

THE CONTROL OF MOVEMENTS WHICH VARY IN  
ACCURACY AND COMPLEXITY

by

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## ABSTRACT

The time required to program a movement response (reaction time) has been found to be directly related to the accuracy requirements of the response (Sidaway, 1991) as well as to the number of movement segments comprising the response (Henry & Rogers, 1960). However, since many of the experiments which have manipulated response complexity have concurrently manipulated the amplitude of the entire movement (Fischman, 1984; Lajoie & Franks, 1995), it was not possible to determine which of these factors was responsible for the change in reaction time. The main purpose of the present experiment was to determine whether the time required to program a limb movement was affected by response complexity, by movement amplitude, by target size, or by some combination of these factors. To answer this question, fourteen subjects made forearm extension and extension-flexion movements of varying amplitudes in the horizontal plane, to targets of varying sizes. The kinematic properties of these movements and the muscular activity which accompanies them (measured by EMG) were also investigated to determine whether these movements were exclusively programmed prior to movement initiation or whether some programming occurred during the execution of the movement. Pre-motor reaction time was found to be dependent upon response amplitude more than it was on response complexity or target size. However, a variation in the terminal target size was found to effect the kinematics of the entire movement, while a variation in the size of the start target was found to effect the kinematics of the initial portion of the movement. In addition, subjects adopted on-line control when the amplitude of the movement was increased and when the terminal target size was decreased. Finally, subjects appeared to control the EMG activation of their muscles by pre-programming the pattern of activity prior to movement initiation as well as controlling it during movement execution.

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*To my mother,*

*For teaching me to confront challenges*

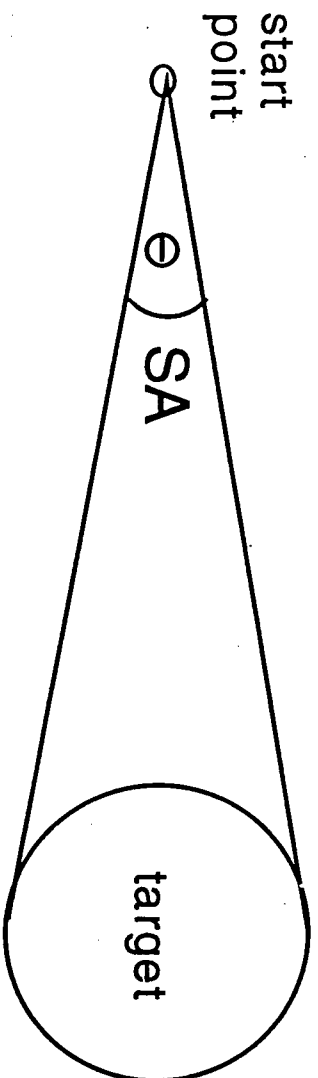
*and for listening.*

## INTRODUCTION

The time required to program a response was originally thought to be dependent upon response complexity, as defined by the number of movement segments comprising the response (Henry & Rogers, 1960). However, it has also been suggested that the accuracy demand of a response primarily determines programming time. Accuracy has previously been quantified in terms of the index of difficulty (ID) of a movement (Fitts, 1954). Relating the ID of a movement to the amplitude and target width of that movement,  $ID = \log_2(2A/W)$ , Fitts found that movement time increased with ID. Further, Fitts and Peterson (1964) found that ID also had a small but consistent effect on reaction time. In a modification of Fitts equation, Sidaway, Christina, & Shea (1988) based ID on the angle subtended (SA) by the target at the start position (figure 1),  $ID = \log_2(\cot[SA/2])$ , and hypothesized that reaction time would increase with an increase in ID.

In a further investigation of this hypothesis, Sidaway et al. (1988) re-evaluated the results of a previous study (Fischman, 1984) which found that programming time increased with an increase in response complexity. Fischman investigated straight line movements and movements which involved perpendicular directional changes under different complexity conditions. While gripping a stylus, subjects were required to contact a series of circular targets. Regardless of whether a change in direction occurred, the premotor reaction time increased as the number of movements in the response increased. However, all targets were of equal size and the distance to the final target always increased with an increase in the number of targets. Therefore, the angle subtended by the final target (at the start point) decreased as the number of targets increased. Sidaway and colleagues (Sidaway, Schoenfelder-Zohdi, & Moore, 1990) identified these factors as potential confounds in Fischman's experiment and applied a more stringent test of the ID hypothesis by manipulating both ID and the position of the highest ID target, within a series of three targets. While reaction time increased with an increase in ID, it was not affected by target position. A further test of this hypothesis

FIGURE 1



$\Theta$  = Subtended Angle as defined by  
Sidaway et al. (1988)

manipulated ID under conditions of constant response complexity (Fischman & Mucci, 1990) and also found that reaction time increased as the ID of the task increased.

