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# Neck range of motion and use of computer head controls

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**Abstract—**Head controls provide an alternative means of computer access. This study determined whether neck movement limitations are associated with reduced performance with such head controls. This study also identified features of the cursor movement path that could aid in assessing computer access limitations. Fifteen subjects without disabilities and ten subjects with disabilities received neck range of motion evaluations and performed computer exercises using head controls. Reduced neck range of motion was correlated with reduced accuracy ($R^2$ = 93.5%) and speed ($R^2$ = 79.5%) in icon selection. A model was developed with the use of cursor positioning time and number of velocity peaks to identify when a person was having difficulty with target acquisition ($\kappa$ = 0.81). Models such as this may allow head controls to adapt to a user's needs, accommodating difficulties resulting from neck range of motion limitations.

**Key words:** computer access, head controls, man-machine systems, multiple sclerosis, spinal cord injury.

## INTRODUCTION

Many people are unable to operate a standard computer mouse because of disabilities affecting their hands or arms. Head controls offer one alternative by allowing people to use head movements to control the computer cursor. However, disabilities may affect movements of the head and neck as well as movements of the hands and arms. Many people with cervical spinal cord injury (SCI) or spinal stenosis experience neck weakness as a result of damage to the affector neurons for the neck muscles. In a study of a head-operated robotic system, Stanger et al. found that the mean ranges of neck motion were lower for subjects with SCIs than for subjects without disabilities and that some subjects with SCIs had ranges of motion less than half the mean for unimpaired subjects [1]. People with multiple sclerosis (MS) may also experience neck weakness, reducing their ability to make large head movements, or head tremor, reducing their fine motor control [2]. People may also acquire neck movement limitations because of secondary conditions, because of a treatment, such as spinal fusion, or because of the aging process. Neck range of motion limitations can therefore result from damage to the cervical neurons (SCI, spinal stenosis, MS), muscles (atrophy in SCI or MS), vertebrae (spinal fusion), or joints (arthritis).

Active neck range of motion is the number of degrees through which a person can move his or her head in various directions. Range of motion is measured in three directions: (1) bending the head forward and backward (flexion-extension), (2) turning the head left and right (axial rotation), and (3) bending the head left and right (lateral bending). Reduction in range of motion could limit

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**Abbreviations:** ANOVA = analysis of variance, MS = multiple sclerosis, SCI = spinal cord injury, SD = standard deviation, VR = virtual reality.

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Journal of Rehabilitation Research and Development Vol. 40, No. 3, 2003

effective use of head controls. For example, if a computer head-control system is calibrated so that a person with average range of motion can access the entire screen, then a person with limited range of motion may be able to access only a small portion of the screen. Without access to head controls or a standard mouse, a person may have to resort to slower, more inefficient methods or may give up using a computer altogether. Given our increasing reliance on computers in the workplace and society, this will limit the individual's ability to function independently, maintain employment, and complete other tasks of daily living.

To reduce fatigue, reductions in strength or endurance may also make limiting the extent of head movements desirable. Other symptoms, such as head tremor, can make the precise selection of small targets difficult. This can also limit functional computer use and can complicate attempts to correct for range of motion limitations. For example, simply increasing the head-control sensitivity not only may allow the person to move the cursor further across the screen but also may reduce the ability to make small, controlled movements to precisely select targets.

Another alternative method of computer access for people with disabilities is voice recognition. While voice recognition is an excellent means of text entry, it can be an inefficient replacement for the mouse. Therefore, its desirability may depend on the computer tasks that are most important to the user. Furthermore, voice-recognition systems depend on the user's ability to speak clearly and consistently. This can be a problem for people who have aphasia or use a ventilator. Even people who speak clearly may need a backup system if their voice is temporarily affected by a cold or other illness, or by fatigue.

In addition to determining whether neck movement limitations interfere with the use of head controls, determining how people's movement patterns change as a result of neck movement limitations is also important. Movement patterns during computer access often occur in the context of target acquisition tasks—using the computer cursor to acquire (or select) a target (such as an icon on the computer display). One model of human movement during target acquisition tasks is Fitts' Law [3]. Fitts' Law is frequently applied to hand movements. It also has been found to apply to head movements in computer control scenarios [4–6]. However, in studying another interface design model, the Model Human Processor [7], Keates et al. found that parameters derived for people without disabilities were not applicable to individuals with various disabilities [8]. The parameters of Fitts' Law may also be different for people with disabilities.

Fitts' Law is associated with a three-phase model of human movements [3,8,9]: (1) During the reaction phase, the person perceives the target and initiates a movement; (2) during the ballistic phase, the person performs a rapid movement toward the target; and (3) during the homing phase, the person performs a slower, more controlled movement directly onto the target. These three phases are illustrated in **Figure 1**.

It is desirable to determine whether this three-phase model of human movement applies to head movements as well as hand movements. If so, the pattern may be different for individuals with disabilities. For example, a person having difficulty with cursor movement may stop short of the target and need to perform a second distinct movement to reach the target, or he or she may overshoot the target and need to reverse the direction of cursor movement. Either of these situations would result in an additional peak in the velocity profile, aside from the ballistic phase peak of the primary movement. Alternatively, a person who has difficulty with precise movements may spend an exceptional amount of time in the homing phase attempting to maneuver the cursor onto the target.

