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Myoelectric control system and task-specific characteristics affect voluntary use of simultaneous control

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Abstract

Clinically available myoelectric control does not enable simultaneous proportional control of prosthetic degrees of freedom. Multiple studies have proposed systems that provide simultaneous control, though few have investigated whether subjects voluntarily use simultaneous control or how they implement it. Additionally, few studies have explicitly evaluated the effect of providing proportional velocity control. The objective of this study was to evaluate factors influencing when and how subjects use simultaneous myoelectric control, including the ability to proportionally control the velocity and the required task precision. Five able-bodied subjects used simultaneous myoelectric control systems with and without proportional velocity control in a virtual Fitts' Law task. Though subjects used simultaneous control to a substantial degree when proportional velocity control was present, they used very little simultaneous control when using constant-velocity control. Furthermore, use of simultaneous control varied significantly with target distance and width, reflecting a strategy of using simultaneous control for gross cursor positioning and sequential control for fine corrective movements. These results provide insight into how users take advantage of simultaneous control and highlight the need for real-time evaluation of simultaneous control algorithms, as the potential benefit of providing simultaneous control may be affected by other characteristics of the myoelectric control system.

Index Terms

Prosthesis control; Intramuscular electromyography; Fitts' Law

I. Introduction

Conventional myoelectric control uses the surface electromyogram (EMG) from muscles in the residual limb to control degrees of freedom (DOF) in the prosthesis. Conventional dual-site methods use an antagonistic muscle pair in the residual limb to control the prosthetic DOFs [1]. Though multiple specific control strategies exist (e.g. differential, first-come-first-served, maximum-wins, etc.), each works primarily by using the flexor EMG signal to control flexor movements (e.g. pronation or hand closed) and the extensor EMG signal to control extensor movements (e.g. supination or hand open). Patients must use co-contractions to switch modes in order to sequentially control different DOFs, thus disrupting the continuous control of the device. A notable limitation to all currently available myoelectric control systems is the inability to simultaneously control independent DOFs of the prosthesis. Although targeted reinnervation surgery [2] may allow some patients to simultaneously control up to two DOFs using conventional methods [3], the vast majority of patients are forced to control each prosthesis DOF sequentially. Furthermore, no clinically available myoelectric control system allows for simultaneous control of three or more DOFs.

There has therefore been a large emphasis in the research community on improving the controllability of myoelectric devices, focusing on providing simultaneous control of multiple DOFs in a way that also allows for proportional control [4]. Multiple promising approaches have resulted. The recent development of implantable EMG-recording devices [5–7] allowed conventional methods to be extended to provide simultaneous control, by configuring multiple dual-site strategies in parallel. Using this approach, a transradial amputee with IMES[®] implants in the forearm demonstrated simultaneous control of wrist rotation and a two-DOF hand [8]. Parallel dual-site control has additionally been investigated for individual finger control [9] and for a 3-DOF wrist/hand system [10]. Using the surface EMG signal has also demonstrated potential. Pattern recognition has been used to provide accurate predictions of intended simultaneous DOF motion classes [11, 12], but with limited methods to allow for proportional independent velocity control of the DOFs. Neural networks have been used to predict joint kinematics [13, 14] or kinetics [15] of the wrist. Blind source separation algorithms for extracting muscle synergies have been used to control a 2-DOF wrist system [16]. Projection of the EMG signal energy onto an orthonormalized set of principle movement vectors has also been investigated [17].

A few studies have recently demonstrated the potential benefit of providing simultaneous control compared to sequential control, allowing for faster completion times and greater efficiencies in tasks requiring use of more than one DOF [10, 16]. However, when and how a person may choose to use simultaneous control has not been studied in detail, and are crucial factors in whether such advanced myoelectric control systems will provide clinical benefit to the patient. Few studies have evaluated whether subjects voluntarily use the simultaneous control that is provided to accomplish a task. Most studies have focused on offline analyses [11, 13–21], where the proposed algorithms predict the subject's intended movement from labeled data sets after an experimental session. Some studies included real-time, closed-loop evaluation of myoelectric systems, but required subjects to use simultaneous control to complete the task [16]. Other studies have not commented on

whether or not subjects were encouraged to use simultaneous control during the experiment [12, 22].