In order to specifically compare the hypothesis that programming time is dependent upon response complexity to the hypothesis that predicts programming time is determined by the ID of a movement, Sidaway performed an experiment in which the number of movements was varied separately from ID (Sidaway, 1991, experiment 3). In this experiment, subjects were required to contact a series of one, two, or three targets, all of which had the same ID. This procedure was repeated with three different IDs for a total of nine movement tasks. While the premotor reaction time was found to increase with an increase in ID, it did not increase when the number of movements increased. While these results supported Sidaway's ID hypothesis, the response complexity hypothesis was not supported despite the fact that other experiments have found a complexity effect to exist for tasks in which ID was held constant (Canic & Franks, 1989; Garcia-Colera & Semjen, 1987; 1988; Hulstijn & van Galen, 1983; Lajoie & Franks, 1995).

The majority of research which has investigated the effect of ID on reaction time has utilized a straight line target tapping task (Fischman & Mucci, 1990; Gordon & Christina, 1991; Sidaway, 1991; Sidaway et al., 1988; Sidaway et al., 1990), such as that used by Fischman (1984). However, two experiments have utilized reversal movements (Fischman & Yao, 1994; Lajoie & Franks, 1995) in which the first target was placed farther away from the start position than were the subsequent targets. After contacting the first target, subjects reversed the direction of their movement to contact the second target. Fischman and Yao found that the reaction time for a single movement was faster than that for a reversal movement and they concluded that ID was likely not the sole crucial element that determined programming time in their particular task. However, since the subtended angle is defined by the total distance from the start position to the target (Sidaway et al., 1988) and since all of the targets in Fischman and Yao's study were of equal size, the ID of the task increased as the number of movement segments increased. Therefore, it is not possible to determine whether

response complexity or ID was responsible for the increase in reaction time.

In contrast, Lajoie and Franks (1995) varied the number of movement segments in a response under conditions of constant ID. Specifically, subjects made single and reversal arm movements by moving a hand held stylus across a computer screen in the horizontal plane. In the single movement condition, subjects made a rightward movement to a high or a low ID target. In the reversal movement condition, subjects first made a rightward movement to the low ID target and then reversed direction to contact a second target which had either a high or a low ID. When both targets had a low ID, the size of the second target was greater than that of the first, such that the ID of the second target was equal to that of the first target; ID was calculated as the total distance from the start position to the target. The reaction time for the reversal movement condition was greater than that for the single movement condition. In addition, the reaction time was found to increase when the ID of the task increased, regardless of whether the accuracy constraints were imposed by the first or the second target. These results provided support for Sidaway's ID hypothesis as well as for the original response complexity hypothesis proposed by Henry and Rogers (1960).

Previous experiments which have supported the response complexity hypothesis (Henry & Rogers, 1960) have typically maintained the initial movement segment of the response constant across changes in response complexity (Canic & Franks, 1989; Fischman, 1984; Garcia-Colera & Semjen, 1987; 1988; Hulstijn & van Galen, 1983, Lajoie & Franks, 1995, van Donkelaar & Franks, 1991a; 1991b). This procedural design is generally used to eliminate any variation in the electromechanical delay of the muscles (motor reaction time, Anson, 1982; 1989). If the motor reaction time remains constant across movements which differ in response complexity, then any variation in reaction time can be attributed to a change in the amount of programming time required for those movements (represented by pre-motor reaction time). However, the maintenance of a constant initial movement segment confounds the analysis for the effect of response complexity. If response complexity is increased by the addition of a second movement segment to a constant initial movement segment, then the total amplitude



and duration of the movement increases with the increase in response complexity. Further, other experiments have found reaction time to increase when the duration of the response was increased (Klapp & Erwin, 1976; Siegel, 1986). It is therefore not possible to determine whether movement amplitude or response complexity was responsible for the increase in reaction time in these experiments (Canic & Franks, 1989; Fischman, 1984; Garcia-Colera & Semjen, 1987; 1988; Hulstijn & van Galen, 1983, Lajoie & Franks, 1995; van Donkelaar & Franks, 1991a; 1991b). One method of protecting against the erroneous attribution of a variation in motor reaction time to that in the time required to program a response is to independently measure pre-motor and motor reaction time (using the onset time of the electrical activity in the agonist muscles). The present experiment measured both of these dependent variables and also separated the effects of response complexity from those of movement amplitude by using two different methods to vary response complexity. Specifically, response complexity was increased by adding a second movement segment to a constant initial movement segment and by maintaining a constant movement amplitude while increasing the number of movement segments in the response.