Details of the cursor movement patterns may also provide the computer with information about how to adapt to a particular user. In research on eye movements, larger movement amplitudes are associated with higher

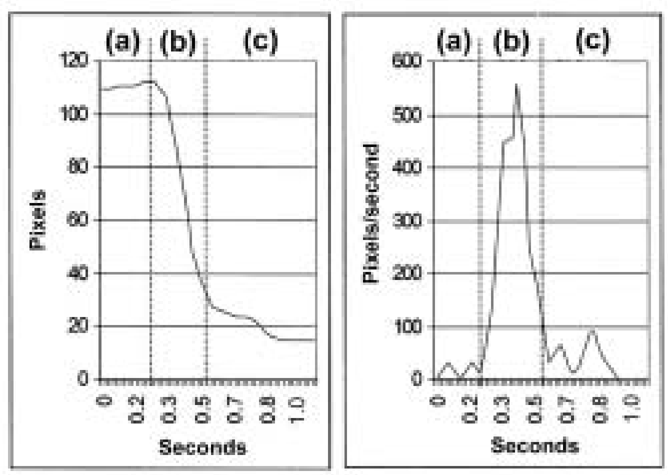


**Figure 1.**
Three phases of movement for a sample head movement: **(a)** reaction phase, **(b)** ballistic phase, and **(c)** homing phase. Shown for distance between cursor and target over time (left) and instantaneous cursor velocity over time (right).

peak movement velocities [10]. An analogous relationship may exist for head movements. In the realm of functional head movements for computer control, the peak velocity would be the maximum instantaneous cursor velocity resulting from a single head movement (e.g., the peak in the rightmost plot of **Figure 1**). Movement amplitude would correspond to the total distance traveled by the cursor as a result of the same head movement (e.g., the difference between the start and end points of the leftmost plot in **Figure 1**). If the same relationship is true for head movements as for eye movements and if the relationship between movement amplitude and peak velocity is consistent, then the magnitude and direction of the peak velocity could be used to predict the eventual movement amplitude.

This study analyzed head movements in the context of two computer exercises: an icon selection task and a tracking task. This study determined whether neck movement limitations are associated with reduced accuracy or speed for computer access tasks when a person is using a head-control interface. This study also identified features of the cursor movement path that could help assess and remediate computer access limitations.

## METHOD

### Equipment

Subjects used a HeadMaster Plus$^{TM}$ head-control system (Model HM-1P, 1994, Prentke Romich Company, Wooster, Ohio) to perform computer exercises. In this system, shown in **Figure 2**, the user wears a headset containing three ultrasonic sensors. A stationary transmitter on the computer sends an ultrasonic signal to these sensors. Information from the three sensors is then used by the transmitter to determine the location and orientation of the user's head in space. The computer cursor is moved across the screen as the user turns his or her head up, down, left, or right. The HeadMaster Plus was selected as a representative head-control system commercially available at the time of the study.

A calibration procedure indicated that the HeadMaster required a 75° of axial rotation to move the cursor horizontally across the entire screen and a 47° of flexion-extension to move the cursor vertically across the screen [11]. The calibration procedure also indicated that the HeadMaster had a gain of 13.7 mickeys/° of head rotation, where one mickey is one unit of mouse movement. For the

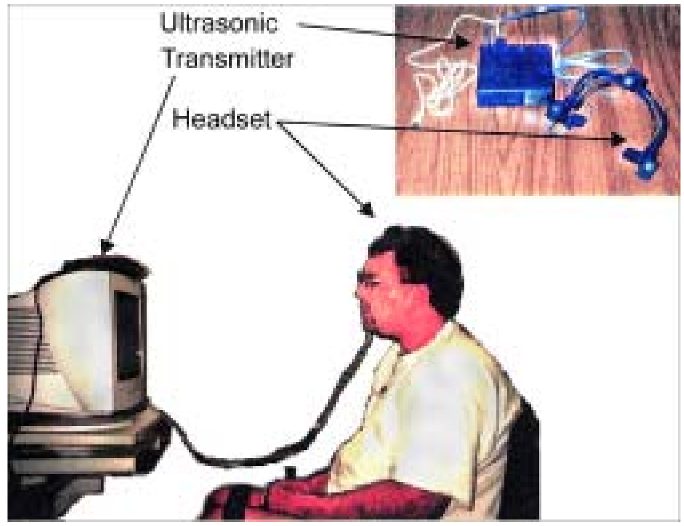


**Figure 2.**
HeadMaster Plus$^{TM}$ head-control system.

display settings used in this study (given in subsequent paragraphs), this corresponds to 12.75 pixels/° of head rotation, or 0.34 cm/°. The gain settings on both the HeadMaster and the Windows mouse control panel were constant throughout the study. Note that distance is often measured in pixels rather than centimeters in the results, because the head-control system has a more direct relationship between degrees of head rotation and pixels of cursor movement than between degrees of head rotation and centimeters of cursor movement.

The HeadMaster was connected to a personal computer (PC) (Dell Computer Corporation, Round Rock, Texas) running Windows 95 (Microsoft, Redmond, Washington). For this study, we used a 14 in. monitor (27.8 cm × 22.1 cm; Gateway 2000, Gateway, North Sioux City, South Dakota) with a 1,024 × 768 pixel display. Pixel size for this monitor was 0.027 cm. A 14 in. monitor was selected as a typical monitor size at the time of the study. Visual C++ (Microsoft, Redmond, Washington) was used to write computer software, which presented two computer exercises and collected data on subject performance.

The first computer exercise was a tracking task. We chose this task primarily to measure the distance across the screen for which the subjects could move the cursor. We measured this distance to determine whether a subject's physiological range of motion limitation resulted in a functional range of motion limitation for computer access, that is, a limitation in the accessible region of the screen. A tracking task was used in observing the subject's ability to access a continuous range of target positions across the screen, rather than discrete target positions as in the icon selection task described shortly. This task was not used to measure the dynamics of cursor movement (i.e., the specific path taken by the cursor), since this would be influenced by the unusually slow speed of the target (60 pixels/s, or 1.6 cm/s) and the imposition of a specific straight-line path (an unusual situation in functional computer use).