Of the studies that have allowed for voluntary use of simultaneous control, results have been variable, suggesting that both characteristics of the tasks being performed and of the control system itself may affect whether subjects use simultaneous control. In two studies where voluntary use of simultaneous control was evaluated, able-bodied subjects voluntarily controlled two of the three available DOFs simultaneously without prompting [9, 10], and occasionally all three DOFs simultaneously [10]. These studies qualitatively observed that subjects tended to use simultaneous control mostly for gross movements, implying that the amount of simultaneous control used may depend on the required precision of the task. In other rehabilitative engineering applications, subjects have not always voluntarily used simultaneous control. Tetraplegic subjects rarely used simultaneous control [23] when using head and neck muscle EMG to control a cursor using a control scheme similar to [9]. The authors suggested that this was because the control system was less natural and intuitive than other control methods evaluated in the study, with which subjects did use simultaneous control.

Though many studies have focused on the simultaneous aspect of intuitive myoelectric control, far fewer studies have investigated the proportionality component. No previous studies have evaluated how these two aspects of myoelectric control may interact to influence prosthesis controllability, despite the consensus of the field that “simultaneous proportional control” is needed. Most myoelectric devices available today map increased EMG amplitude to greater velocity at a DOF (“proportional control”), though historically, myoelectric devices only allowed each DOF to be controlled at a constant speed (“on-off control”) [24]. Although clinical practice has experienced a shift in velocity control paradigm, the literature explicitly investigating the differences between on-off and proportional control is scarce and inconclusive. Some studies have indicated that subjects perform better when provided proportional velocity control in virtual tasks [25], and that users prefer proportional control, with anecdotal reports of improved controllability and “naturalness” compared to on-off control [26]. However, other studies explicitly comparing the two control methods in amputees using physical prostheses demonstrated equivocal results [27]. More studies are therefore needed that directly evaluate proportional versus on-off control. Given previous work suggesting that more intuitive control systems may encourage greater use of simultaneous control [23], the potential interaction between providing proportional control and simultaneous control is interesting and particularly relevant for simultaneous control approaches that to date have not demonstrated full independent proportional control capabilities [3].

The objective of this study was to evaluate factors influencing when and how subjects use simultaneous control in a myoelectric control application. Given the variable usage of voluntary simultaneous control in previous studies, we hypothesized that differences in the myoelectric control system provided and/or the task being performed would influence the subject’s choice of whether or not to use simultaneous control. In particular, we investigated the effects of (1) providing proportional velocity control and (2) presenting tasks that required differing levels of gross movement and precision to complete. We hypothesized

that the difference in controllability and naturalness between proportional and on-off control may influence subjects' willingness to increase the complexity of their movements by controlling DOFs simultaneously. Additionally, we hypothesized that, similar to able-bodied subjects in pointing tasks [28], subjects using myoelectric control may modify their movement strategy depending on the distance of travel necessary and the required precision of movement. Both hypotheses were evaluated in the following experiment, in which able-bodied subjects used myoelectric control to move a cursor in a virtual target acquisition task.

II. Methods

The following experiment was approved by the Northwestern University Institutional Review Board. Subjects participated after giving informed consent. Use of simultaneous control was evaluated as five able-bodied subjects completed a virtual cursor-positioning task using two different myoelectric control systems. Both systems used intramuscular EMG in an extension of conventional dual-site differential control, which was chosen in favor of surface EMG simultaneous control methods because the intramuscular approach was previously demonstrated to control three DOFs that include both the wrist and hand [10, 29]. One of the control systems allowed proportional velocity control of the cursor, as is typical for parallel dual-site control. The other control system was identical except that the velocity control was forced to on-off velocity control. The experiment consisted of two sessions, spaced a minimum of one week apart. Subjects used one type of control system during each session; the order in which the control systems were used was randomized across subjects. Subjects' use of simultaneous control was evaluated as they acquired targets with varying properties and different complexity levels in a virtual Fitts' Law task.