Since the reaction time for a movement with a high ID is longer than that for a movement with a low ID (Fischman & Mucci, 1990; Fitts & Peterson, 1964; Gordon & Christina, 1991; Lajoie & Franks, 1995; Sidaway et al., 1990; Sidaway, 1991), high ID movements require a greater amount of programming time prior to movement initiation (referred to as pre-programming). However, it does not necessarily follow that these high ID movements are exclusively pre-programmed. Rather, this increased pre-programming could be accompanied by programming which occurs after the initiation of movement, during movement execution (referred to as on-line programming). Measures which have previously been used to indicate the occurrence of on-line programming include features of the acceleration profile, such as zero line crossings and significant deviations (generally found to occur during the negative acceleration phase of a movement, Carlton, 1981; Elliott, Carson, Goodman, & Chua, 1991; van Donkelaar & Franks, 1991a, 199b), as well as movement time

(Chamberlin & Magill, 1989). However, the use of movement time as an appropriate indication of on-line programming has been disputed by some researchers (Fischman & Reeve, 1992). Recently, Lajoie and Franks (1995) investigated the occurrence of on-line programming for movements with a high ID. Although these movements had a greater movement time than did movements with a low ID, the occurrence of significant deviations for these two types of movements was similar. Further, the significant deviations which did occur did not predominate in the negative acceleration phase. Thus, Lajoie and Franks (1995) concluded that the slower, more precise movement trajectory of the high ID movements had been pre-programmed.

Another method of investigating the extent to which movements are pre-programmed is to manipulate the size of the second target of a two segment response while maintaining a constant size of the first target. If the ID of a movement affects the kinematics of that movement and if both segments of a two segment response are pre-programmed, then a manipulation of the second target size will affect the kinematics of both the first and the second movement segments. Experiments by Adam, Paas, Eyssen, Slingerland, Bekkering, & Drost (1995), Sidaway, Sekiya, & Fairweather (1995), and Lajoie & Franks (1995) found that the first segment of a two segment response took a longer time to complete when the size of the second target decreased and the size of the first target was held constant. These results were used to support the hypothesis that the movements in each of these experiments had been pre-programmed. The present experiment extended this investigation of the programming of high ID movements by independently analyzing the effects of amplitude and target size on the movement kinematics and pre-motor reaction time.

In addition, the present experiment was designed to investigate the effects of amplitude and target size on the electrical activation patterns of the primary muscles involved in forearm movements (triceps and biceps). Muscular activation patterns can be grouped into two general categories: reciprocal innervation and co-contraction (Ghez, 1991). First, in reciprocal innervation, movement is initiated by a contraction of the agonist muscle and a simultaneous

relaxation of the antagonist muscle. The movement is then slowed to a stop by a contraction of the antagonist muscle with a simultaneous relaxation of the agonist. Finally, a second burst of electrical activity often occurs in the agonist muscle in order to clamp the movement (Enoka, 1994, p.251). Since movements which reverse on a target often lack this second agonist burst (Enoka, 1994, p.14), the time required to produce this burst has previously been hypothesized to be responsible for the increase in movement time which occurs for movements which terminate on a target, as compared to those which reverse on a target (Adam, van de Bruggen & Bekkering, 1993; Lajoie & Franks, 1995). However, neither of these experiments measured EMG in order to test this hypothesis. The present experiment measured EMG and investigated the stopping processes of both discrete and reversal movements.

In the co-contraction muscular activation pattern, both the agonist and the antagonist muscles contract at movement onset. Movement is initiated as the force produced by the agonist muscle contraction is greater than that produced by the antagonist muscle contraction. Similarly, to slow the movement down, the antagonist muscle contracts with a greater force than does the agonist muscle. In the present experiment, the co-contraction and reciprocal innervation strategies were investigated to determine if a variation in movement amplitude or target size would alter the rate of occurrence for either of these strategies.