In the tracking task, a circular symbol would first appear at the center of the screen. The user would attempt to move the cursor within this circle. Once the cursor was selected by dwelling within the circular target, the target would begin moving in one of eight directions. At this time, the computer also began recording cursor position. The user was instructed to keep the cursor within the target circle, or as close as possible. Once the target reached the end of its path, it would disappear and a new target would appear in the center of the screen. Each target moved from the center of the screen to one edge of the screen. The distance traveled by the center of the target was 475 pixels (12.7 cm) for horizontal movements, 320 pixels (8.3 cm) for vertical movements, and 452 pixels (11.7 cm) for diagonal movements. The target circle had a radius of 0.75 cm (30 pixels). Each repetition of the task included eight targets, one for each possible movement direction. The movement paths were presented in the same order for each trial, and this order was selected initially with the use of a random number table.

The second computer exercise was an icon selection task. We chose this task to measure the subject's speed and accuracy for selecting targets on the screen. At the beginning of an icon selection trial, a home circle would appear at the center of the screen. The subject was instructed to hold the cursor in this location. Once the cursor remained in the home circle for 500 ms, a target symbol would appear elsewhere on the screen. At this time, the computer also began recording cursor position. The subject would move the cursor to the target and attempt to hold the cursor within the target circle for 500 ms. If the subject was successful, the target disappeared. If the subject was unsuccessful in selecting the icon, the icon disappeared in 10 s. In either case, the computer recorded whether the target was selected successfully, the time elapsed from target appearance to target disappearance, and the path taken by the cursor. The subject then returned the cursor to the home circle at the center of the screen. Once the cursor remained in the home circle for 500 ms, a new target appeared elsewhere on the screen. Subjects selected the icons using the 500 ms "dwell time" so that the time to actually select an icon was constant, without consideration of the time that would be required to press a switch.

Icons appeared at one of three distances (2.7 cm, 5.3 cm, 8.0 cm, corresponding to 103 pixels, 206 pixels, 308 pixels) and in any of eight directions from the center of the screen, for a total of 24 possible required movements. Each repetition of the exercise included all 24 targets, presented in a random order. The targets and home circle all had a radius of 0.75 cm (30 pixels).

We measured subjects' active neck range of motion using a magnetic tracking/virtual reality (VR)-based system (**Figure 3**). As described shortly, this range of motion assessment was performed separately from the computer tasks described previously to avoid interference between the tracking system and the head-control system. Magnetic sensors (Flock of Birds$^{TM}$, Ascension Technologies, Burlington, Vermont) attached to the head and torso enabled measurement of the translational and rotational movements of the head with respect to the torso. Visual feedback regarding the rotational movements was provided to the subject using VR glasses (Virtual i-O$^{TM}$ Personal Viewing Glasses, Virtual i-O, Seattle, Washington). A visual interface developed with Visual Basic 5.0 (Microsoft, Redmond, Washington) and viewed through the VR glasses simulated a virtual environment in which

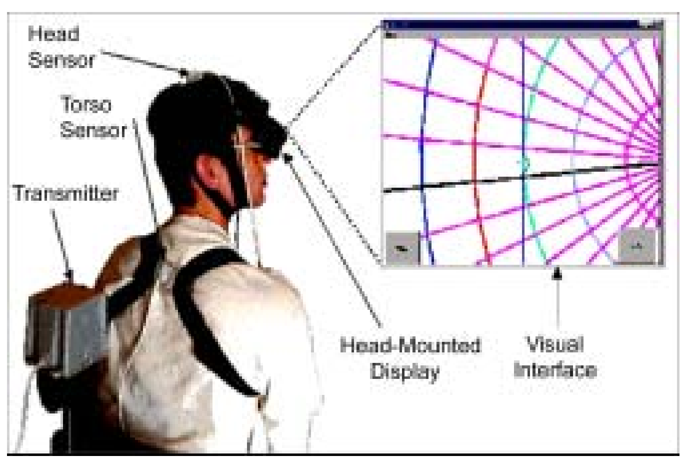


**Figure 3.**
Magnetic tracking/virtual reality (VR)-based system consists of a magnetic tracking system, head-mounted display (VR glasses), and programmable visual interface, operating under control of a personal computer.

the subject is seated within a large wire-mesh sphere. Crosshairs in the foreground of the display moved against the wire-mesh background according to the movements of the head relative to the torso. The subject then performed specific head rotation movements. The movement of the crosshairs along the background reflected these movements. This system has been shown to help subjects perform standardized movement patterns, therefore, assisting in a standardized measure of active neck range of motion [12]. We defined neck rotations by applying the conventions of Chao and Grood and Suntay to the head-torso system [13,14].

### Subjects

Fifteen subjects without disabilities (mean age 23.8 years, standard deviation (SD) 6.2 years) participated in this study. Six subjects were male and nine were female. Ten subjects with physical disabilities (mean age 46.5 years, SD 19.4 years) participated in the study. Six of these subjects had MS, three had sustained cervical SCIs, and one had experienced spinal stenosis. Five of these subjects were male and five were female. Subjects were selected based on self-reported neck movement limitation.