A. Signal Acquisition and Processing

Intramuscular EMG signals were recorded using fine wire electrodes (Natus Neurology Inc. and Motion Lab Systems Inc.) from six forearm muscles: pronator teres, supinator, flexor carpi radialis, extensor carpi radialis longus, flexor digitorum profundus, and extensor digitorum communis. Bipolar fine wire electrodes were inserted using 25 gauge hypodermic needles. The insertion sites were guided by [30] and palpation, then verified by electrical stimulation and EMG activity during test contractions. EMG signals were collected with a Motion Lab Systems MA300 system, which amplified at 350 $\times$ and band-passed filtered the signals between 10–2000 Hz. Signals were sampled at 5 kHz using a 16-Bit National Instruments data acquisition system (NI-USB 6218). A 3rd order high-pass Butterworth filter with a cutoff frequency of 20 Hz was also applied digitally. After the electrodes were inserted, subjects were placed in a custom forearm/hand brace to ensure isometric contractions as they completed the virtual tasks.

B. Myoelectric Control System

Subjects used a myoelectric control scheme termed *parallel dual-site control* (Fig. 1), based on conventional dual-site differential control [10]. The difference in intramuscular EMG amplitudes from an antagonist-agonist muscle pair (i.e., from *dual sites*) controlled a physiologically appropriate DOF. Multiple muscle pairs were used in *parallel* to simultaneously control multiple DOFs.

The mean absolute values (MAVs) of the EMG signals were calculated from 250 ms sliding windows, with a frame increment of 50 ms (similar to [9]). For the condition where proportional velocity control was provided, the output velocity was calculated using the MAVs of the corresponding antagonistic muscle pair by the following equation:

$$V_{\text{prop}} = \max[0, (G_1 M_1 - T_1)] - \max[0, (G_2 M_2 - T_2)] \quad (1)$$

where M_1 is the MAV of the first muscle in the antagonistic pair, G_1 is the gain applied, and T_1 is the threshold. Similarly, M_2 , G_2 , and T_2 represent the MAV, gain, and threshold for the second muscle. Eq. 1 was used to calculate the output velocity for each of the three DOFs, using the corresponding pair of antagonistic muscles and DOF-specific gains and thresholds. The gains and thresholds were set manually by the experimenters to minimize unintended DOF activity, to maximize the dynamic range of velocities, and so that 50% of the maximum possible velocity was achieved through comfortable-intensity contractions. A post-processing velocity-dependent ramp that was previously developed for pattern recognition control [31] was also implemented to minimize abrupt changes in DOF activity. The ramp caused the output velocity to linearly increase to 100% of the intended velocity, calculated by Eq. 1, over 500 ms of continuous activity. Subjects practiced the virtual task before beginning the experimental trials, and were allowed to request modifications to gains and thresholds until they were satisfied with the control system.

For the condition where on-off control was used, subjects were unaware that they could not control the cursor velocity. Therefore, gains and thresholds were manually configured as described above. However, in the virtual task, the output velocity at each DOF was governed by:

$$V_{\text{const}} = V_0 \times \text{sign}(V_{\text{prop}}) \quad (2)$$

where V_0 was the constant velocity required to move through the range of motion of the DOF in 3 s.

C. Online Virtual Task

A pseudo three-dimensional Fitts' Law task originally described by Scheme et al. [32] was used to evaluate subjects' use of simultaneous control. Subjects were instructed to move a ring cursor into annulus-shaped targets as quickly as possible. Wrist flexion/extension controlled horizontal cursor speed, supination/pronation controlled vertical cursor speed, and hand open/close controlled the speed of the change in cursor radius. To achieve the target, the cursor was required to dwell within the target for 2 s. Trials exceeding 30 s without a successful 2 s dwell, or in which the cursor overshot the target (crossed the target boundary) five times were counted as unsuccessful. Subjects were neither encouraged nor discouraged from using simultaneous control, but were told that movements could be controlled simultaneously if desired.