The EMG profile of the agonist muscle has previously been used to describe a set of rules or strategies for controlling voluntary movements (Gottlieb, Corcos, & Agarwal, 1989). Specifically, these researchers searched for regularities in the slope and the height of the initial agonist burst and then attributed these regularities to control strategies utilized by the central nervous system. Two distinct strategies for initiating movements to defined targets were discovered. First, a speed-sensitive strategy was utilized when a subject specifically controlled the speed or movement time of a movement. This strategy applies to movements with varying target sizes as accuracy constraints were suggested to implicitly control movement speed (Gottlieb et al., 1989). The rate of rise in the initial burst of agonist EMG activity was found to vary dependent upon the target size of the task; the slope increased with an increase in target

size. Second, a speed-insensitive strategy was utilized any time the subject did not specifically control the speed of a movement. This strategy applies to movements with varying amplitudes and the slope of the initial burst of EMG activity was found to remain constant regardless of movement amplitude. However, movements with greater amplitudes reached a higher peak EMG than did movements with smaller amplitudes.

Although Gottlieb and colleagues (1989) found regularities to exist in their EMG data, it does not necessarily follow that the nervous system explicitly uses these regularities as strategies to control movement. The main question concerns whether these strategies are, in fact, different. It is likely that saturation plays a role in the speed-insensitive strategy. The similar slope of the initial agonist burst activity for the variation in movement distance is a steep slope. Further, the mechanical limitations of muscle restrict the maximum rise of EMG activity that can be reached. Once this maximum slope is reached, the only way to increase the overall force of a contraction is to increase the height of the EMG activity, since the force of a movement is related to the area under the EMG curve (Enoka, 1994, p.168). If saturation explains the speed-insensitive strategy, then Gottlieb's two strategies do not differ; both strategies relate to an increase in force due to a variation in an independent variable.

To test the speed-insensitive strategy, Gottlieb and colleagues (1989) compared movements of different distances under conditions of a large target size. Further, these authors found that a large target size related to a steep slope in the initial agonist burst activity. More support for the existence of two distinct strategies could be found if different distances produced a variation in height at a consistent sub-maximal slope. One way to explore this possibility would be to compare the agonist EMG activity of varying amplitudes under conditions of a smaller target size. In the present experiment, the agonist EMG profiles of movements which varied in amplitude were compared under conditions of both small and large target sizes.

The purpose of the present experiment, therefore, was to determine whether the time required to program a limb movement is affected by response complexity, by movement

amplitude, by target size, or by some combination of these factors. It was hypothesized that response complexity would affect the pre-motor reaction time of a response for each of the two methods used to increase complexity: (1) the addition of a second movement segment to a constant initial movement segment, and (2) increasing the number of movement segments in the response while maintaining a constant total movement amplitude. In addition, since reaction time has previously been shown to increase with an increase in index of difficulty (Fitts & Peterson, 1964; Sidaway, 1991), pre-motor reaction time was hypothesized to increase with an increase in movement amplitude and with a decrease in target size. The kinematic properties of these movements and the muscular activity which accompanies them were also investigated to determine whether they were exclusively programmed prior to movement initiation (pre-programming) or whether some programming occurred during movement execution (on-line programming). Based on the results of Lajoie & Franks (1995), it was expected that the majority of the movements in the present experiment would be pre-programmed. A decrease in the size of the second target was also hypothesized to affect the kinematics of the initial movement segment of a two segment response when the size of the first target remained constant. Finally, the present experiment investigated the muscular activation patterns of the triceps and biceps muscles during forearm extension and extension-flexion movements in addition to the slope and the height of the initial triceps EMG burst. Both the pattern of muscular activation and the profile of the initial triceps EMG burst were hypothesized to vary dependent upon the amplitude and target width of the movement task.

## METHOD

### *Subjects*

Fourteen right hand dominant volunteers participated as subjects in the present experiment. These volunteers were students at the University of British Columbia or members of the university community. All subjects received ten dollars for their participation in the experiment. In addition, to motivate the subjects to perform well, two 20 dollar prizes were awarded: one for the subject with the fastest overall reaction time and one for the subject with the fastest overall movement time. All subjects were naive to the hypothesis being tested and were inexperienced at the task. The experiment was carried out according to the ethical guidelines laid down by the University of British Columbia Behavioral Sciences Screening Committee for research and other studies involving human subjects.

### *Task and Apparatus*

Using a manipulandum, subjects made forearm extension and extension-flexion movements in the horizontal plane through a range of 60 degrees. The manipulandum consisted of a horizontal lever which had a vertical handle at one end and was attached to a bearing-mounted vertical shaft at the other. The right forearm of each subject was positioned on the lever such that the elbow was coaxial with the axis of rotation and the position of the vertical handle was then adjusted to accommodate for the length of each subject's forearm. Subjects grasped the handle with their hand in a supinated position. In order to keep the contribution from the shoulder muscles constant across all subjects, subjects were secured to their seat with a shoulder harness and their forearms were attached to the horizontal lever with Velcro straps.