Three subjects without disabilities had limited prior experience with head controls (two in assistive technology equipment demonstrations, one in a VR game). One subject with disability had previously used a head-operated power wheelchair. Otherwise subjects were novice head-control users. Subjects without disabilities had between 5 and 16 years experience as computer users (mean 11.2 years); subjects with disabilities had between 0 and 30 years experience as computer users (mean 6.4 years).

### Protocol

Each subject attended two sessions. During the first session, the subject received a neck range of motion evaluation using the magnetic tracking/VR-based system described previously. The evaluation measured neck range of motion for flexion-extension, axial rotation, and lateral bending. Subjects performed three repetitions of each movement pattern. For each repetition, the subject was asked to move his or her head as far as possible without discomfort in one direction, hold this posture for 3 s, then move as far as possible in the other direction for 3 s.

The second session took place between 3 and 14 days after the initial session. During the second session, each subject used the HeadMaster head-control system to perform the computer exercises described previously. The subject was seated with his or her face 60 cm from the computer monitor. The investigators encouraged a constant viewing distance to avoid a confounding effect of viewing distance as described by Schaab et al. [6], but most subjects did shift position during the course of the trials.

The subject first had the opportunity to practice using the head controls for as long as the subject wished, up to 15 min. Once the subject was comfortable with the interface, she or he performed the exercises. The subject performed four repetitions of the tracking task, followed by 16 repetitions of the icon selection task. Three subjects with disabilities completed fewer than 16 icon selection repetitions because of fatigue and time constraints. These subjects completed 7, 10, and 13 icon selection sets. Two subjects without disabilities and two subjects with disabilities tended toward longer capture times for their final two sets, which could indicate fatigue. However, these increases in capture time were not significant. Rest periods were provided after the first and fourth tracking sessions, after the first icon selection session, and subsequently after every third icon selection session.

During data analysis, one-way analysis of variance (ANOVA) was conducted across icon selection trials for each subject so as to examine this data for learning effects. If the results showed significant differences in icon selection time based on trial ($p < 0.1$), the differences were assumed to be caused by learning effects. The earliest set was therefore removed from consideration. This procedure was repeated until AVOVA showed no significant differences (at the $p = 0.1$ level) between sets. The remaining data were used for further analysis.

## RESULTS

### Range of Motion

The results of the neck range of motion evaluations are shown in **Figure 4** and **Table 1**. Ranges of motion for subjects without disabilities are within the normal range based on previous literature [15]. Subjects with disabilities tended to have lower ranges of motion for all three-movement patterns (**Table 1**). The results also indicate a higher variability in the ranges of motion among people with disabilities, compared to the subjects without disabilities.

Journal of Rehabilitation Research and Development Vol. 40, No. 3, 2003

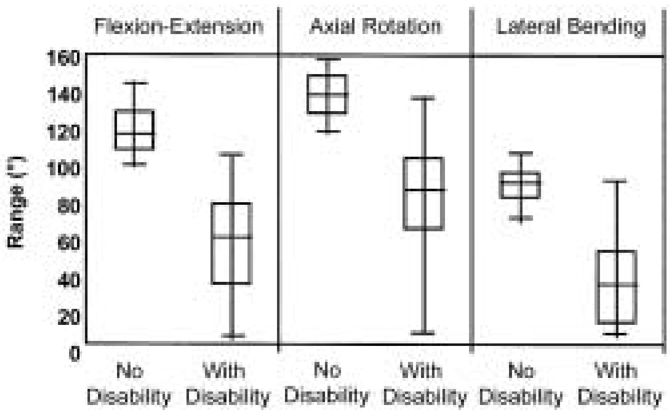


**Figure 4.**
Neck range of motion. For each boxplot, top and bottom of vertical line mark highest and lowest ranges of motion, while top and bottom of box mark 75th and 25th percentiles. Horizontal line within box marks mean range of motion.

## Computer Exercises

Results of the computer exercises are summarized in **Table 2** and **Figure 5**. For the icon selection task, two performance measures (accuracy and selection time) are shown. Accuracy refers to the percentage of target icons presented in the icon selection task that were successfully selected. Selection time is defined here as the time from a target icon's appearance until the cursor moved onto the target, immediately before selection. It does not include the 500 ms "dwell time" during which the cursor pauses on the icon to select it. For the tracking task, one performance measure is shown (distance across screen). "Distance Across Screen" refers to the distance across the screen traveled by the cursor, as a percentage of the distance traveled by the target. This measurement only accounts for the maximum excursion of the cursor in the direction of target movement, without regard for how precisely it followed the target path.

The results indicate that people with disabilities tended to have lower accuracy and longer selection times for the icon selection task. Further, their cursor movements were shorter for the tracking task. These differences appear to be significant for accuracy and icon selection time, but not for distance traveled in the tracking task. Significance scores for Mann-Whitney tests are given in the third row of **Table 2**.

The results also show a higher variability among individuals with disabilities. Some individuals with disabilities had performance measures comparable to subjects without disabilities, while others had considerably reduced accuracy and speed. The high variability seen in the performance of people with disabilities may be related to the variability already seen for neck range of motion. Therefore, we used regression analysis to analyze the correlation between neck range of motion and these performance measures. A linear scale was used for the performance measures and a logarithmic scale for the range of motion data. The $R^2$ values resulting from regression analysis (**Table 2**, rows 4 through 6) indicate a relationship exists between decreased range of motion and decreased accuracy, increased icon selection time, and decreased distance traveled. These relationships are true for both flexion-extension range of motion and axial rotation range of motion. Performance measures do not correlate as strongly with neck lateral bending range of motion. This regression analysis assumes a normal distribution of the data; the applicability of this assumption is reduced by the small subject population and the high variability of the data for subjects with disabilities.

