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Evaluation of Head Orientation and Neck Muscle EMG Signals as Command Inputs to a Human-Computer Interface for Individuals with High Tetraplegia

Matthew R. Williams [Student Member, IEEE] and
Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH 44106 USA (mrw8@case.edu)

Robert F. Kirsch [Member, IEEE]
Department of Biomedical Engineering, Case Western Reserve University, Cleveland, OH 44106 USA and also with the Cleveland Louis Stokes Department of Veterans Affairs Medical Center, Cleveland, OH 44106 USA (rfk3@case.edu)

Abstract

We investigated the performance of three user interfaces for restoration of cursor control in individuals with tetraplegia: head orientation, EMG from face and neck muscles, and a standard computer mouse (for comparison). Subjects engaged in a 2D, center-out, Fitts' Law style task and performance was evaluated using several measures. Overall, head orientation commanded motion resembled mouse commanded cursor motion (smooth, accurate movements to all targets), although with somewhat lower performance. EMG commanded movements exhibited a higher average speed, but other performance measures were lower, particularly for diagonal targets. Compared to head orientation, EMG as a cursor command source was less accurate, was more affected by target direction and was more prone to overshoot the target. In particular, EMG commands for diagonal targets were more sequential, moving first in one direction and then the other rather than moving simultaneous in the two directions. While the relative performance of each user interface differs, each has specific advantages depending on the application.

Index Terms

User interfaces; spinal cord injury; electromyography; velocity control

I. INTRODUCTION

A high level cervical spinal cord injury can result in significant loss of function and impact both the injured individual as well as their family and care givers. Currently, there are about 250,000 individuals with spinal cord injury (SCI) in the U.S., with 11,000 new occurrences each year [1]. Of this population, approximately 18% are classified as having high-tetraplegia (spinal cord injury at cervical levels 1 to 4) with significant impairment from the shoulders downward [1]. To restore function to these individuals, multiple user interface methods are available to enable command and control of external devices. The aim of this paper is to investigate the means by which an individual with a high cervical SCI can control cursor motion to enable computer operation.

In an increasingly computerized world, the potential benefits of restoring computer operation to individuals with a spinal cord injury are immense. As of 2003, approximately 55.5% of all jobs involved the use of a computer [2], yet only 24.2% of individuals with tetraplegia are employed by year 10 post injury [1]. Beyond employment benefits, computer use to access the internet could provide opportunities for a host of activities, ranging from communication and commerce, to education, leisure and entertainment [3]. Internet access by individuals with SCI is reported to produce higher quality of life measures and was found to be used at least weekly by 81% of participants [4].

While a number of computer interfaces either specifically designed for (or at least useable by) the SCI community have been developed over the years, only limited quantitative analysis of their cursor control performance has been performed. These interfaces have been based on mouthsticks [5], chin operated devices [6], voice commands [7], tongue manipulated devices [5], [8], and head position [9], [10]. Several studies have explored the use of electromyography (EMG), either to determine head orientation using neck EMG signals [11], [12] or using other voluntary muscles to directly control cursor position [13], [14], [15]. Many of these earlier studies had little in the way of quantitative assessment, often were not consistent with other human-computer interface studies, were not always applicable to individuals with high tetraplegia, or were more focused on text entry performance than cursor control.

Fitts first quantified human motor performance in 1954 in his seminal paper describing the limits of human speed and accuracy in a one degree of freedom tapping task [16]. This work, based on Shannon's original work in communication theory [17], demonstrated that any motor task conveys a finite amount of information (user intent) that is limited by the capability of the system to perform a task both rapidly and as accurately as possible. This speed/accuracy trade off became known later as Fitts' Law, and has been shown to hold for a number of human motor tasks, including head motion [18], leg motion [19], and assembly tasks [20].

In 1978, Card demonstrated that human commanded cursor motion follows a Fitts' Law model [21], initiating the field of human computer interface evaluation. Since that time, a number of now common computer interfaces have been thoroughly studied including joysticks [21], mice [21], [22], and trackballs [22], and an international standard has been developed for their evaluation (ISO9241-9) [23].

Despite the quantification of performance of several conventional computer interfaces, few of those applicable to users with a spinal cord injury have been as thoroughly investigated. The work of Jagacinski [24], Radwin [25], and LoPresti [26], [27] assessed the performance of head commanded cursor position control using a two dimensional Fitts' Law task similar to that employed in this study. These studies found that subjects were able to effectively control a computer cursor, though not as accurately as a conventional joystick, and that Fitts' Law does indeed hold for head commanded cursor motion. Aside from these, little other quantitative analysis has been performed on human-computer interfaces viable to the SCI community.

This study quantitatively compares the performance of two command interfaces applicable to individuals with high tetraplegia for control of a computer mouse: head orientation and the EMG of the muscles of the neck and face. Evaluation of conventional mouse performance was also performed to serve as a baseline for comparison and to assist in comparing the performance of the two novel command sources to previously published literature.

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II. METHODS

Subjects participated in a Fitts' Law style experiment, moving a cursor to randomly presented circular targets using one of the three command inputs (head orientation, EMG, or computer mouse). Performance was assessed using six performance measures. A custom cursor control and evaluation program was written using Matlab (The MathWorks, Inc.) with targets displayed within a 1000×1000 pixel field (fig. 1a). The following sections will detail this approach.

A. Task

A center-out task similar to those used in previous studies [24], [25], [27] was employed, with targets radially distributed in eight directions, at five distances (25, 50, 100, 200, and 400 pixels) from the center and five target widths (13, 25, 50, 100, and 200 pixels) for a total of 120 targets. Targets were presented in random order in terms of size and location on a circle about the center of the field. Targets were located on eight evenly spaced, 45° radial lines, with target number 1 located at the 12 o'clock position. Fig. 1b illustrates the target locations and sizes used in the study.

A two second target dwell time within the target area was used to indicate successful target acquisition. Upon target acquisition, the cursor was automatically re-centered and the target was removed from the screen. This task was selected as it provided a high amount of information about the command source under consideration, accounted for directionality, and has been found to be well tolerated by subjects in terms of attention requirements and experiment duration. Each command source was tested over four blocks of 120 targets each, with a five minute break between blocks.

Circular targets were used to eliminate the effects of approach angle on target width [23]. The Shannon form of the Index of Difficulty (Equation 1) was used to compare different combinations of target distance and width, consistent with current literature and human-computer interface evaluation standards [23].

$$ID=\log_2\left(\frac{D}{W}+1\right) \quad (1)$$

Table 1 details the distances, widths, and corresponding Indices of Difficulty (ID) used in the experiment. Five different distances (D) and target sizes (W) were used for a total of 15 distance-target size combinations that produced Indices of Difficulty ranging from 1.58 to 5 bits.

B. Command Sources

Three different command sources were evaluated: head orientation, EMG of the muscles of the neck and face, and a standard computer mouse. These first two command sources were selected for evaluation as they remain under voluntary control following a high cervical spinal cord injury and do not significantly interfere with activities of daily living such as eating, grooming and communicating [28]. Mouse performance was evaluated to compare to the previous two mentioned command sources and to serve as a comparison to similar studies [22], [23].

Head orientation was measured using a three degree of freedom head orientation sensor (MicroStrain 3DM) attached to the subject's head using an elastic headband (Fig. 2a), similar to other studies [9], [26]. The sensor weighed approximately 75g and was small enough (89mm × 64mm × 25mm) to not encumber the subject. Data was sent to a PC via serial port (RS-232, 9600 bps, 8N1) as a seven byte signal that was decoded into three orientation angles. Head pitch controlled vertical motion, while yaw commanded horizontal motion. Head roll was not used in the study.