The targets appeared on an oscilloscope screen that was positioned 70 cm directly in front of each subject. A 60° movement of the manipulandum was calibrated to equal a distance of 8.3 cm on the oscilloscope screen. The view on the oscilloscope screen consisted of a

response cursor and two targets. Each target was defined by two solid vertical lines drawn on a transparent overlay which was placed directly in front of the oscilloscope screen (both targets appeared on one overlay). These vertical lines were drawn accurate to within 0.005 cm. One target appeared on the left side of the screen while the other appeared either in the center of the screen (4.15 cm to the right of the left target, center to center distance) or on the right side of the screen (8.3 cm to the right of the left target). The center of each target was indicated by an illuminated dot on the oscilloscope screen and the center of the left target served as the start position (figure 2). Subjects either made an extension movement from the start position to the right target or an extension-flexion movement in which the initial extension movement was followed by a flexion movement back to the left target. Thus, subjects stopped on the right target in the extension movement, but reversed on this target in the extension-flexion movement. Both targets remained visible throughout each trial.

The angular position of the manipulandum was sampled at a rate of 1000 Hz, with the use of an optical encoder (Dynapar E20-2500-130) and a custom made computer interface card (for details see Nagelkerke & Franks, 1996). In addition, angular acceleration data were obtained from a Kistler accelerometer (type 8638B50,  $\pm 50$  G) which was positioned at the end of the horizontal lever, 42 cm from the axis of rotation. The signal from the accelerometer was filtered with a 50 Hz active lowpass filter (Krone-Hite, #3750) and sampled at 1000 Hz.

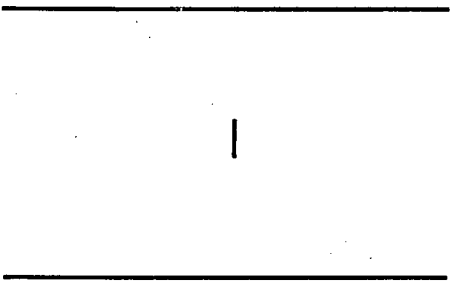
Electrical activity from the right triceps brachii and biceps brachii muscles was measured with the use of Ag/AgCl surface electrodes (8 mm diameter). A multichannel electromyographic (EMG) system (model 544, Therapeutics Unlimited Inc.) amplified the electrical signal from the two sets of surface electrodes (maximum  $\pm 10$  V). The EMG data were then sampled at a rate of 1000 Hz.

### ***Experimental Conditions***

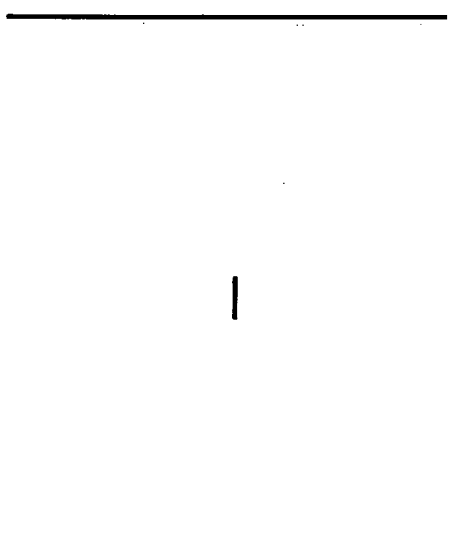
Four independent variables were manipulated: response complexity, movement amplitude, left target width, and right target width. Response complexity was varied by

FIGURE 2: Targets on oscilloscope screen  
(small left target, large right target)

left target  
(start target)



right target





manipulating the number of movement segments in the response. Subjects made forearm extension movements (E, one response segment) as well as forearm extension-flexion movements (EF, two response segments). These movements were made with an amplitude of either 30° or 60°, defined from the center of the left target to the center of the right target. In the EF condition, the amplitudes of the extension and flexion segments of the movement were equal. Finally, the left and right target widths were varied independently to be either 6° or 12°. Since a 2 x 2 x 2 x 2 repeated measures design was used, all subjects completed each of the 16 conditions.