Although a relationship was found between reduced range of motion and reduced accuracy and speed with the head controls, 6 of 10 subjects with disabilities had at least the minimum range of motion required to use the head controls (75° of axial rotation and 47° of flexion-extension). These subjects tended to have higher accuracy and speed than individuals with less range of motion, but they still had lower accuracy and higher icon selection times than subjects without disabilities ($p < 0.05$).

**Table 1.**
Neck range of motion.

| Statistics | Flexion-Extension | Axial Rotation | Lateral Bending |
|---|---|---|---|
| Mean ± SD (Without Disability) | 118.4° ± 15.0° | 137.9° ± 13.6° | 87.4° ± 10.6° |
| Mean ± SD (with Disability) | 59.3° ± 32.23° | 85.6° ± 39.7° | 36.9° ± 30.4° |
| *p* Value for Effect of Disability | 0.0002 | 0.0025 | 0.0005 |

SD = standard deviation

**Table 2.**
Results of computer exercises.

| Performance Measures | Accuracy | Selection Time (s) | Distance Across Screen |
|---|---|---|---|
| Mean ± SD (without disability) | 99.93% ± 0.14% | 1.18 ± 0.12 | 99.77% ± 3.14% |
| Mean ± SD (with disability) | 83.23% ± 26.45% | 2.74 ± 1.25 | 90.46% ± 19.72% |
| Significance* | 0.0017 | 0.0008 | 0.1018 |
| $R^2$ for Axial Rotation ROM | 86.0% | 68.6% | 86.7% |
| $R^2$ for Flexion-Extension ROM | 93.5% | 79.5% | 85.3% |
| $R^2$ for Lateral Bending ROM | 48.0% | 45.0% | 48.7% |

*Based on Mann-Whitney tests.
SD = standard deviation
ROM = read only memory

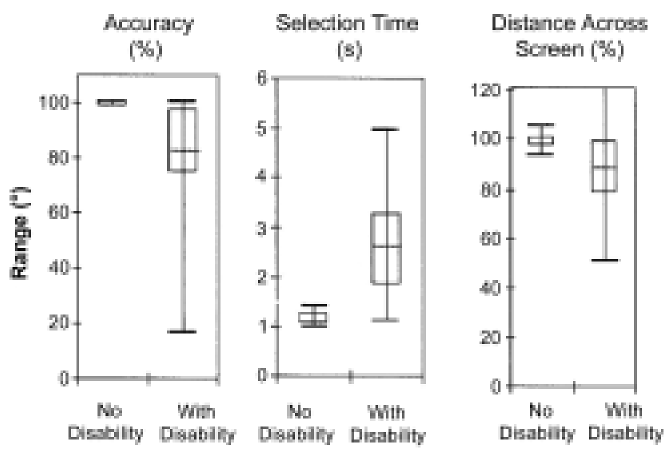


**Figure 5.**
Results of computer exercises. For each boxplot, top and bottom of vertical line mark highest and lowest ranges of motion, while top and bottom of box mark 75th and 25th percentiles. Horizontal line within box marks mean range of motion.

## Fitts' Law

Previous research has indicated that Fitts' Law applies for head as well as hand movements [4–6]. Therefore, we analyzed the data for this study using Fitts' Law. True Fitts' Law analysis was not possible, since the target size was a constant and not variable in this study. However, the effect of movement distance on movement time was analyzed. Using regression analysis on data for half the subjects without disabilities resulted in a model with Fitts' Law slope equal to 0.30 s/bit. Predictions from this model were compared to actual movement times for the remaining subjects without disability, leading to a 27 percent mean error. Model predictions were also compared to movement time data, resulting in a 49 percent mean error. Fitts' Law models that were developed using data from subjects with disabilities led to a 36 percent mean error. This analysis is described in more detail elsewhere [11].

## Movement Patterns

For subjects without disabilities, cursor movements appeared to fit the three-phase model observed for mouse-controlled cursor movements, with reaction, ballistic, and homing phases (**Figures 1** and **6**). The three-phase model also tends to apply for subjects with disabilities, but these subjects spent more time in each phase (**Figure 7** and **Table 3**). Subjects with disabilities were also more likely to have more than one peak in the movement velocity profile ($p < 0.01$), as shown in **Table 3** and illustrated in **Figure 8**.

For the velocity profiles in **Figures 6** to **8**, instantaneous velocity was defined as

$$V_i = \frac{\sqrt{(X_i - X_{i-1})^2 + (Y_i - Y_{i-1})^2}}{T} ,$$

where $V_i$ = instantaneous velocity at sample $i$, $X_i$ = horizontal cursor position at sample $i$, $Y_i$ = vertical cursor position at sample $i$, and $T$ = sampling period. The reaction time was defined as the time between a target icon's appearance and the time when the instantaneous velocity exceeded one-half the maximum instantaneous velocity for the movement or 138.1 pixels/s (3.68 cm/s), whichever was less. The homing time was defined as the time from the end of the first velocity peak until the target icon was selected. The end of the first velocity peak was defined as the time when the instantaneous velocity became less than one-half the maximum velocity or 147.1 pixels/s (3.92 cm/s), whichever was less. The velocity thresholds 138.1 pixels/s for reaction time and 147.1 pixels/s for homing time were