Surface EMG signals were collected from three muscles of the neck and one facial muscle (Fig. 2b). Signals were recorded from the left and right platysma (left and right motion commands), the left trapezius (for upwards motion commands), and the frontalis (downwards motion commands). The muscles selected were intended not to measure head orientation as in previous studies [11], [12], but were to serve as independent voluntary actions. Differential, bipolar surface EMG was recorded and amplified to between 10 and 20V peak-to-peak using CED 1902 amplifiers with an anti-aliasing low pass filter at 1000Hz and 60Hz notch filter. This amplified signal was passed into a controller PC running custom control and acquisition software programmed in xPC Target (The MathWorks, Inc.) running at 2kHz. The controller performed A/D conversion, rectification, and amplification by a factor of 1000. Additional signal processing consisted of a 1 Hz low pass filter for smoothing and a 5% dead-zone to remove baseline noise (Fig. 2c). The signal was then passed to the PC via the serial port (RS-232, 8-N-1, 115.2Kbaud) with a 10msec packet interval. The system operated in real-time, with all signal processing and transmission steps occurring during the 60msec loop-time of the main evaluation program such that no lag in cursor motion was noticeable by the subject.

C. Velocity Algorithm

A proportional velocity gated ramp algorithm converted user signal levels into cursor velocity commands. User signals were required to exceed a threshold for detection, and then were converted into a velocity cursor signal that was proportional to the square of the ratio of the amplitude above threshold and the overall range of the user signal, as indicated by equation 2. This “joystick-like” velocity control was employed as it has been found in previous studies to be preferred by subjects because it requires less absolute accuracy and was less fatiguing [29]. Preliminary testing indicated that the parabolic velocity profile provided fine, slow motion control at low command levels while also providing brisk, responsive motion control at higher command levels to allow rapid motion across the screen. The maximum velocity was set to 500 pixels per second (pps), as preliminary testing indicated that this was the most controllable for all tested command sources while not overly limiting the subjects’ performance or cursor speed. For head orientation, the maximum signal inputs were set to correspond to neck angles of 30°, such that subjects could still see the screen comfortably. For the EMG command source, the maximum user signal was calculated to be 70% of the maximum voluntary contraction EMG. (EMG_{mvc}), a level that was repeatable and sustainable for the subject without producing undue fatigue during the course of the experiment.

$$CursorVelocity = MaxVelocity^{*}\left(\frac{user\_signal}{user\_signal\_range}\right)^{2} \quad (2)$$

For head orientation, the threshold for detection was 10° off-center, which allowed for natural drift within a command “dead zone” [27] (as subjects are unable to hold their heads perfectly still [24]) but was small enough that a reasonably small head movement would initiate cursor movement. The threshold for EMG was set at 20% of maximum voluntary contraction (MVC) but also included compensation for baseline shifts due to motion artifacts and changes in electrode impedance. Specifically, the baseline was computed as the minimum level over a 10 second window and was reset every 10 seconds (Eq. 3). This floating threshold algorithm allowed greater use of the dynamic range of the EMG signal, as the threshold could closely follow the current minimum value without the need to set a threshold higher than the expected level of drift. This also reduced the number of false-positive commands.

$$Threshold=0.2^{*}EMG_{MVC}+EMG_{moving\_minimum} \quad (3)$$

D. Performance Metrics

Several measures of command source performance were used. These performance measures include traditional performance metrics used to assess user interfaces, but also include measures that give a more detailed picture of the individual components that affect overall command source performance. Additionally, they serve to describe performance aspects that are not obvious and often lost in summary performance measures [22].

Throughput (TP, also known historically as Information Transfer Rate, ITR) is a measure of the amount of information the subject can convey through a particular command source as it relates to the task, in this case, cursor control. The *Throughput* for each individual target trial was computed (Eq. 4) and averaged across all factors (trials, locations, and indices of difficulty). The overall *Throughput* for a particular command source was the grand mean of these averages across all target sizes. This method is similar to that proposed by Soukoreff [23]. While this approach does incorporate the individual effects of each target aspect (direction, size, and distance) and individual subject differences, it summarizes the overall performance of the command source with a single value. *Throughput* was computed using Equation 4, where ID is the index of difficulty as defined in Equation 1, and MT is the movement time required to acquire the target. The movement time only includes the time the cursor is moving to the target and does not include the initial pause for *Reaction Time*, or the 2 second target dwell time. In Equation 4, it can be seen that if the movement time was 0 seconds, the amount of information transferred would be infinite (as the cursor would acquire the target instantly), while if the movement time was infinite, the *Throughput* would be 0 as the command source would convey no information regarding intended cursor position.

$$TP=\frac{ID}{MT} \quad (4)$$

Path Efficiency (PE) is a measure of the straightness of the cursor path to the target. It is computed by dividing the straight-line distance by the actual distance traveled (Eq. 5). A perfectly straight trajectory, from the center starting point to the target, would result in a perfect Path Efficiency of 100%. This performance metric affects Throughput and indicates a subjects' ability to continuously control cursor position.

$$PE=100\%\frac{\text{straightline\_distance}}{\text{actual\_distance}} \quad (5)$$

Overshoot is the number of occurrences of the cursor being on target and then leaving the target before the end of the 2 second dwell time (across all targets), divided by the total number of targets (see Equation 6). *Overshoot* can occur either during the initial cursor motion to the target or during fine adjustments to acquire the target. Each time the cursor exits the target area, the number of overshoot occurrences for that target is incremented. While this metric affects both *Throughput* and *Path Efficiency*, it also is indicative of a subject's ability to accurately control cursor velocity. The higher the *Overshoot* score, the more occurrences of *Overshoot* were observed. A perfect *Overshoot* measure would be zero, indicating that all subjects were able to acquire all targets, stopping within the target boundaries every time.

$$Overshoot=\frac{number\_of\_times\_leaving\_target}{number\_of\_target} \quad (6)$$

Reaction Time (RT) is the time between the start of the trial and the initiation of cursor movement. This was quantified to evaluate planning difficulty.

Average Speed is the average non-zero speed of the cursor over the course of the trial. This affects the *Throughput*, and illustrates the subject's gross ability to control the cursor - a more unwieldy user interface requires subjects to move more slowly to maintain the same level of accuracy.

Direction Ratio. A *Direction Ratio* (DR) was calculated for each of the command sources and each of the performance measures described above. Each DR illustrates the effect of moving in diagonal directions (which require generation of two separate commands simultaneously) versus moving horizontally or vertically (which require only a single command) on the performance metrics. It is defined as the average performance when moving to diagonal targets divided by the average performance when moving to targets located on the horizontal or vertical axes. The greater the deviation from unity (identical single direction and diagonal performance) the greater the effect of target direction on command source performance.

E. Protocol

All subjects were recruited from the graduate student population of Case Western Reserve University and were healthy in regards to their ability to voluntarily control facial and neck muscles and head orientation. None of the subjects had a spinal cord injury. Proper informed consent was obtained and pertinent human subject protections observed, including approval by the Metro Health Medical Center Institutional Review Board. Seven subjects participated in the head orientation and mouse experiments. Eight subjects (the original seven from the head orientation and mouse experiments, plus an additional subject) participated in the EMG portion of the study, but two subjects were not included in the analyses because they were unable to independently control the left and right platysma muscles. Thus, data from six subjects were used to summarize EMG-based performance and the performance of seven subjects was used to assess the head orientation and mouse command sources.

Subject performance with each command source was evaluated on different days, with each experimental session focusing on a single command source. The experiments consisted of a 5 minute practice with the command source being tested, followed by four blocks of 120 trials. The first block was performed for practice only, although the data were recorded. Blocks 2, 3, and 4 were used to calculate individual subject performance. Preliminary testing indicated that while some subjects exhibited an increase in performance between blocks 1 and 2, no statistical performance difference ($p=0.62$) was observed across the last three blocks (2, 3, and 4). The total experiment time (including set-up, practice, four experimental blocks and rest periods), for each command source varied from 1 hour (mouse experiments) to 2 hours (EMG experiments).