### ***Procedure and Design***

Each subject attended one testing session which lasted approximately two hours. At the beginning of this session the experimenter described the experiment and obtained informed consent from the subject. After the subject was secured in the shoulder harness, EMG electrodes were attached to the skin over the short head of the biceps brachii muscle and over the lateral head of the triceps brachii muscle, of the right arm, following standard EMG procedures (Basmajian, 1974; O'Connell & Gardner, 1963). Prior to electrode placement, the skin at each electrode site was shaved, rubbed with an abrasive pad (to remove the dead surface layer of skin), cleaned with a solution of 91% isopropyl alcohol, and rubbed with electrode gel (Ingram & Bell Medical, Cardio-Cream) to reduce skin impedance. Each electrode was filled with electrode gel and then attached to the skin with double sided adhesive tape (Converters, Inc., #AET-250). To assist in the correct placement of the electrodes, subjects were asked to flex their biceps and triceps muscles. The electrodes were then aligned longitudinally with the direction of the muscle fibers and the electrode wires were taped to the skin to prevent any pull on the electrodes.

At the start of each condition, subjects first performed three practice trials. To establish a baseline movement time for each condition, subjects then performed three control trials in which they did not react to an imperative stimulus and were, instead, given a 10 s time frame in

which to make each movement. Finally, subjects completed seven testing trials in each condition. While the 13 trials in each condition were blocked, the order of the 16 conditions was randomized across subjects.

After each condition was completed, the transparent overlay which defined the outside lines of each target was replaced with the overlay for the subsequent condition. The experimenter then calibrated the placement of the overlay, using a display which appeared on the oscilloscope screen.

At the beginning of each trial, the response cursor and the right and left targets were visible on the oscilloscope screen. Subjects positioned the manipulandum such that the response cursor was directly over the center of the left target and indicated when they were prepared to begin the trial. A low tone of 1000 Hz served as the warning stimulus and, after a variable foreperiod of 800 - 2500 ms, a higher tone of 2000 Hz occurred. Subjects were instructed to react to the 2000 Hz tone as quickly as possible, to move as quickly as possible, and to contact the target. Further, subjects were instructed to aim for the center of each target, but not to make a secondary movement toward the center if their initial movement ended inside of the target area. The instructions also emphasized that contact with the target was a priority. At the completion of each trial, the experimenter provided the subject with verbal feedback as to their reaction time and their movement time.

Trials in which the subject did not contact one or both of the targets, made a movement which was not continuous (indicated by a pause time of greater than 50 ms in the acceleration profile), or had a reaction time which was not between 100 ms and 500 ms were discarded. This bandwidth of time was used following several pilot studies which have revealed consistent means and standard deviations for similar reaction time tasks. The discarded trials were then repeated until each subject completed three control trials and seven testing trials which met these criteria in each condition. The three practice trials were not subject to these criteria.

In the testing condition, catch trials occurred with a probability of 15%. In these trials, the variable foreperiod was extended to five seconds and no imperative stimulus occurred.

After this foreperiod, the experimenter reported the catch trial to the subject and recorded any movement as error. In cases where a subject moved on a catch trial, the subject was reminded to react only to the imperative stimulus.

### ***Dependent Variables***

The time required to program a response was measured by simple reaction time, premotor reaction time, and motor reaction time. Simple reaction time was measured from the onset of the imperative stimulus to the initiation of movement, defined as the first indication of movement on the displacement trace of the arm movement. Marking the onset of the triceps EMG activity allowed the simple reaction time to be broken down into its premotor and motor reaction time components. Premotor reaction time was measured as the time from the onset of the imperative stimulus to the onset of EMG activity and motor reaction time was measured as the time from the onset of EMG activity to movement initiation.

The onset of EMG activity was determined by the following procedure (Ketelaars, Franks, Sanderson, & Nagelkerke, 1993). First, the raw EMG signal was full-wave rectified and then filtered using a low-pass, fourth-order, zero-phase-shift Butterworth filter with a cut-off frequency of 20 Hz. Second, the experimenter was presented with two EMG signals on the computer screen: a raw, rectified EMG signal, and a raw, rectified, filtered EMG signal. A cursor was placed at the first indication of heightened EMG activity (above the baseline) on the filtered EMG signal. The placement of this cursor was then compared to the unfiltered EMG profile. In the case of a discrepancy (the filtered EMG signal sometimes indicated onset prior to the unfiltered signal), the placement of the cursor was based on the EMG onset of the unfiltered signal.