Multiple combinations of annulus thicknesses (W) and distance (D) were presented to the subjects (Table I). Target distance was defined as:

$$D = \sqrt{X^2 + Y^2 + R^2} \quad (3)$$

where X is the horizontal translational distance, Y is the vertical translational distance, and R is the difference in radii between the cursor starting position and the target. The index of difficulty of a given target was calculated by:

$$ID = \log_2 \left(\frac{D}{W} + 1 \right) \quad (4)$$

Three levels of target complexity were presented with equal frequency: “1-DOF targets” required use of only one DOF, “2-DOF targets” required use of two DOFs, and “3-DOF targets” required use of all three DOFs to acquire the target. For a trial with a given distance (D) and target complexity, the corresponding triplet (X, Y, R) values were chosen at random. Each of the six types of 1-DOF movements (supination/pronation, wrist flexion/extension, and hand open/close), as well as all possible 2- and 3-DOF combinations, were equally likely to be presented.

Data were collected over six experimental blocks. Subjects were provided with rest periods between blocks. Performance metrics for the Fitts’ Law test included throughput and path efficiency. Throughput (TP) was calculated by:

$$TP = \frac{1}{N} \sum_{i=1}^N \frac{ID_i}{MT_i} \quad (5)$$

where N is the number of target conditions and MT is the mean time to acquire the target condition. Path efficiency (PE) was calculated as in [23] as:

$$PE = 100\% \times \frac{\text{shortest_possible_distance}}{\text{distance_taken}} \quad (6)$$

For the trials where proportional control was provided, the shortest possible distance was the shortest straight-line path to the target. For trials using on-off control, which enforced the same velocity in each DOF, the shortest possible distance was calculated as the shortest path to the target given that multi-DOF movement must occur with equal displacements in each DOF.

Use of simultaneous control was quantified by identifying the number of EMG windows that contained simultaneous activity above 1% of maximum in two or three DOFs. Simultaneous control activity was characterized for the entire trial; trials were also partitioned into ten time deciles and simultaneous control activity was characterized for each decile.

Use of simultaneous control was evaluated in relation to the presence of proportional velocity control, and the distance and width of the targets. The differences in use of simultaneous or sequential control within a given experimental trial were also characterized.

Cursor dynamics (average cursor velocity and average distance to the target) were calculated for EMG windows where subjects used either simultaneous or sequential control.

D. Statistical Analysis

All sample means are reported $\pm$ standard error. Significance was evaluated at $\alpha = 0.05$.

The difference in completion rates between the experimental sessions with and without proportional velocity control was evaluated using a paired t-test. The differences in throughput, path efficiency, and use of simultaneous control were evaluated between (a) the experimental session with proportional control and (b) the session with on-off control, using repeated measures ANOVA. The ANOVA models included the following factors: target complexity, presence of proportional control, and an interaction term. The effects of target distance and width on simultaneous control use was also evaluated using a repeated measures ANOVA with the following factors: target complexity, target distance, target width, and all interactions. The relationship between use of simultaneous control and the cursor dynamics (velocity and distance to target) was evaluated using a repeated measures ANOVA with the following factors: target complexity, use of simultaneous control, and an interaction term.

III. Results

Subjects commented that control was more difficult using the on-off control system. Additionally, success rates between the two experimental sessions were significantly different ($p < 0.001$). With proportional velocity control, subjects were able to successfully acquire $99.9\% \pm 0.1\%$ of targets without timeout or overshoot penalties. However, average trial success was $93.1\% \pm 0.6\%$ for on-off control. Fitts' Law performance metrics also differed between the two control schemes (Fig. 2, Table II). Subjects exhibited a statistically greater throughput and path efficiency when provided proportional velocity control than with on-off control ($p < 0.05$). Other significant factors in the ANOVA models predicting Fitts' Law performance metrics included subject (path efficiency only, $p < 0.05$) and the DOF-complexity of the target (both metrics, $p < 0.001$).

