces, assisting motion impaired computer users.

1. INTRODUCTION

Cerebral Palsy, Muscular Dystrophy, spinal injuries and the after-effects of stroke, give rise to symptoms such as reduced strength, restricted movement and symptoms involving spasms, tremors and motion control problems. We report exploratory studies that investigate the potential for enhancement of user interfaces for such computer users by the use of modulated haptic feedback in conjunction with information derived from cursor movement parameters. We have previously reported preliminary work examined the threshold for detection and relative effectiveness of vibrotactile and force-feedback haptic interactions in a click selection task, concluding that force-feedback held more potential for assistive technology than vibrotactile particularly for highly impaired computer users (Langdon, Keates, Clarkson, and Robinson, 2000).

The use of force-feedback input devices to generate haptic and kinaesthesic sensations during interaction with a computer interface has been widely investigated for able-bodied interaction. In particular, haptic devices have been used to enhance VR interaction and tactile or tactual feedback through a mouse pointing device. For able-bodied users tactile feedback increases positioning times (Akamatsu, MacKenzie and Hasbrouc 1995) , while target selection has been shown to improve with the use of attractive basin around targets and force feedback tunnels (Dennerlein, Martin and Hasser 2000, Dennerlein and Yang, 2001). Although described as tactile, interactions with force feedback mice may be better described as tactual in that the sensation results from both cutaneous and kinaesthetic feedback during mouse manipulation (e.g. Klatsky and Lederman, 1993). However, this such force-feedback also has a great deal of potential for improving the design of assistive interfaces to aid impaired movement or positioning or for rehabilitative purposes by initiating or enhancing therapeutic physical interactions.

2. ASSISTIVE HAPTIC INTERFACES

The existing GUI paradigm relies principally on visual feedback, often supported by sound and with minimal involvement of haptic feedback. Haptic perception is the gathering of information about objects outside of the body through the tactile and kinaesthetic senses (Klatsky and Lederman, 1993). The use of haptic feedback is restricted to the physical interaction with the specific input device, but is under-utilised. In the current graphical user interface (GUI) paradigm, icons and windows are directly manipulated but there is no resulting tactile or kinaesthetic feedback to the manipulating limbs. This suggests a new potential interaction mode to complement the existing ones.

2.1 Functional Impairments

Medical conditions such as Cerebral Palsy, Parkinson's disease, Muscular Dystrophy, spinal injuries and the after-effects of stroke, give rise to symptoms such as reduced strength, restricted movement and a continuum of impairments involving spasms, tremors and movement control problems. These populations display irregular, jerky movements, possibly in conjunction with slower, linked writhing (athetosis and chorea). They may also be poor at sequencing and co-ordinating movements (apraxic) or may have essential tremor with repetitive movements (dyskinesia) and spasms (rhythmic myoclonus). Movement impairments may arise from central nervous system dysfunction or be muscle spasms and dystonia arising from other neurological damage or dysfunction. Many of these impairments are also prevalent in the older population.

2.2 Haptic Assistance

Motion-impaired users often exhibit decreased motor control and muscle strength, but not necessarily a decreased haptic sensitivity. The sensitivity of able-bodied users to haptic feedback has been demonstrated using devices such as the Phantom (e.g. Oakley, McGee and Brewster and Grey, 2000). However, this is an expensive research tool that is unlikely to be used routinely as a general-purpose interaction device. Fortunately, haptic technology is also available using the Logitech force-feedback mouse (Logitech. Ltd.) with software from the Immersion corporation (The Immersion Corporation) that is, in principle, capable of generating both cutaneous and kinaesthesic haptic interactions with the user as a result of its very wide range of movement generation capabilities.

2.3 Motivation

The relative utility of haptic feedback using devices such as the force-feedback mouse has been demonstrated by the authors in work previously reported (Langdon, Keates, Clarkson, and Robinson, 2001). This paper describes experiments extending those findings by examining the improvement in users performance in a point and-click selection task with a number of haptic interface techniques and also shows how it may be possible to modify the dynamic force feedback necessary to improve interaction using parameters obtained from analysing user cursor movements. In particular, properties of a number of analytical measures of the characteristics of motion-impaired target selection movements can be related to gross performance measures in haptic interface tasks, such as time to target. The movement correlates they then represent may be (1) used to discriminate specific motion impairments or functional deficits (2) used to set the parameters of an adaptive haptic interface or (3) form the basis of specific, predictive models of motion-impaired pointing device usage.