The EMG data were further analyzed by classifying the E and the EF movements into categories based upon the pattern of their agonist and antagonist bursts. The extension movements were grouped into three categories: triphasic EMG patterns (triceps-biceps-triceps, figure 3A), biphasic EMG patterns (triceps-biceps, figure 3B), and co-contraction. EMG

FIGURE 3A: Triphasic EMG Pattern, Extension Movement

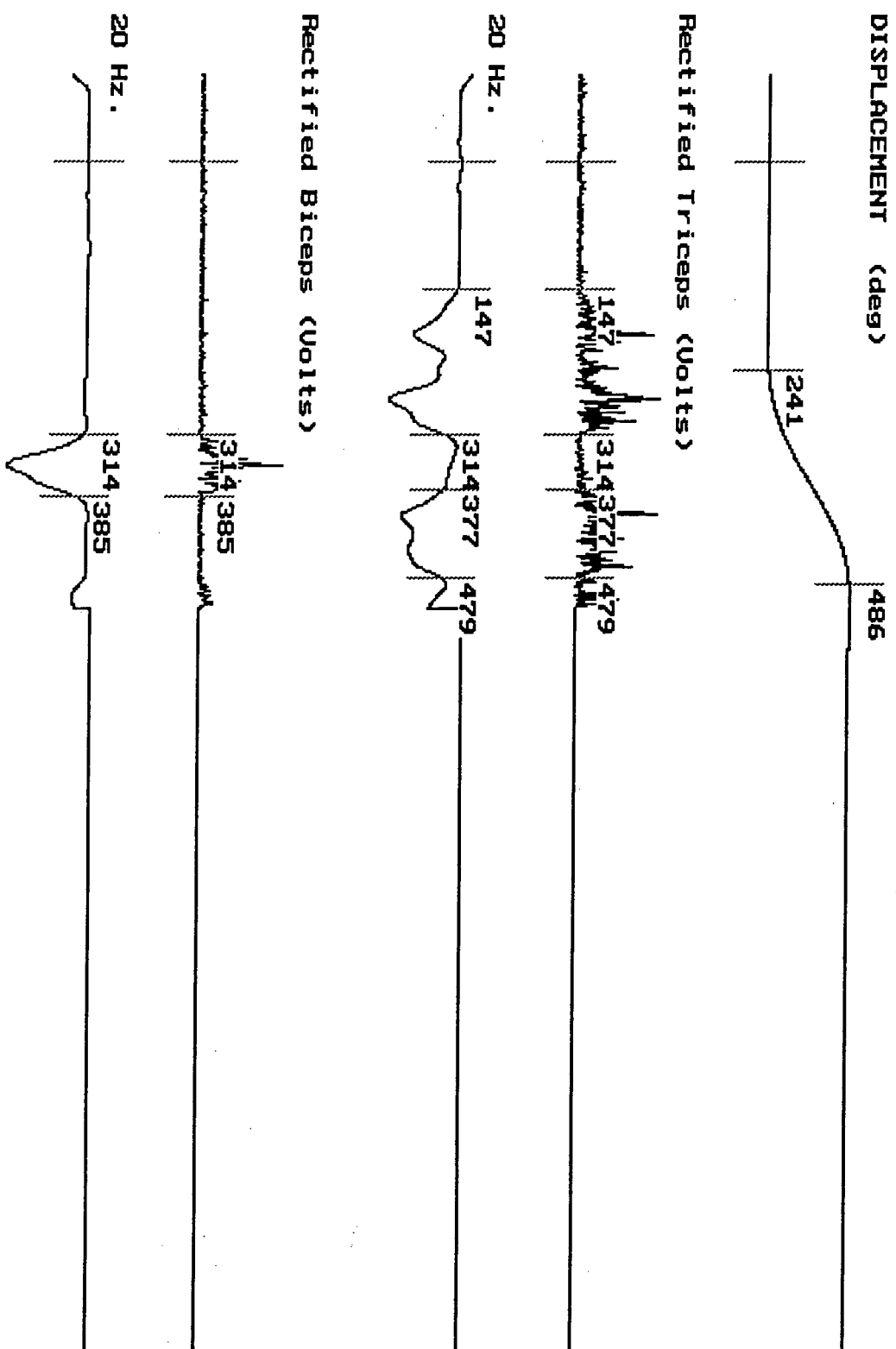
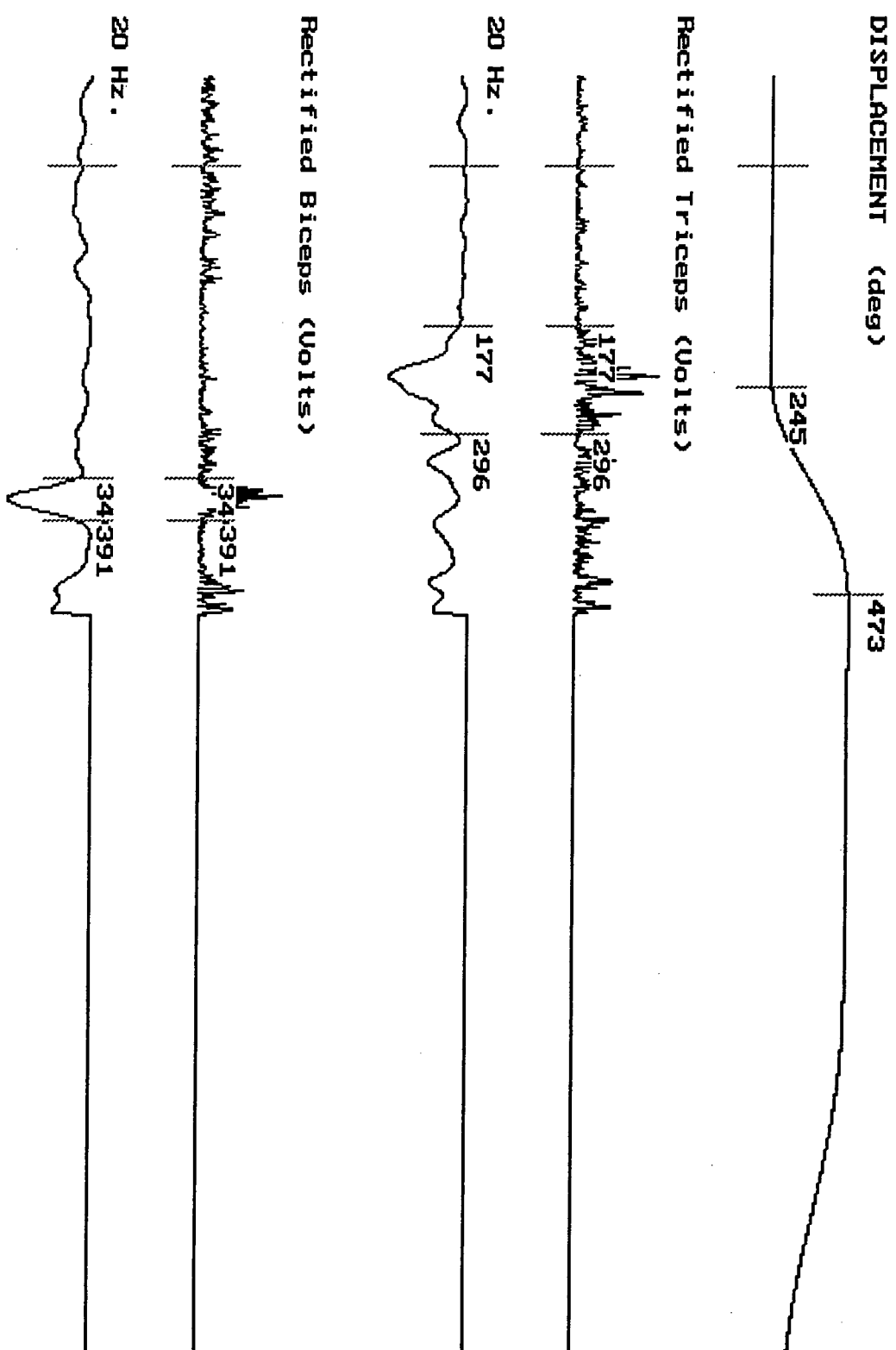