Performance measures across users (overall performance) and across target directions (directionally-dependant performance) for each command source were tested for normality and having been found to fit a Normal distribution, compared to each other using between measures ANOVA to check for significant differences in the means. Tukey's "Honestly

Significantly Different" method was used to identify performance measures that were not significantly different for pair-wise, one-tailed t-test comparisons. The statistical power was greater than 80% for tests that showed 95% confidence differences in the compared quantities.

III. RESULTS

Fig. 3 illustrates typical 2D cursor trajectories, time records of the×and y movements, and time records of the user input signals for one subject. Each row corresponds to a given command source, and the illustrated trials used the same target direction, distance, and size. The mouse-commanded cursor position exhibited a smooth, only slightly curved approach to the target (Fig. 3g, h). The head orientation-commanded motion (Fig. 3b) was characterized by steady commands for both×and y motion (Fig. 3c) and a more curved but still smooth motion to the target (Fig. 3a). The EMG user command signals (Fig. 3f) were essentially independent across the various muscles and pulsatile rather than sustained and smooth. This resulted in cursor movements (Fig. 3d, e) that were directionally sequential rather than simultaneous, with the cursor moving in one direction at a time toward the target.

Fig. 4 shows the cursor motions and velocity histograms for all targets and all subjects. Each row indicates a different command source, with the left column showing the cursor movements and the right column the velocity histograms. The mouse-commanded cursor movements (Fig. 4e) were almost always directed straight towards the target and exhibited minimal *Overshoot*. Head orientation-commanded motions (Fig. 4a) were similar to the mouse motions, although the movements to targets in pure×or y directions were extremely straight and even more consistent than for the mouse. Motions toward targets at 45 degrees (which required simultaneous use of the two head motions) exhibited a bit more spread than the mouse trials. The EMG-commanded cursor movements (Fig. 4c) were characterized by sequential movements in one direction and then the other, producing rather boxy cursor trajectories that also showed significant *Overshoot*. Fig. 4b, d, and f show the velocity histograms for head orientation, EMG, and mouse-commanded movements, respectively (note the different velocity scale for the mouse-commanded movements). The mouse-commanded movements (which could be performed easily without limiting the cursor speed) were the fastest. The head orientation and EMG-commanded movements showed similar speed characteristics at lower velocities, although note the occurrence of the highest-permissible speed (500 pixels/sec) in the EMG-commanded movements (Fig. 4d). This also indicates that some speed limiting was present in EMG commanded cursor movement.

Fig. 5 illustrates the relationship between movement time (MT) and index of difficulty (ID). For all three command sources, MT increased essentially in proportion to ID. Mouse-commanded cursor movements displayed a very tight relationship (R^2=0.94) between ID and MT (Fig. 5c). Head orientation and EMG command sources (Fig. 5a, b) had lower overall correlation between ID and MT (R2 = 0.70 and 0.67, respectively), and the relationship depended more strongly on target size.

Fig. 6 summarizes the performance of each command source across the various performance measures. The mouse was the superior command source for each of these measures. Between head orientation and EMG command sources, no statistical difference (p=0.23) was observed in the *Throughput* (1.02±0.42 and 0.84±0.40 bits/sec respectively). The mouse *Throughput* (5.11±1.06 bits/sec) was significantly greater than both head orientation ($p=8.83\times10^{-5}$) and EMG ($p=6.60\times10^{-5}$) command sources. The *Path Efficiency* of the mouse was 97±2% and was statistically greater than that of head orientation (88±2%, $p=1.52\times10^{-5}$) and EMG commanded cursor motion (61±10%, $p=1.60\times10^{-4}$). Head orientation also exhibited statistically greater *Path Efficiency* than EMG ($p=4.62\times10^{-4}$)

EMG exhibited the largest amount of *Overshoot* (83±40%) compared to head orientation (32±8%, p=7.90×10^{-3}) and the mouse (4±6%, p=1.39×10^{-3}). Head orientation had the second highest *Overshoot* and was significantly greater than that of the mouse (p= 1.39×10^{-5}). No significant difference (p=0.21) was observed between the head orientation and EMG *Reaction Time*s (1.15±0.30 sec and 1.02±0.25 sec), while the mouse was significantly faster (p=0.0005 and p=0.0002 for head orientation and EMG respectively) and required approximately half as much time (0.53±0.07 sec). The mouse *Average Speed* was the fastest (390±93 pixels/sec), followed by EMG (173±34 pixels/sec) and head orientation commanded motion (101±36 pixels/sec). The *Average Speed* of the mouse (390±93 pixels/ sec) was significantly greater than that of EMG (173±34 pixels/sec, p= 2.89×10^{-4}) and head orientation (101±36 pixels/sec, p= 4.11×10^{-5}). EMG commanded motion demonstrated a statistically faster average speed than that of head orientation (p= 1.73×10^{-3}).

The effect of direction on performance was quantified by the various *Direction Ratios*. Overall summary averages are listed for each command source and each performance measure in Table 2. These results are broken out by movement direction and portrayed graphically in Fig. 7. The left column of Fig. 7(a, c, e, g, & i) illustrates the *Direction Ratios* of the various performance measures by target direction, normalized to the highest performance across the eight directions (i.e., the performance values across all directions were divided by the maximum of these 8 values). The right column (Fig. 7b, d, f, h, j) compares the overall average (i.e., the average across all 8 individual directions) performance to the average single-direction movements (i.e., purely horizontal and vertical targets requiring a single user command) and the average diagonal (i.e., targets located on the diagonals requiring coordination of two separate user commands) performance. In the plots of normalized performance by direction, (Fig. 7, left column) an ideal direction-independent performance would be illustrated b the plot taking the shape of an octagon. The farther the plot deviates from octagonal, the more of an effect target direction had on performance. Distinct directional differences in *Throughput* can be seen in Fig. 7a, with EMG *Throughput* being the most striking with its cross-like shape and a DR of 0.34±0.04, illustrating a large disparity between single direction and diagonal performances. Head orientation also had some directional differences (DR=0.60±0.05), with a “diamond” shape to the *Throughput*. The mouse exhibited very little direction effect on *Throughput*, with a near octagonal *Throughput* plot and a DR of 0.96±0.08. In Fig. 7b, it can be seen that mouse single direction *Throughput* (5.08 bits/sec) was significantly greater than both head orientation (1.27 bits/sec, p=3.5×10^{-5}) and EMG (1.27 bits/sec, p=4.6×10^{-6}) command sources. No statistical difference is observed between single direction *Throughput* for head orientation and EMG commanded motion (p=0.49). For targets located on the diagonals, the mouse *Throughput* (4.89 bits/sec) was greater than both head orientation and EMG (0.76 bits/sec, p=6.61×10^{-5} and 0.43 bits/sec, p=5.09×10^{-5} respectively). Head orientation diagonal *Throughput* was significantly greater than that of EMG (p=2.16×10^{-6}).

For *Path Efficiency*, the effect of direction was not as pronounced for the EMG command source as was seen for *Throughput*, but this was still noticeable with a DR of 0.61±0.03 and a diamond shaped plot as shown in Fig. 7**c**. Head orientation had a DR of 0.83±0.01 and a slight indentation of the plot for diagonal targets. Direction had very little effect on mouse *Path Efficiency* (DR=0.98±0.01). Fig. 7d illustrates that single direction mouse *Path Efficiency* (98±1%) is significantly greater than that of head orientation (96±1%, p=0.03) and EMG (76±4%, p=6.66×10^{-4}). Single direction motion commanded by head orientation is greater than that directed by EMG (p=7.18×10^{-4}). Diagonal mouse commanded cursor motion has a greater *Path Efficiency* (96±1%) compared to both head orientation (80±1%, p=4.29×10^{-7}) and EMG (47±2%, p=5.27×10^{-8}). Head orientation *Path Efficiency* for diagonal targets was significantly greater than EMG (p=1.02×10^{-6}).