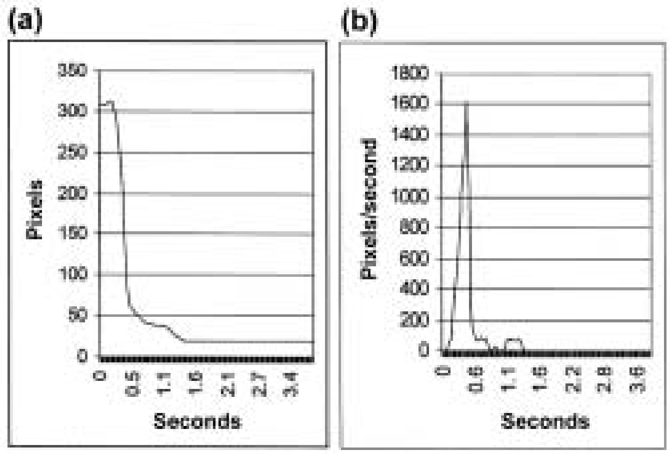


**Figure 6.**
**(a)** Distance from target and **(b)** velocity profile for one path for one subject without disability.

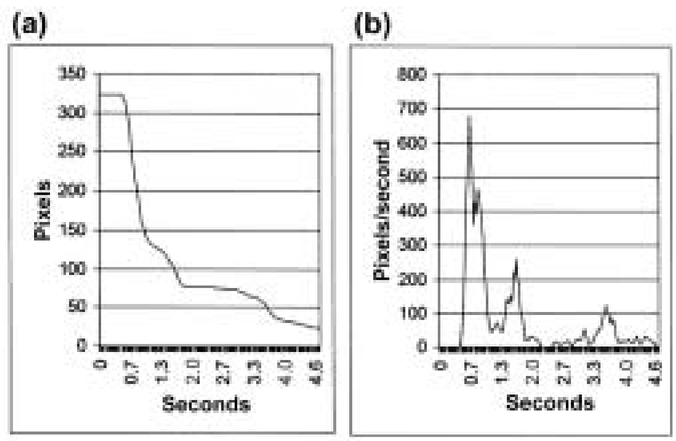


**Figure 7.**
**(a)** Distance from target and **(b)** velocity profiles for one path for one subject with disability.

derived from the instantaneous velocities during these phases across subjects. Each threshold represents velocity mean ± SD during that phase.

Bayes' Theorem was used to model the differences between subjects with and without disabilities. The model was derived with the time spent in the homing phase and the number of velocity peaks for eight subjects without disabilities and five subjects with disabilities. A multivariate normal distribution was assumed for both the number of velocity peaks and the homing time. According to this analysis, cursor paths for individuals without disabilities typically had fewer than four velocity peaks and less than 1.7 s spent in the homing phase. Cursor paths with four or more velocity peaks or more than 1.7 s in the homing phase were typically associated with individuals having disabilities. This model was tested for the remaining seven subjects without disabilities and five subjects with disabilities. The proportion of cursor paths classified as indicating disability was 4.9 percent for subjects without disabilities and 39.0 percent for subjects with disabilities.

A further analysis compared the decision boundary given previously, using homing time and number of velocity peaks, to a definition of nonoptimal movements using overall selection time and accuracy. A movement was classified as nonoptimal if the target was not selected or the selection time was more than 2 SDs above the mean selection time for subjects without disabilities (i.e., movement time greater than 2.10 s). The Bayesian model predicted actual icon acquisition and speed problems based on this definition of nonoptimal movements with an accuracy of 94.0 percent and $\kappa = 0.81$, indicating an excellent level of agreement [16]. The Bayesian model misclassified nonoptimal movements as not indicating difficulty with a miss rate of 17.7 percent and misclassified normal movements as showing difficulty with a false positive rate of 3.0 percent.

## Movement Amplitude and Peak Velocity

We also analyzed movement velocity relative to movement amplitude. The peak velocities for each of the three movement amplitudes used in the icon selection task are given in **Table 4**. Paired t-tests across subjects indicate

**Table 3.**
Velocity characteristics. All differences shown between subjects with and without disabilities are significant ($p < 0.01$) according to Mann-Whitney tests.

| Characteristics | Subjects Without Disabilities | Subjects with Disabilities |
|---|---|---|
| Reaction Time | 0.39 ± 0.04 | 0.60 ± 0.15 |
| Time in Ballistic Phase | 0.32 ± 0.04 | 0.74 ± 0.41 |
| Time in Homing Phase | 0.86 ± 0.08 | 1.75 ± 0.78 |
| Number of Velocity Peaks | 1.75 ± 0.23 | 2.72 ± 0.86 |

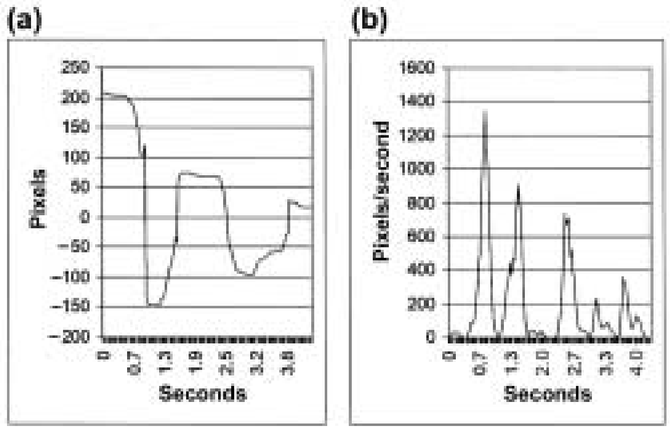


**Figure 8.**
**(a)** Distance from target and **(b)** velocity profiles for one path for one subject with disability.

**Table 4.**
Peak cursor velocity during an icon selection movement for each of 3 movement distances, for all subjects. Values are given as mean ± SD.