3. HAPTIC EXPERIMENTS

The volunteer participants who were involved in the study are described in Table 1. This small sample of users largely represented Cerebral Palsy populations between the ages of 20 –50 and were from three post-clinical vocational rehabilitation centres of the Papworth trust in Suffolk and Cambridge in the UK. Five users, HA1, HA2, IP3, PV2 and PV3, are non-ambulant and severely impaired by tremor, spasm and weakness; PV5, PV6, PV7, PV8 and IP4 are less impaired, four being ambulant. These users can experience changes in their capability over time and may require medical treatment such as surgery during an experimental series. They become fatigued easily, despite extremely high motivation, and sometimes cannot complete trials or conditions. It is necessary for experimenters to run the trials on a long-term basis, and to develop a working relationship with the users to keep experimental conditions constant. Because of the small number of users available, repeated measures designs were generally employed. The users were both selected and screened for the experimental trials. Selection was managed to equally distribute the range of disabilities in the sample from high to medium and low impairments. Screening was also managed to exclude individuals with significant sensory or cognitive impairments that may have interfered with their capability to perform the tasks.

In the experiments reported, where statistical tests were possible without violation of standard assumptions, such as normality of distribution or homogeneity of variance, they were carried out and experimental power reported. Despite variability, effect sizes could be large.

Table 1. *Participants in the haptic feedback trials.*

User PV3	*Athetoid Cerebral Palsy, apraxia (coordination), myoclonus (spasms), Wheelchair*
User PV5	*Athetoid Cerebral Palsy, apraxia (coordination),deaf, non-speaking, Wheelchair*
User PV2	*Athetoid Cerebral Palsy, dystonia, apraxia (coordination), myoclonus (spasms) Wheelchair*
User PV7	*Freidrich's Ataxia, tremor and dyskinesia,myoclonus (spasms), Wheelchair*
User PV6	*Athetoid Cerebral Palsy, deaf, non-speaking, ambulant*
User PV8	*Athetoid Cerebral Palsy, apraxia (coordination), myoclonus (spasms), Wheelchair*
User IP3	*Head Injury, apraxia (coordination), Wheelchair*
User IP4	*Athetoid Cerebral Palsy, Ambulant*
User HA1	*Unknown , apraxia (coordination), myoclonus (spasms), Wheelchair*
User HA2	*Athetoid Cerebral Palsy, apraxia (coordination), myoclonus (spasms), Wheelchair*

3.1 Task and conditions

The task was designed for a detailed investigation of specific parameters associated with a point-and-click, selection task. The aim was to quantify the effect of force feedback on time to complete a selection. The experiment involved the users being presented with 16 target circles arranged equidistantly around a central circle on the screen. The aim was for the users to click on each target circle in a random order determined by the software (Figure 1), returning to the central target between each selection. Trials were carried out in as a set of 16, one selection for each target and blocks of three trials for each condition. This task was used in all the following experiments. Although the primary dependent variable was time to target, cursor movement trajectories were recorded at the same time for future analysis (Figure 1).

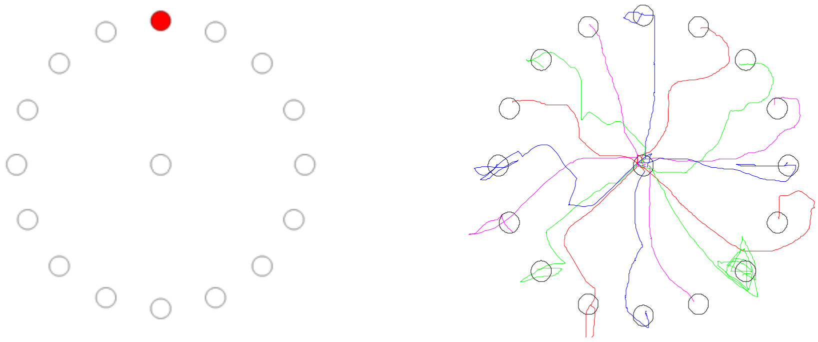

Figure 1. *The selection task layout showing example cursor trajectories (right).*

3.1.1 Device. The force-feedback mouse used was a development of the original FEELit Mouse marketed by the Immersion corporation and manufactured by Logitech as the "Wingman"(model E-UB3). This device generates constant force vectors at a conventionally shaped mouse mounted on a base-plate by means of an electromagnetic voice-coil activating a pantographic mechanism and controlled by an on-board processor under interactive control of a host PC. It is capable of 1.2N constant force with a 40mm square movement range that is mapped to the entire computer display. This device should not be confused with more recent haptic mice that generate only transient vibrational forces with no constant vectored component. Force-feedback within such the input device used can present constant directional forces, and also has the capability of aiding or damping user inputs, in the case of weakness, muscle spasm or tremor.