Directional effects on *Overshoot* were limited. Fig. 7e shows that direction had very little effect on *Overshoot* for the EMG command source, with DR=0.96±0.09. The plot of *Overshoot* for head orientation (Fig. 7e) resembles a "bowtie", with greater *Overshoot* on diagonal targets (DR=1.87±0.38). The *Overshoot* exhibited by the mouse was negligible (Fig. 7f) and not plotted in Fig. 7e. In Fig. 7f, the amount of *Overshoot* exhibited by the mouse for single direction targets (4±2%) was significantly less than that of head orientation (22±4%, p= 5.26×10^{-4}) and EMG (83±8%, p=6.39×10^{-5}) commanded motion. Head orientation also showed far less overshoot than EMG (p=4.13×10^{-5}) for single direction motion. For targets located on the diagonals, the mouse had statistically less *Overshoot* (3±1%) than either head orientation (41±9%, p=1.83×10^{-3}) or EMG (80±6%, p=5.47×10^{-5}). Diagonal motion commanded by head orientation demonstrated less overshoot compared to EMG (p=3.93×10^{-4}).

Little directional difference was observed in the *Reaction Time* for each command source (Fig. 7g), with near octagonal plots and DR's near unity. Mouse on-axis *Reaction Time* (0.53±0.01sec) was significantly less than both head orientation (1.10±0.08 sec, p=3.44×10^{-4}) and EMG (1.07±0.12 sec, p=1.44×10^{-3}) command sources. Between head orientation and EMG, no significant difference was observed in the single direction *Reaction Times* (p=0.35) as seen in Fig. 7h. For diagonal targets, the *Reaction Time* for the mouse (0.53±0.01 sec) was significantly less than that of head orientation and EMG commanded motion (1.19±0.02sec, p=1.23×10^{-8} and 1.05±0.06, p=1.87×10^{-4} respectively). The *Reaction Time* for EMG directed cursor motion to diagonal targets was statistically less than that of head orientation (p=7.17×10^{-3}).

In terms of *Average Speed*, both EMG and head orientation command sources showed some directional effects (Fig. 7i), with slower velocity to diagonal targets and a DR of 0.82±0.09 and 0.80±0.10 respectively. Target direction had no effect on mouse *Average Speed* (Fig. 7i), with a DR of 1.0±0.05 and an octagonal plot. These high DR's are reflected in the relatively similar single direction and diagonal cursor speeds seen in Fig. 7j. For single direction targets, the mouse had a significantly higher *Average Speed* (357±24 pixels/sec) compared to head orientation (107±12 pixels/sec, p=1.09×10^{-5}) or EMG (182±21 pixels/sec, p=1.86×10^{-5}). EMG commanded cursor motion in single directions was notably faster than head orientation (p=8.96×10^{-4}). In moving to targets on the diagonals, the mouse was significantly faster (359±24 pixels/sec) than both head orientation (86±2 pixels/sec, p=8.63×10^{-5}) or EMG (149±9 pixels/sec). EMG exhibited statistically faster motion moving to diagonal targets than head orientation (p=2.62×10^{-4})

IV. DISSCUSSION

This study investigated the performance of three human-computer interfaces, two of which (head orientation and face/neck EMG) could serve as an effective command source for individuals with a high cervical spinal cord injury, and one (standard computer mouse) that served as a baseline for comparison. The mouse, as expected, displayed performance superior to head orientation and EMG. The mouse *Throughput* values we measured were within the range of values found in other similar studies [23], validating the experimental design and allowing for comparison of the novel command sources to other human-computer interface literature.

Overall performance: head orientation versus EMG cursor movements

Comparing head orientation and EMG (i.e., command sources available to a paralyzed individual), the *Throughput* performance of head orientation and EMG-commanded motions were similar. Head orientation performance was superior to EMG performance in measures related to accuracy and precision (i.e., *Path Efficiency* and *Overshoot*), indicating that

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subjects had both better position and velocity control over the cursor. The higher *Average Speed* of EMG commanded motions, however, allowed this command source to overcome limitations in accuracy to achieve a similar overall *Throughput*.

Overall, head orientation performance closely resembled that exhibited in manually operated joysticks, though with a slightly lower *Throughput* [23]. This comparison is apt, as commanding cursor velocity via changes in head orientation is similar to using the head as a joystick. A head orientation-based command interface, with long term practice, could thus potentially achieve performance similar to joysticks, with *Throughput*s in the range of 1.6 to 2.55 bits/sec [23]. Although very little has been published regarding EMG-commanded cursor movements, the data that does exist is consistent with our results that EMG performance is lower than for head orientation, with bit rates around 1 to 1.2 bits/sec [13], [14].

Single direction versus diagonal performance

Single direction cursor movements (i.e., along the x-axis or y-axis only) could be performed by single actions from the command sources (i.e., one head motion or contraction of a single muscle to generate EMG). To reach diagonal targets, however, required the subject to command both×and y cursor motions using two independent actions (both head pitch and head yaw or EMG in two muscles). From the plots of performance by target and comparison of single direction to diagonal performance in Fig. 7, it is clear the subjects could perform the diagonal movements much more effectively with the head orientation signals than with the EMG signals as sources. This difference in performance is particularly noticeable when comparing Fig. 4(a) (head orientation controlled cursor movements) to Fig. 4(c) (EMG controlled cursor movements). Head orientation-controlled movements were noticeably better to single-direction targets, but the diagonal performance was much better than comparable EMG-controlled movements. The EMG-controlled cursor traces (Fig. 4c) had a square shape and EMG had a rather low *Throughput Direction Ratio* of 0.34, indicating that subjects preferred controlling cursor movements via EMG first in one direction and then the other, rather than simultaneously controlling the two cursor directions.

The directional effects seen in head orientation commanded cursor velocity and target acquisition match those in similar studies that compared head orientation commanded cursor position to joystick performance [24], [25], [27]. While diagonal cursor motion requires simultaneous control of two head angles, intact proprioception and the resulting precision appears to allow for more accurate diagonal movements. Long term practice may also affect subject directional performance. Jagacinski [24] reported on subjects who were tested over a period of weeks until they reached a performance asymptote. Even after this extensive practice, subjects still showed a *Throughput* DR of just 0.92, i.e., diagonal *Throughput* was still lower than single-direction *Throughput*. Both Radwin [25] and Jagacinski [24] have postulated that diagonal cursor motion based on head orientation is a result of both sequential and simultaneous muscle activations controlling head rotation and flexion, so to a certain extent diagonal movements may always be characterized by a degree of sequential movements that will decrease performance relative to single-direction movements. Such behavior is reflected in Fig. 3a, where it can be seen that when moving to a diagonal target, the subject first initiated a movement in a one direction (upward in this case) and then changed direction to proceed to the target.

Impact of limiting cursor velocity

Fig. 4d shows that some speed limiting occurred in EMG commanded movements as a result of the cursor speed being capped at 500 pixels/sec. In preliminary testing, it was observed that as the maximum cursor speed was increased above 500 pixels/sec, subject performance dramatically decreased, largely the result of increased overshoot and poor overall velocity control. This was found to be true for both head orientation and EMG command sources. Based on this, the maximum cursor speed was set to limit *Overshoot* to a reasonable level while still providing sufficient speed to reach far targets in a timely manner. While it is possible that allowing higher cursor velocities would have allowed a higher overall *Throughput* for EMG-commanded cursor motions, it is more likely that a corresponding increase in *Overshoot* would have degraded performance to an even greater extent. It is also possible that as subjects become more experienced with the user interface though long term practice, that the speed limit could be increased. It is not believed, however, that limiting cursor velocity significantly impacted the computed measures of performance in our study.

The velocity algorithm used in this study was observed in preliminary studies to perform better that either a linear or a third order polynomial velocity algorithm. The parabolic velocity algorithm seen in Equation 2 out-performed the others as it allowed for slow speed at the onset of motion, which is particularly important for close targets, while retaining a high maximum cursor rate to rapidly reach far targets. While a different algorithm could produce somewhat different results, the velocity algorithm used in this study was probably near optimal for these command sources.