| Movement Amplitude (cm) | Peak Velocity (pixels/s) |
|---|---|
| 2.67 | 522.9 ± 279.2 |
| 5.3 | 874.7 ± 564.4 |
| 8.0 | 1151.8 ± 822.9 |

that peak velocities for 5.33 cm movements are higher than peak velocities for 2.67 cm movements ($p < 0.01$), and peak velocities for 8.0 cm movements are higher than peak velocities for 5.33 cm movements ($p < 0.01$). We used data from eight subjects without disabilities and five subjects with disabilities to define decision boundaries among these three movement amplitudes. We derived the decision boundary using Bayes' Theorem and assumed a normal distribution for peak velocity. Three outliers (with peak velocity greater than 10,000 pixels/s) were omitted, leaving 1,829 samples. According to this analysis, a peak velocity less than 566.8 pixels/s (15.1 cm/s) corresponds to a short movement amplitude, a peak velocity between 566.8 pixels/s and 1131.5 pixels/s (30.2 cm/s) corresponds to a medium movement amplitude, and a peak velocity greater than 1131.5 pixels/s corresponds to a large movement amplitude.

We tested this model for the remaining seven subjects without disabilities and five subjects with disabilities using peak movement velocity to predict total movement amplitude. The model correctly predicted movement amplitude for 52.9 percent of cursor paths for subjects without disabilities ($\kappa$ = 0.29), and correctly predicted movement amplitude for 46.9 percent of cursor paths for subjects with disabilities ($\kappa$ = 0.20). With $\kappa$ values under 0.40, these results indicate a fairly poor predictive power [16]. To account for the variability between subjects, individual models were defined for each subject's relationship between peak movement velocity and movement amplitude. We derived these models using half the data for the subject and tested using the remaining data for that subject. Percent error for these models ranged from 34.7 percent to 64.3 percent (mean 48.1 percent) with values between 0.04 and 0.46 (mean 0.27), so the accuracy of the models was still poor to moderate.

## DISCUSSION

Subjects with disabilities demonstrated reduced range of motion scores when compared to subjects without disabilities. The data show a relationship between these neck movement limitations and reduced performance with computer head controls. Reduced neck range of motion was strongly correlated with reduced accuracy and speed on icon selection tasks and with a reduced distance traveled across the screen for tracking tasks (**Table 2**). The correlation was weaker for lateral bending range of motion, but most likely, axial rotation and flexion-extension are used more frequently than lateral bending in the use of head controls. The reduction in accuracy and the increase in icon selection time were most significant for subjects with range of motion less than 75° for axial rotation or less than 47° for flexion-extension. However, even subjects who appeared to have sufficient neck range of motion to perform the trials had reduced accuracy and longer icon selection times.

The prevalence of reduced neck range of motion in this study does not characterize the general population of people with MS or SCI. The primary goal of this study was to investigate the effects of range of motion limitations on computer head-control use, rather than the effect of a particular disability on head-control use or the prevalence of range of motion limitations within particular disability populations. Therefore, the study was directed toward recruiting people who have neck movement limitations. While these results do not indicate the prevalence of neck movement limitations, they do indicate the degree of limitation that people with these disabilities may experience. These results support previous literature [1,2].

One limitation of this study is the variability within the subject population. Subjects without disabilities tended to be younger and to have more computer experience than individuals with disabilities. Either of these factors could have influenced performance. In particular, age has been shown to affect range of motion [17]. Among subjects with disabilities, three different diagnoses were represented (MS, SCI, and spinal stenosis) in addition to a large variance in age and computer experience. Although our study was directed toward the effect of range of motion limitations regardless of the source of the limitation (e.g., particular disability or the aging process), the variance within subject populations for factors other than range of motion (e.g., spasticity, endurance, computer experience) could have had a confounding effect on the results. Also, fewer subjects were recruited in the disability group because of the difficulty of recruiting subjects who met the inclusion criteria and who were able to travel to the experimental site. The small sample size also limits the applicability of regression analysis and Bayesian models, which assume a normal distribution of data. In the future, investigations should include data collected from a larger pool of subjects so as to reduce the effect of such confounding factors and to analyze the effects of different neck movement limitations (e.g., fine motor control limitation as well as range of motion limitation).

The computer access difficulties that subjects with disabilities experienced were reflected in their cursor movement paths and velocity profiles. Subjects with disabilities had longer reaction times and spent more time in both the ballistic and homing phases of movement compared to subjects without disabilities. Also, subjects with disabilities had more peaks in their velocity profiles, indicating episodes of rapid acceleration. These velocity peaks are associated with one of two events: (1) stopping short of a target and then accelerating toward the target a second time or (2) moving past the target and then changing directions.

Analysis of these movement patterns could provide information about the difficulties that individuals using head controls face. Persons who frequently stop short of targets or overshoot targets may have difficulty controlling the cursor. Extra peaks in the velocity profile could indicate either of these problems. Someone who spends extra time in the homing phase of movement but moves smoothly without extra acceleration events may adequately control the cursor but move more slowly than others.

People with these different problems may benefit from adjustments to their head-control systems that specifically address their problems. People with smooth but slow movements may simply need increased cursor speed or acceleration. People who are able to move quickly but who have difficulties with fine motor control may benefit from a reduced gain or filtering of the head-control signal. These options are available to varying degrees in existing head-control systems and can be implemented by people with disabilities. Consumers may benefit from greater support in understanding and applying these features in ways that are appropriate to their needs. More recent research by the authors indicates the importance of selecting an appropriate head-control gain for user performance [18].