3.2 Attraction basins

Our previous study (Langdon, Keates Clarkson, and Robinson, 2001) examined specific parameters associated with a point-and-click, selection task. The aim was to quantify the effect of a number of variables including: pointer trails, 66Hz vibration, colour change and force feedback attraction basins, on time to complete a selection when the target was indicated by the effect. Amongst those variables was the gravity well haptic effect that gives the sensation that that there is a second, larger circle around the target that corresponds to the extent of the gravity field. Entering that outer circle causes the cursor to become subject to a spring force towards the centre.

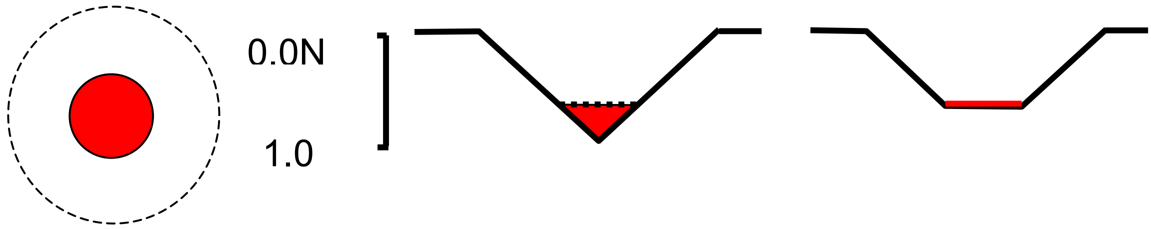

Figure 2. *An attractive Basin with the old (right) and new (left) force profiles.*

It was found that the use of a gravity well around a target improved the time taken to complete the task by approximately 10-20%. However it was also found that implementation of the gravity well as a spring force acting to the centre of the target rather than the boundary improved average time to target even more to levels approaching a 50% improvement (Figure 3). Analysis of individual differences for the users suggested that the greatest improvement occurred with the most impaired users.

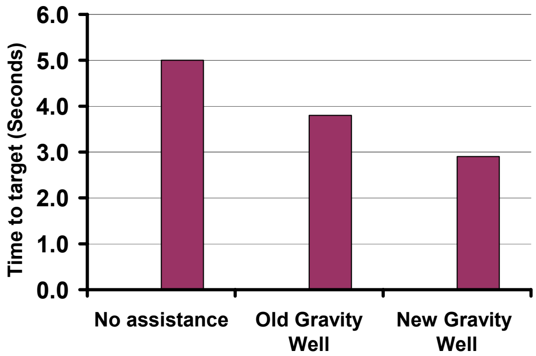

Figure 3. *Time to target for gravity well methods.*

A possible explanation for the improved performance may be that overshoot, target re-entries and movements away from the centre of the target are resisted by the inwardly directed spring force. In effect, the gravity well then acts as a directional damping mechanism.

3.3 Force channels in the direction of the target

Haptic tunnels were intended to assist users in moving the cursor in a straight line to the target. It was expected that tunnels would help improve overall times to target by reducing deviations during navigation. It was hypothesised that the unlimited wall condition would prevent highly impaired users jumping beyond the channel wall, reducing times to target.

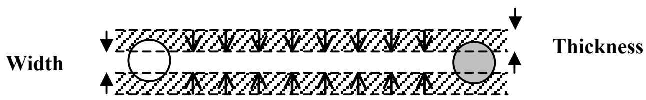

Figure 4. *The relative wall thickness and channel width.*

There were four channel conditions and one unassisted condition. Haptic tunnels have a channel width (i.e. distance between the tunnel's inside walls) and a wall thickness. When the cursor passes over a tunnel wall, a spring force pulls the cursor to the inside wall. Two conditions were presented with a 0 or 20 pixel channel width, and two conditions presented with either a 20 pixel tunnel wall thickness or an "unlimited" thickness. Hence, with 0 pixel channel width, the cursor experienced a spring force towards the centre-line of the channel and in the unlimited wall thickness condition the spring force acted toward the centre of the channel irrespective of the cursor location, with no outer limit on the wall thickness (Figure 4).