Fitts' Law for head orientation-commanded and EMG-commanded cursor movements

From Fig. 5a & b, it can be seen that the fit between the index of difficulty (ID) and movement time (MT) of the head orientation and EMG data to a Fitts' Law model was less than ideal, with R^2 values of 0.70 and 0.67, respectively. However, this does not rule out the use of the Fitts' Law based *Throughput* performance measure. It was found in previous studies that the smallest diameter targets, similar to those used in this study, resulted in abnormally long movement times that did not always follow a strict Fitts' Law model of movement [24]. When these targets are removed from the regression, the fit achieves an R^2 of 0.95 and 0.77 for head orientation and EMG commanded motion, respectively. Overall, the fit to Fitts' Law seen in this study compares favorably to similar other studies [24], [14]. The deviations seen are most likely a result of the original definition of Fitts' Law to directed, continual, position commanded movement (similar to that seen when using a mouse). When the command source is a velocity command (as in the case of head orientation and EMG commanded movement in this study, or for a joystick as studied by Card [21]), a strict fit to Fitts' Law is often not observed. That said, it is still useful as a means of summarizing human-computer interface performance, and has been so for close to 30 years [21]. In addition to the *Throughput* (a summary performance measure), the use of additional performance measures to compute *Path Efficiency, Overshoot, Reaction Time* and *Average Speed*, also provided additional detail regarding the finer aspects of command source performance that do not depend on the Fitts' Law model [22].

Head orientation versus EMG as a command source

Our results indicate that control of a cursor via head movements is more natural and intuitive than via neck and head muscle EMG signals. It has been previously demonstrated that human subjects are able to control only gross levels of EMG amplitude, with a resolution (for a maximum error rate of 1.1%) of at most five states from zero to 100% of maximum voluntary contraction [31]. Comparing this to the few degree resolution available for accurate control of head orientation [27], EMG is clearly at a disadvantage – which was borne out by our results here. This was particularly true for diagonal cursor motions that required subjects to exhibit fine control over two EMG signals simultaneously. The fact that two of the eight subjects participating in the EMG experiments could not independently control the left and right platysma muscles was unexpected. If such lack of independent control is found routinely and for other muscles, this could limit the use of head and neck EMG as a command source.

The processing methods used in this study are those currently in use by EMG controlled prosthetic systems (functional electrical stimulation and upper extremity prosthetics as examples) and as such, serve as a “standard” for EMG command interfaces. While additional pattern recognition techniques may be applicable, many features of the EMG signal are typically correlated to the rectified, windowed, average EMG amplitude used in this study. Such pattern recognition techniques may be employed in future studies.

While head orientation did out-perform EMG as a user interface for many of our performance measures (especially those related to precision), EMG signals as command inputs have other advantages, specifically implantability, that no existing orientation sensor can currently match. As an implanted sensor, the minute muscle contractions necessary to operate an EMG interface, with minimal to no worn equipment, may afford a very unobtrusive means of human-computer interaction. Given that both obtrusiveness and the extent of worn equipment are related to abandonment rates of prosthetic systems [32], EMG may be an attractive alternative, especially for implanted systems for the foreseeable future.

V. CONCLUSION

While a high cervical spinal cord injury can result in significant loss of function, technology has been developed that can assist in restoring the ability to operate a computer. The benefits of computer operation by individuals with tetraplegia are numerous, and in an increasingly more computerized world, ever more significant. This project investigated the performance of head orientation and EMG commanded cursor motions, voluntary actions available to individuals with a cervical SCI, and compared their properties to that of a standard computer mouse. Comparing head orientation and EMG command sources, the former better matched the mouse performance, being more accurate, having less *Overshoot*, and was less affected by target direction. Although head orientation was superior in many performance measures, EMG signals can be recorded unobtrusively and simply and thus may be a viable, although lower performance, alternative.

The use of multiple performance measures and the performance details they illustrate provided a more complete picture of command source performance than using the summary variable of *Throughput* alone. Thus, our general approach should be useful to future evaluations of additional user command interfaces.

Acknowledgments

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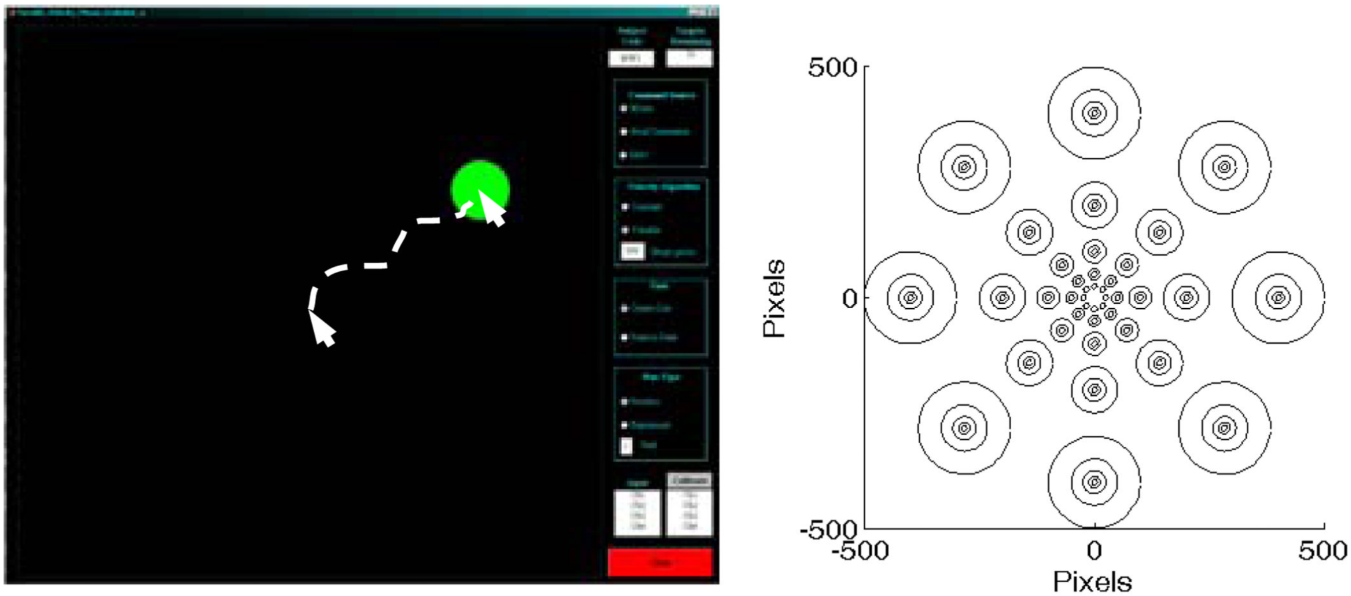

(a) (b)

Fig. 1.

Screen capture of evaluation interface (a). The dashed path represents an example of user commanded cursor motion from the center, out to the target. (b) Plot showing all possible targets.