Subjects' activation of two or three simultaneous DOFs differed depending on whether proportional velocity control was present (Fig. 3, $p < 0.001$). When proportional velocity control was present, subjects used simultaneous control during $40.0\% \pm 2.9\%$ of the 2-DOF trial durations and $36.6\% \pm 4.2\%$ of the 3-DOF trial durations. For 3-DOF targets, simultaneous control of all three DOFs made up $13.4\% \pm 5.7\%$ of all simultaneous activity. However, with on-off control, subjects primarily activated DOFs sequentially. Subjects simultaneously activated DOFs during only $10.8\% \pm 2.9\%$ of 2-DOF trial durations and $8.3\% \pm 2.7\%$ of 3-DOF trial durations. Other significant factors in the ANOVA models predicting use of simultaneous control included DOF complexity of the target ($p < 0.001$) and the interaction term between proportional velocity control and target complexity ($p < 0.001$).

Given the lack of simultaneous control used with on-off control, the analysis of how subjects voluntarily used simultaneous control was limited to when proportional velocity control was

present. This is also a more clinically relevant myoelectric control scheme, as most systems now provide proportional velocity control. Subjects' use of simultaneous control during a trial varied with the distance and width of the target annulus (Fig. 4). When targets were placed farther from the starting cursor position, subjects used simultaneous control more frequently ($p < 0.01$). Additionally, subjects used more simultaneous control when the target width was greater ($p < 0.001$). There was no significant interaction term between target distance and width in the ANOVA model. Other significant factors in the model predicting the use of simultaneous control included subject ($p < 0.001$), the DOF-complexity of the target ($p < 0.001$), and an interaction term between distance of the target and the DOF-complexity of the target ($p < 0.05$).

Subjects' use of simultaneous control followed a characteristic pattern (Fig. 3A). For 1-DOF targets, subjects primarily used one DOF at a time, with occasional simultaneous activation of two DOFs. For 2- and 3-DOF targets, simultaneous control use increased and peaked during the first half of the trial. Subjects then completed the second half of the trial with an increased use of sequential DOF control. When subjects used simultaneous control, the cursor was, on average, farther from the target than when they used sequential control (Fig. 5A, $p < 0.001$). Subjects also moved the cursor at greater overall velocities when using simultaneous control than when using sequential control (Fig. 5B, $p < 0.001$). Other significant factors in the ANOVA models predicting the distance from target and cursor velocity during use of simultaneous control included subject (velocity only, $p < 0.05$), and the target complexity (both metrics, $p < 0.05$).

Subjects rarely experienced coactivity of opposing movements (occurred only $1.0\% \pm 0.4\%$ of the time). Subjects were therefore able to access the full dynamic range of velocities with appropriate proportional perception (strong contraction results in high velocity) when proportional control was provided.

IV. Discussion

The current study explored the voluntary use of simultaneous myoelectric control for a 3-DOF wrist/hand system in a virtual environment. The results of this study indicate that the characteristics of the myoelectric control strategy provided, as well as the properties of the tasks being performed, have the potential to influence subjects' choice of whether or not to use simultaneous control. This was indicated most notably by the significantly reduced use of simultaneous control with constant velocity (on-off control) compared to proportional control (Fig. 3). Both experimental conditions (proportional velocity control and on-off control) allowed subjects to activate DOFs simultaneously, and therefore provided the opportunity to acquire targets more efficiently than if sequential control of DOFs had been enforced. When subjects were required to use a constant velocity, subjects relied heavily on sequential DOF control. However, when proportional velocity control was available, subjects used approximately four times as much simultaneous-DOF movements to acquire targets. The results of this study highlight an important consideration for simultaneous control of myoelectric prostheses: the potential benefit of providing simultaneous control may be affected by other characteristics of the myoelectric control system. More real-time evaluations of proposed simultaneous control strategies are therefore needed, which should

include an evaluation of whether subjects choose to use the simultaneous control that is provided.