3.3.1 Results. There were significant differences between tunnel types overall with 36% of the variance in times accounted for by channel type. However significant non-sphericity (Greenhouse-Geisser) ($F_{1.7,\ 10.2}$ = 3.442, p = 0.077, Eta^2 = 0.365, Power = 0.481 reduced the difference to non-significance and the observed power from 0.77 to 0.48. Despite this, corrected pair-wise comparisons (Tukey HSD) revealed a significant difference between the "No Assistance" and "Unlimited – no Channel" conditions (p = 0.045), and between the "Unlimited – no Channel" and "Unlimited with Channel" conditions (p = 0.025). An ANOVA carried out using Subjects as a factor confirmed differences between highly, medium and mildly impaired users evident in the interaction diagram ($F_{6,24}$ = 104.3, p <0.0001, Eta^2 =0.963, Power = 1.0). Further pair-wise comparisons confirmed significant differences between PI3 and all others and by PI5 and PI6 and all others (all p < 0.001).

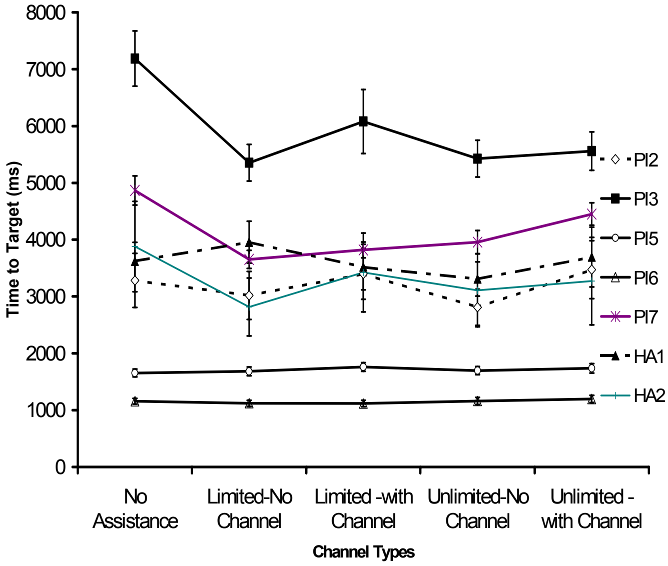

Figure 5. *Mean time to target for 5 channel types*

3.3.2 Discussion. There was slight evidence that the use of force channels in the direction of target was more effective than no assistance over all users. There was some evidence that the presence or absence of a central channel affected times to target indicating that constraining movement to a line was more effective than constraining movement to a tunnel. It is possible that for users experiencing difficulty navigating in a straight line, the extra freedom allowed by presence of a 20 pixel channel was a hindrance. No significant difference in times between the limited and unlimited wall thickness was observed, implying that the width of the tunnel wall does not affect performance. A possible explanation for this is that the majority of users rarely moved with sufficient force and direction to escape the tunnels. It appears that none of the tunnels give improved times for PI2, PI5, PI6, and HA1. This may be because these users do not experience difficulty moving in straight paths. However, all tunnel types appear to be of some benefit to PI3, PI7, and HA2 who had greater difficulty navigating to the target than the other users.

3.4. Isotropic Damping

It was possible that the gravity well implementation was effective because of a damping effect exerted on the users' athetoid spasms and tremors that caused the cursor to move away from the target. This would be a form of directional damping. However, another possible assistive haptic technique would involve a non-directional overall damping effective across the whole target field.

The task was performed under 4 damping conditions – *None, Acceleration Damping, Velocity Damping,* and *Combined Damping*. Non-directional damping was implemented as a viscous force that increases linearly with mouse acceleration (*Acceleration Damping*), mouse velocity *(Velocity Damping)*, and a combination of the two *(Combined Damping)*. The results are shown in Figure 6, with averages shown for individual users as well as overall. While the differences between overall performance levels of our motion-impaired users are evident, there appears to be no overall effect of the type of damping used, while the average times to target are not greater overall that those obtained for the attractive basins alone, as will be discussed below. The two users with low levels of impairment: PV5 and PV6 both perform at a level comparable with that of able-bodied users, whereas the most impaired user PV3, who displays spasm and athetoid movement, performs poorly but appears to show some benefit from damping. All forms of damping have a favourable effect for this user, reducing times by over 50%. Users PV7 and PV2 show intermediate levels of impairment commensurate with the degree of impairment in their targeting behavior.