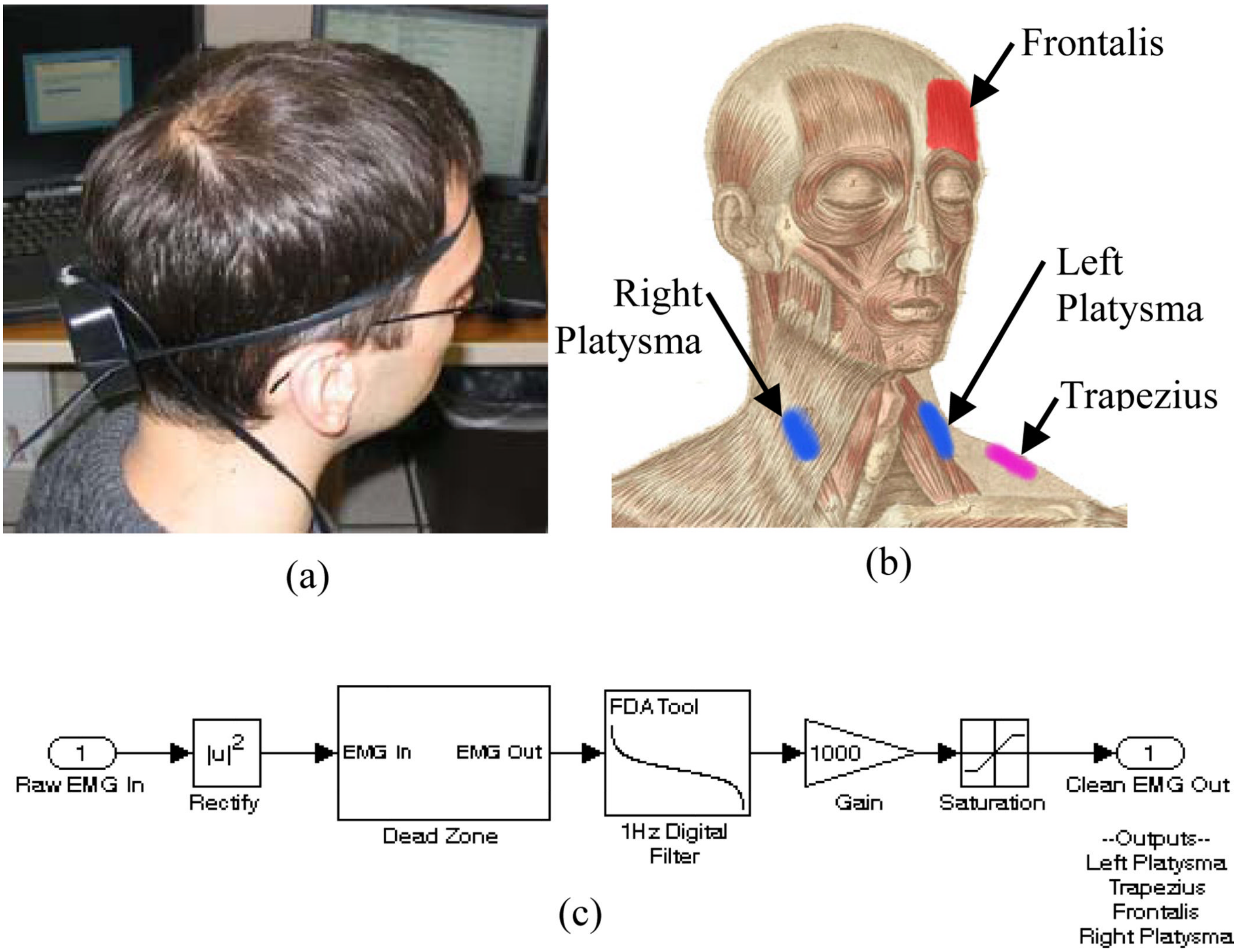

Fig. 2.

Photograph of subject wearing head orientation sensor (a). Illustration of muscles used for the EMG command source (b). Diagram of EMG signal processing system (c).

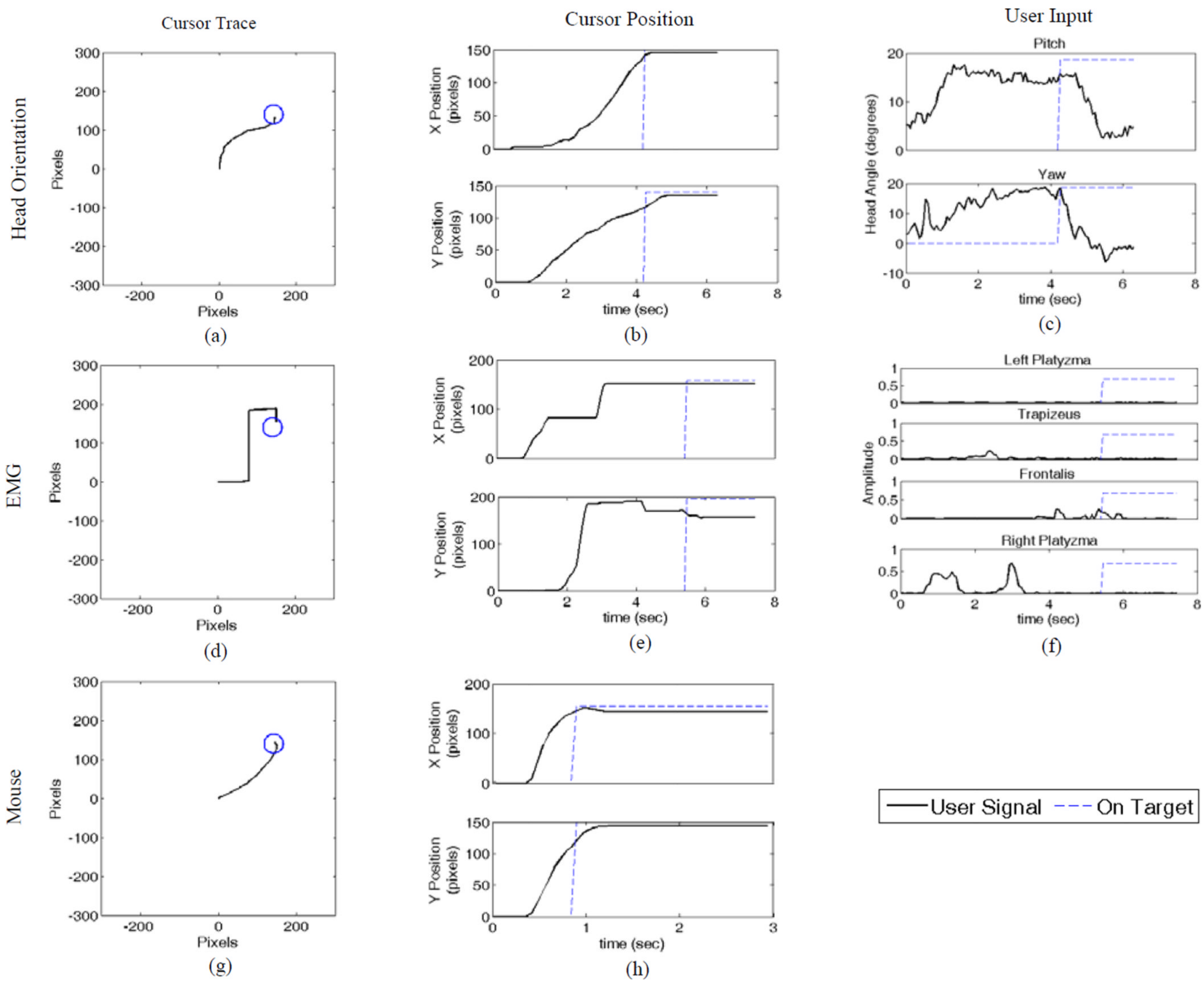

Fig. 3.

Example of a single user's performance to an identical target across command sources. The left-most column shows the cursor path to the target. The center column is the X and Y position of the cursor (zeroed at center screen) over the trial. The right column is the signal passed by the user to the evaluator. Note the more sustained user signal in the case of the head orientation command source compared to the more sporadic pulses in the case of EMG, yielding a smoother, straighter path.