In the current study, differences in trial completion rates and in Fitts' Law performance metrics (Fig. 2) suggested that constant velocity control produced a myoelectric control system that was more challenging to use. This result was consistent with previous literature comparing on-off control and proportional control [25, 26], and is significant given the sparse literature explicitly controlling these two types of velocity control. Possible reasons for the decreased use of simultaneous control during on-off control include the subjective difficulty experienced, the decreased ability to produce fine movements, or the difference in the perceived naturalness/intuitiveness of control [26]. Such results are consistent with previous reports [23], which demonstrated little use of simultaneous control with a myoelectric control system concluded to be less natural and intuitive than other methods of cursor control, and which also produced lower throughputs and path efficiencies than either control system reported in this current study. Future studies should therefore focus on identifying with greater detail factors that may influence a user's willingness to use simultaneous control.

Subjects also modified their use of simultaneous control depending on properties of the target task (Fig. 4). Subjects used greater levels of simultaneous control when cursor placement did not need to be as precise (larger target radius), or when greater distances needed to be traveled. Interestingly, these trends also held for 1-DOF targets, for which use of simultaneous control could only be detrimental to performance. The increased target width and the opportunity to correct movement errors over longer target paths likely allowed subjects to be less careful in isolating 1-DOF movements. Also of note, different levels of simultaneous control were used for targets with the same index of difficulty, but different widths/distances, e.g., ($D = 40$, $W = 10$) and ($D = 80$, $W = 20$). As in previous similar studies in able-bodied subjects, these results highlight that while Fitts' Law analysis provides useful summaries of performance, it is also informative to independently consider the effects of target width and distance on how users accomplish a task [28].

These patterns of simultaneous control use for different target widths and distances reflect a general strategy of how simultaneous control was used throughout the duration of the tasks. Subjects were likely to use simultaneous and sequential control at different times throughout a trial and for different purposes. Similar to previous reports of simultaneous myoelectric control of individual fingers [9], simultaneous wrist/hand activity was concentrated within the first half of the trial duration (Fig. 3A). Compared to use of sequential control, subjects used simultaneous control when the cursor was farther away from the target (Fig. 5A), and moved the cursor at overall higher velocities (Fig. 5B). These characteristics reflect the use of simultaneous control to grossly position the cursor in the general vicinity of the target. In contrast, sequential control was more likely to be used later in the trial for smaller corrective movements. This general strategy for cursor placement is similar to that used by individuals with intact limbs; subjects began with a high-velocity phase, followed by a deceleration phase where subjects used slower velocities to accurately place a stylus in the target [28].

How subjects used simultaneous control in this experiment has implications on the design and testing of simultaneous myoelectric control strategies. Subjects frequently used sequential control for fine-corrections, suggesting that design of simultaneous control systems should also focus on easy isolation of 1-DOF movements when desired, in addition to providing control of multiple DOFs simultaneously. Future studies should evaluate for isolation of 1-DOF control, such as by explicitly evaluating performance criteria for both multi-DOF and 1-DOF tasks. In addition, the differences in simultaneous control use for different target distances and widths indicate that control should be evaluated for tasks that require both large and small movements with the prosthesis, and in tasks that require both high and low levels of endpoint precision.

This study is limited by the use of able-bodied subjects performing a task in a virtual environment, as user's control strategies (including use of simultaneous and/or proportional control) may be different for amputees or when interacting with a physical environment. Future studies should extend this work to evaluate use of simultaneous control of a prosthesis by subjects who have an upper limb amputation. The ability to implement such a study will be possible as implantable myoelectric recording devices become more readily available [29]. This study was also limited to a single five-hour experimental session for each control system. Future studies should also investigate whether learning over multiple experimental sessions changes the degree of voluntary use of simultaneous control. Additional studies should also explore in greater detail the control system-specific and task-specific factors that influence how subjects use simultaneous control. In particular, future studies should investigate whether changes in the control system parameters tested here (such as the duration of the post-processing velocity ramp, gains, and speed of the on-off controller) produce differences in the use of simultaneous control. The long duration of this experiment's sessions limited the ability to fully characterize the effects of these parameters on the use of simultaneous control. Such information will inform the development of novel myoelectric simultaneous control strategies, as well as training methods to help users take full advantage of advanced prosthesis functionality.