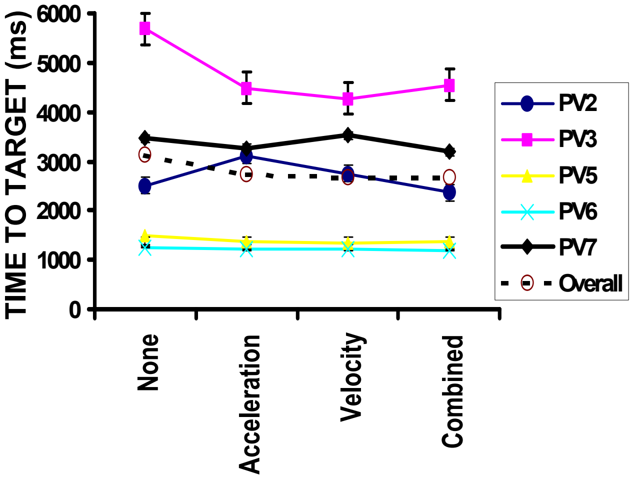

Figure 6. *Effects of Damping Types on Selection Times by Users.*

Figure 6 shows the average time to target for the damping experiment. There is no evidence for differences in performance for different damping techniques. Damping alone does not appear to have a great effect on times for users other than PV3. It may be that the nature of his impairment, which is characterised by inappropriate deviations from trajectory as a result of muscle spasms and poor coordination, may be particularly susceptible to isotropic damping. A further possibility is that resistive force of damping (up to 1.2 N) may be adequate to influence PV3's movements but ineffective at preventing the tremor of PV7. The effect of isotropic damping was to slow movement, irrespective of whether it was towards the target or not. This suggests the possibility that time to target performance may have been slowed overall despite becoming more accurate.

4. CURSOR MOVEMENT ANALYSIS

Modulating the parameters of an adaptive user interface requires an understanding of the user's cursor behaviour during an interaction. Hence, by studying cursor trajectories throughout a target selection task, differences in the cursor movement behaviour of users may be identified and related to gross performance. A range of cursor characterisation measures were examined. An example measure: the radius of curvature of the cursor path, was developed in conjunction with observations of motion impaired movements made in the previous experiments.

4.1 Radius of Curvature

A curved path can be represented geometrically as a series of differential arc segments, each formed from the arc of an associated circle having a particular radius of curvature (Hibbeler, 1998). Small radii indicate highly curved regions of a path, and large radii indicate relatively straight regions.

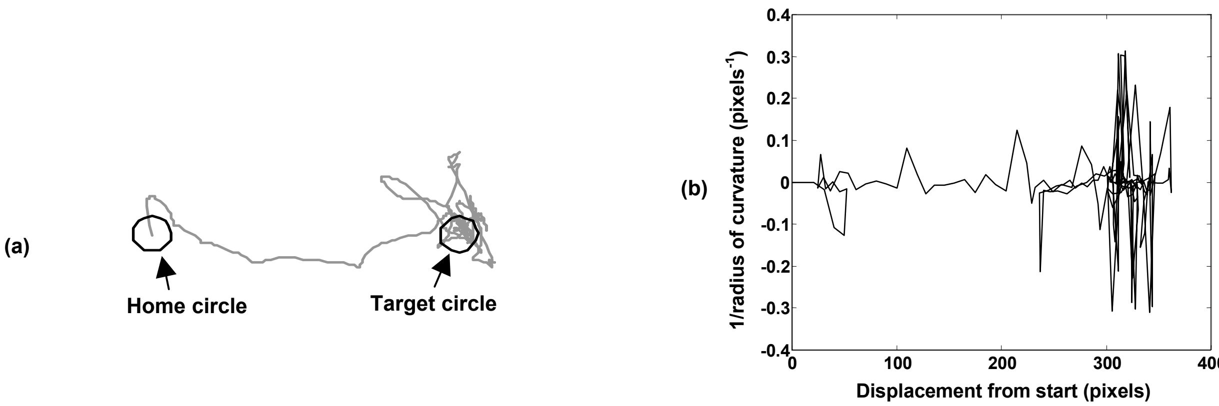

Figure 7. *The radius of curvature measure.*

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The radius of curvature along a path can provide information about the number and proximity of curves in the path at a chosen scale. Figure 7a shows a representative cursor path for user PV7 using the Wingman mouse without gravity-well haptic assistance. Rather than the smooth ballistic and homing movement phases displayed by able-bodied users, this trace displays a modified ballistic and homing phases with an erratic progress to target followed by multiple attempts and failures to select the target. This behaviour is captured by the curvature measure graph in Figure 7b which shows the reciprocal of radius of curvature (approximated for an arc length of 10 pixels) plotted against displacement from the start point. High values of this measure indicate a small curvatures or "kinks" in a smooth trajectory and it can be seen that the measure is highly sensitive to this aspect the movements of motion impaired user.