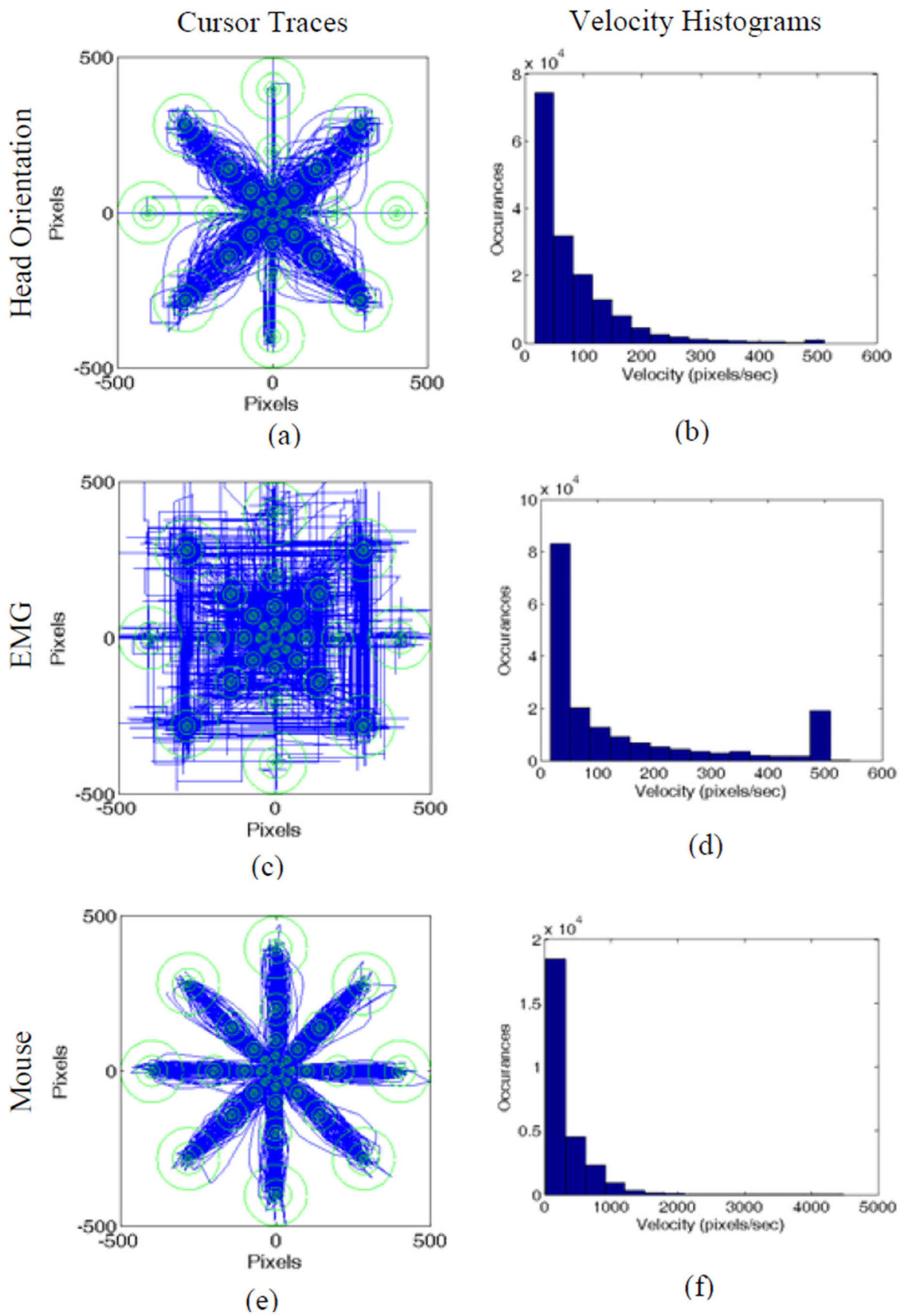

Fig. 4.

Cursor traces (left column) and velocity histograms (right column) across all subjects for all command sources.

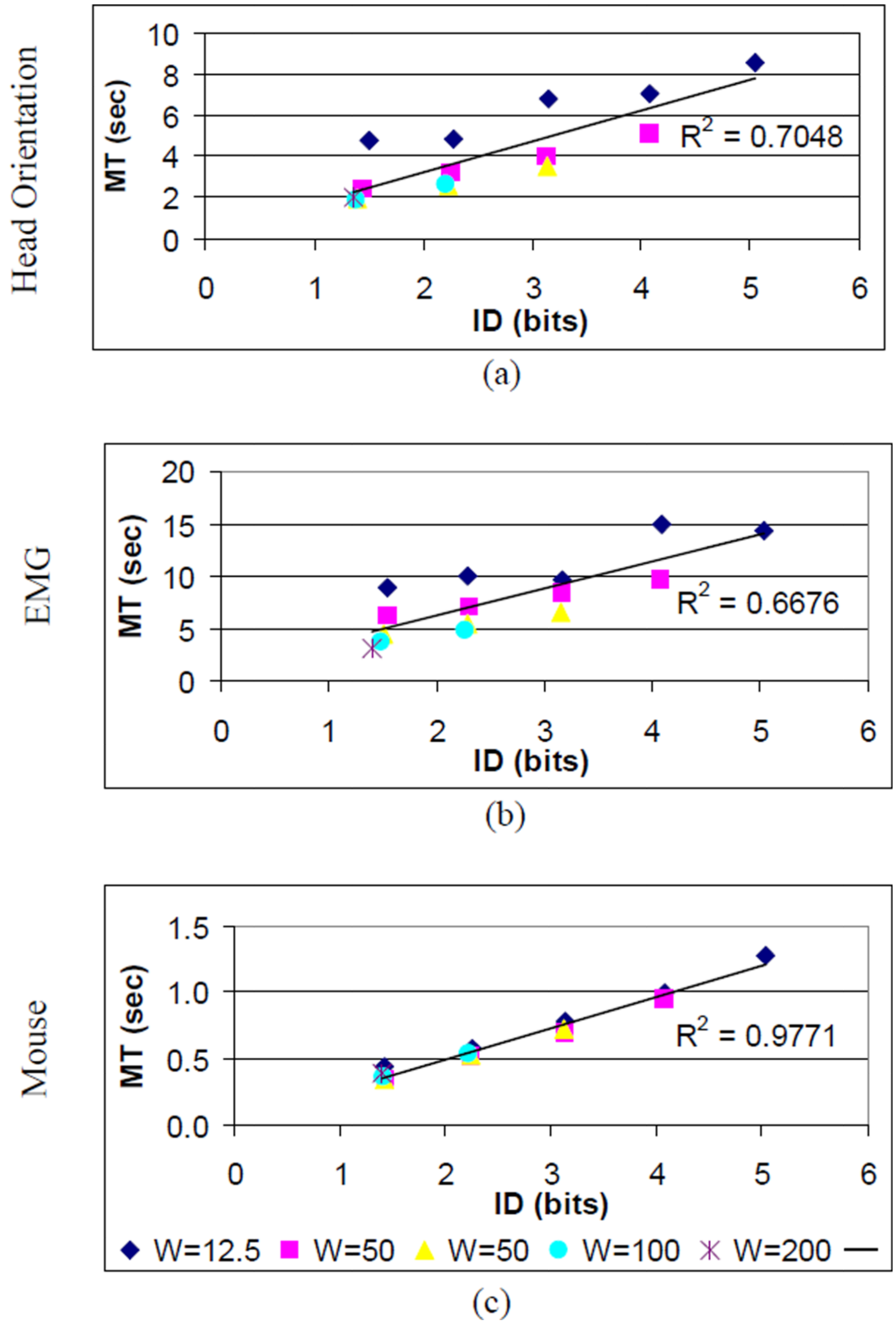

Fig. 5.

Regression plots of cursor Movement Time to Index of Difficulty for head orientation commanded cursor motion (top), EMG commanded cursor motion (middle) and mouse commanded cursor position (bottom).