Greater problems will exist for people who have combined difficulties. Someone with range of motion limitations may need an increased cursor gain to reach all areas of the screen. However, if the individual also has reduced fine motor control, an increased gain could render the cursor uncontrollable. Even with advanced features available in some current head-control systems, some people find them difficult or impossible to use. Devices with improved filtering algorithms may help solve this problem. For others, appropriate head-control parameters may be available but difficult to find with a trial-and-error process. Therefore, a more desirable situation may be for the head-control system to measure the person’s performance and to predict appropriate parameter settings. This will require an accurate model relating the user’s performance to appropriate parameter settings to improve performance. If appropriate settings are not available by current means and the user is unable to move the cursor to his or her desired target location, a more desirable situation may be for the head-control system to predict the user’s desired target locations based on his or her attempted movements and to automatically move the cursor to that position. This will also require an accurate model of the user’s goals.

For the data in this study, Fitts’ Law did not appear to provide a good model for subjects with disabilities. Additional models were derived to predict a user’s goals and difficulties based on features of the movement path. The first model used Bayes’ Theorem to classify whether a person had a disability based on the person’s time spent in the homing phase and the number of peaks in the velocity profile. The proportion of cursor paths classified as indicating disability was 4.9 percent for subjects without disabilities and 39.0 percent for subjects with disabilities.

A goal for such a model was to predict whether a user is having difficulty with use of the computer, rather than simply whether the user has a disability. For this preliminary model, the assumption was (based on the observations from this research) that users with disabilities were also those who were having more difficulty. A further analysis compared this decision boundary to a definition of nonoptimal movements using overall selection time and accuracy. The model predicted actual icon acquisition and speed problems with an accuracy of 94.0% and $\kappa = 0.81$. A model predicting difficulty based on movement patterns is more useful than simply measuring accuracy and movement time. This is because accuracy and movement time measures require knowledge of the desired target location and so would not be as useful in automatic recognition of movement difficulty. Accuracy and movement time also do not provide as much detail about the difficulty that a person might be experiencing.

An additional model attempted to predict movement amplitude based on peak instantaneous velocity during a movement pattern. The results of this study indicate that larger movements use higher peak velocities. The variability in peak velocity for each movement amplitude, both between and within subjects, prevents the use of peak velocity as a predictor of the desired movement amplitude ($\kappa < 0.5$). The peak instantaneous velocity can still provide some information about a user's goals during a computer access task. Together with other movement features identified as desirable, adjustments to a head-control interface may be useful. Further development of these models could lead to head-control systems that can better address the needs of users with advanced disabilities.

## CONCLUSION

A study was conducted to analyze head movements in the context of two computer exercises: an icon selection task and a tracking task. The results of this study indicate that reduced neck range of motion is related to increased difficulty of computer head-control use. This finding is shown by a relationship between reduced range of motion and both reduced accuracy and longer selection times for an icon selection task, and reduced distance traveled across the screen for a tracking task. Subjects with disabilities were also found to have longer reaction times, spend more time making fine adjustments to cursor position (indicated by increased time in the homing phase), and spend more time accelerating and decelerating during a single movement (indicated by increased time in the ballistic phase and an increased number of velocity peaks).

A number of head-control systems are now on the market (**Table 5**). These systems have different sensitivity options, and required ranges of motion are not known for each system. Research conducted with both the HeadMaster Plus and the Tracker 2000™ (Madentec Inc., Edmonton, Alberta, Canada) showed no significant difference between devices in performance by people with disabilities [19]. Some of these devices include filtering and gain adjustment options that allow greater adjustability and improve usability for some people with neck movement impairments. The results of this study could help device manufacturers further refine these options and help users select appropriate adjustment settings.

**Table 5.**
Commercially available head-control devices.

| Device | Manufacturer | Description |
|---|---|---|
| HeadMaster Plus | Prentke Romich Company Wooster, Ohio | Ultrasound head control |
| Tracker 2000 | Madentec Inc. Edmonton, Alberta Canada | Infrared head control |
| HeadMouse | Origin Instruments Corporation Grand Prairie, Texas | Infrared head control |
| TrackIR | NaturalPoint Corvallis, Oregon | Infrared head control |
| Point! | Alfalab Research, Inc. Beaumont, Alberta Canada | Infrared head control |
| Tracer | Boost Technology San Francisco, California | Gyroscope head control |
| Jouse | Prentke Romich Company Wooster, Ohio | Head-operated joystick |
| QuadJoy | SEMCO Cleveland, Wisconsin | Head-operated joystick |

Some people are still unable to use current head-control systems or have difficulty selecting appropriate settings. These individuals may benefit from a system that can help them adjust to their needs or can automatically adjust to the needs of a particular user. Analysis of cursor movement features may help head-control users and clinicians adjust head controls. A model was derived that attempts to predict whether a user is having difficulty based on features of the movement path (time spent in the homing phase and the number of peaks in the velocity profile). Ultimately, models based on cursor movement features may allow the computer to automatically adjust parameters such as the head-control sensitivity to aid a particular user. Features such as the time spent in the homing phase or the number of velocity peaks could be measured by the computer without the user's target location known beforehand. This function could allow the computer to recognize when a person is having difficulty using his or her head controls. Further analysis of the features might allow the computer to choose appropriate adjustments.

Based on the results of this study, software is being developed to compensate for neck range of motion limitations. This software will incorporate adaptive techniques to allow head controls to automatically adjust to the needs and abilities of the user. This software will be evaluated in a series of user trials, which will determine whether it is effective in making head controls more usable for people with neck movement limitations.

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