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Fig. 1.

Configuration for parallel dual-site control. An agonist/antagonist muscle pair was used to control the output velocity for each DOF. For each muscle, the MAV was calculated from the EMG and was conditioned by a linear gain and threshold. When proportional velocity control was present, the difference in the conditioned signals determined the velocity of the DOF (V_{Prop}) by Eq 1. When proportional velocity control was not present, V_{Prop} was transformed to a constant velocity output (V_{Const}) by Eq 2. The muscles used included a pair of rotators: pronator teres and supinator; a wrist flexor and extensor: flexor carpi radialis and extensor carpi radialis longus; and a finger flexor and extensor: flexor digitorum profundus and extensor digitorum communis.

Fig. 2.

Fitts' Law analysis of user performance with both myoelectric control systems. Empirical Fitts' Law regression models for (A) proportional velocity control and (B) on-off control. A linear relationship was observed between completion time and index of difficulty for all three target complexities. (C) Difference in throughput between the two control systems. Percent differences reflect the increase in throughput observed when using proportional velocity control compared to on-off control, and were averaged across subjects. Significantly greater throughput ($p < 0.05$) was present when subjects had proportional velocity control for all target complexities. (D) Difference in path efficiency between the two control systems. Percent difference reflects the increase in throughput observed when using proportional velocity control compared to on-off control. Significantly greater path efficiency ($p < 0.05$) was present when subjects had proportional velocity control for all target complexities. Error bars represent standard error ($N=5$).

Fig. 3.

Average use of simultaneous control versus normalized trial duration for (A) proportional velocity control and (B) on-off control. Subjects used significantly more simultaneous control when proportional velocity control was also available ($p < 0.001$). When proportional velocity control was available (A), subjects primarily used sequential control of a single DOF for 1-DOF targets. For 2- and 3-DOF targets, subjects' use of simultaneous control peaked in the first half of the trial duration. Subjects used more sequential control during the second half of the trials. Shaded region represents standard error ($N=5$).

Fig. 4.

Average use of simultaneous control as a function of target complexity and distance and width parameters. Subjects used more simultaneous control for targets that were farther away from the starting position and for targets with greater annulus widths. This general trend held across all three target complexities. Error bars reflect standard error (N=5).

Fig. 5.

Cursor dynamics as subjects used simultaneous control versus sequential control. (A) For all three target complexities, on average, subjects used simultaneous control when they were farther from the target ($p < 0.001$). (B) For all three target complexities, subjects moved the cursor at greater velocities when they used simultaneous control than when they used sequential control ($p < 0.001$). Error bars represent standard error ($N=5$).

TABLE I

Fitts' Law Target Conditions

Distance, D (normalized distance unit)	Width, W (normalized distance unit)	Index of Difficulty, ID (bits)
40	10	2.32
40	20	1.59
40	30	1.22
80	10	3.17
80	20	2.32
80	30	1.87

TABLE II

Fitts' Law Metrics for each myoelectric control system

Target Complexity	Control Method	Throughput (bits/s)	Path Efficiency (%)
1-DOF	Proportional	2.09 ± 0.12	97.1 ± 0.6
	On-Off	1.86 ± 0.10	92.9 ± 1.0
2-DOF	Proportional	0.88 ± 0.06	70.1 ± 2.1
	On-Off	0.75 ± 0.08	61.2 ± 1.8
3-DOF	Proportional	0.59 ± 0.05	56.2 ± 2.7
	On-Off	0.46 ± 0.07	47.2 ± 1.9