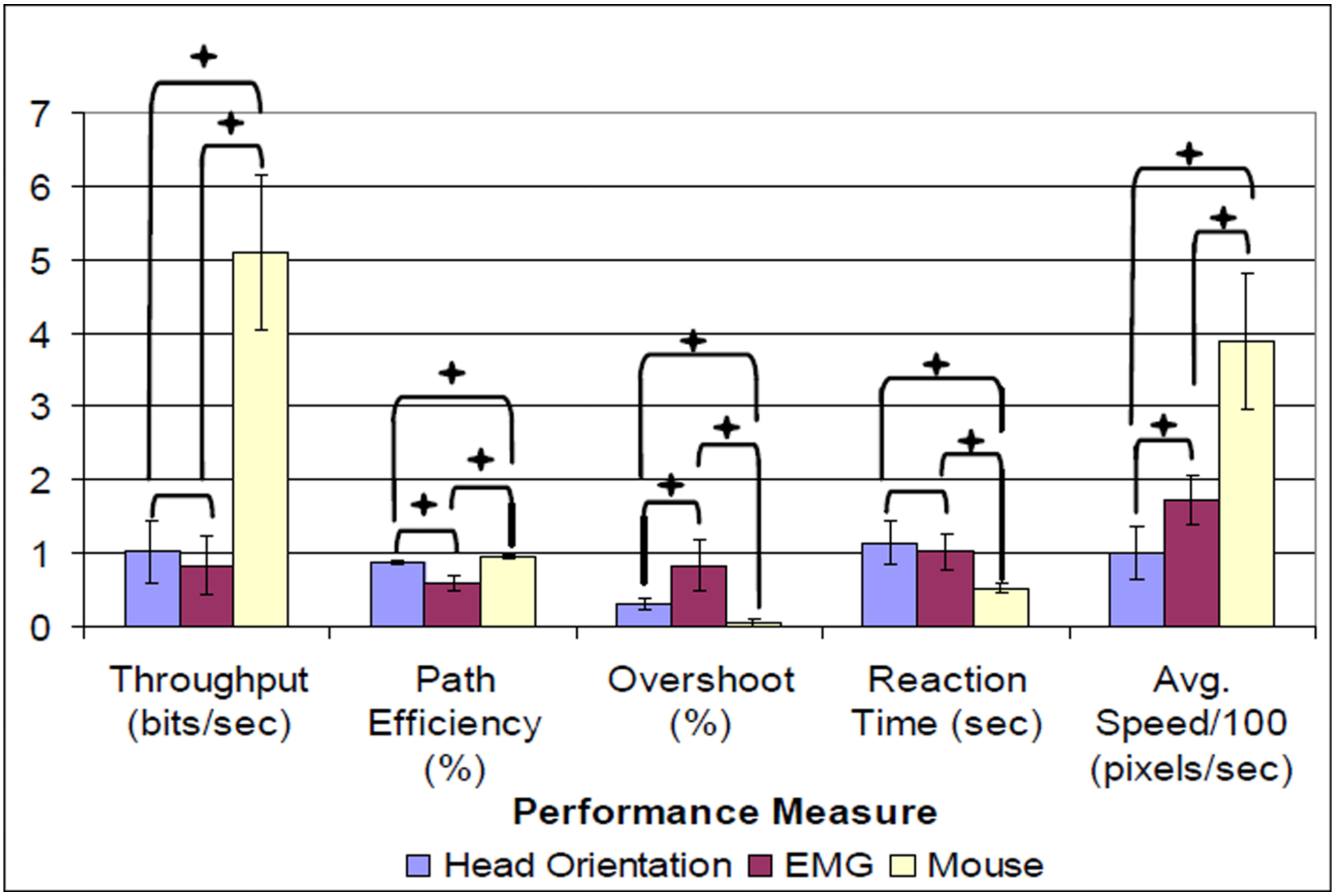

Fig. 6.
Comparison of command source performance measures across sources. Pair-wise comparisons are noted with brackets. Those comparisons that are significantly different ($p<0.05$) within the marked groups are denoted with a star.

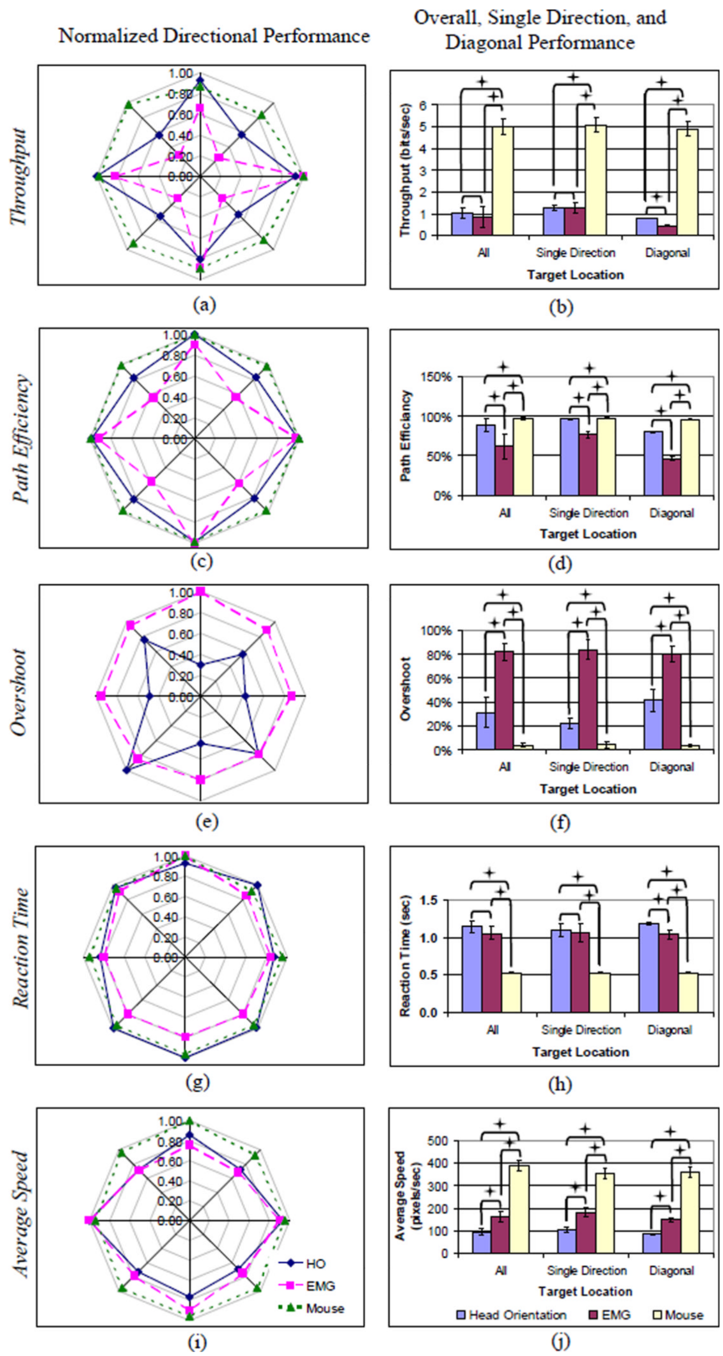

Fig. 7.

Plot of normalized command source performance by target direction (left column) and overall average, single direction, and diagonal performance (right column). In the left column, ideal omni-directional performance is illustrated as an octagon, with departures representing decreased performance in that particular direction. In the right column, pair-wise comparisons across command sources of overall, on axis and diagonal performance are noted with brackets. Those comparisons that are significantly different ($p<0.05$) within the marked groups are denoted with a star

Table 1

Target distances (D) and widths (W), and the resultant Indices of Difficulty used in this study.

	D (pixels)				
W (pixels)	**25**	**50**	**100**	**200**	**400**
13	1.58	2.32	3.17	4.09	5.04
25		1.58	2.32	3.17	4.09
50			1.58	2.32	3.17
100				1.58	2.32
200					1.58

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Table 2

Summary of the Direction Ratios for each performance measure across command sources.

	Head Orientation	EMG	Mouse
Throughput	0.60 ± 0.05	0.34 ± 0.04	0.96 ± 0.08
Path Efficiency	0.83 ± 0.01	0.61 ± 0.03	0.98 ± 0.01
Overshoot	1.87 ± 0.38	0.96 ± 0.09	0.81 ± 0.48
Reaction Time	1.09 ± 0.08	0.98 ± 0.12	0.98 ± 0.04
Average Speed	0.80 ± 0.10	0.82 ± 0.09	1.00 ± 0.05