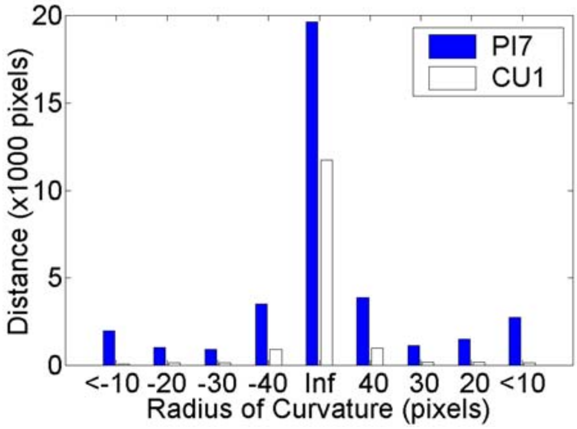

Figure 8. *Distance Travelled for a Range of Curvatures for one user (PV7) and an able-bodied comparison(CU1).*

Calculating this measure at a range of scales, corresponding to different arc lengths allows a frequency histogram to be constructed based on the number of times each scale crossed a threshold. Such a measure reveals differences in cursor behaviour that can be used to discriminate individuals or impairment type. Other measures under test include: distance travelled for a range of cursor speeds; and distance travelled for a range of radii from target (Hwang, Langdon, Keates, Clarkson, and Robinson, 2002).

5. DISCUSSION

Overall a strong positive effect of using force-feedback assistive techniques to enhance interaction was observed for our sample of motion-impaired users. The force feedback appeared to be of most benefit to the more severely impaired, especially those with difficulty performing targeting actions. These assistive techniques serve to minimise the number of inappropriate movements away from the target centre by presenting directional resistive forces for the former and minimising distracting and disruptive clicking movements for the latter. The effectiveness of isotropic damping was greatest for the user with the most spasm and athetoid movement and relatively ineffective for other users. This suggests that force-feedback damping may be most effective when its direction and timing can be linked to a users specific cursor movement patterns. Using a user's cursor measure profile, it may be possible for the interface to detect and compensate for uncontrolled movements such as spasm. For example, appropriate levels of isotropic damping could be generated at the point of the movement where imminent target entry was indicated by measures such as increased frequency of high curvature movements. Likewise, attraction basins could be activated at a given target and their size or strength modified by an algorithm set to detect such "cues" using a range of cursor movement measures. This process of detection might be carried out adaptively during the course of a number of movements or could be pre-set during a system training period in a predictive approach. A number of strategies for assisting motion-impaired steering movement are suggested by the specific findings of the cursor measure comparison. These include: (1) applying directional resistance to reduce high radius of curvature movements during the movement trajectory. (2) reducing the incidence of deviations from direct movement to target by applying resistive movement in a haptic "tunnel".

6. CONCLUSIONS

A number of assistive techniques; namely, attraction basins, force tunnels and isotropic damping were tested and shown to improve the performance of motion-impaired computer users in a selection task as measured by gross performance measures such as time to target. In conjunction with this, the patterns of cursor movement during the same tasks were analysed using a measures that was deemed capable of discriminating specific characteristics of motion impaired movement resulting from spasm and athetosis. The results suggested that such measures were, in principle, capable of discriminating individual users impairments, impairment types and task specific impairments. These measures, such as curvature identify particular features or properties of the motion-impaired movement that could be specifically addressed using modulated haptic force-feedback techniques such as attraction basins, isotropic damping, steering tunnelling and movement curvature limiting. Evaluating the effectiveness of these techniques will require their implementation in a realistic GUI test application, such as an assistive keyboard. The availability of comparatively cheap force feedback devices, such as the Logitech force-feedback mouse, means that the use of haptic interaction has the potential to become extremely important technology for enabling universal access to computers in the future.

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