FIGURE 3B: Biphasic EMG Pattern, Extension Movement



patterns were placed in the co-contraction category if the onset of the initial biceps burst occurred prior to the peak EMG activity of the initial triceps burst (figure 3C). The extension-flexion movements were also classified into three basic categories: quadraphasic EMG patterns (triceps-biceps-triceps-biceps), triphasic EMG patterns (triceps-biceps-triceps), and co-contraction. The initial biceps burst of the quadraphasic and triphasic EMG patterns performed two functions: to slow down the initial extension movement and to initiate the flexion movement (Enoka, 1994, p.14). In some cases this burst appeared as one continuous burst, while in others it appeared as two distinguishable bursts. Thus, the quadraphasic and triphasic EMG patterns were each broken down into two sub-categories based upon the continuity of the initial biceps burst. EMG patterns with a continuous initial biceps burst were classified as quadraphasic-A or triphasic-A patterns (figures 4A and 4B, respectively), while those with a discontinuous initial biceps burst were classified as quadraphasic-B or triphasic-B patterns (figures 4C and 4D, respectively). In addition, the EF co-contraction category was split into two sub-categories dependent upon whether the co-contraction occurred at the beginning of the movement (defined the same as the E co-contraction EMG pattern) or whether it occurred in the middle portion of the movement. Co-contraction in the middle portion of an EF movement was indicated by the occurrence of an additional triceps burst near the reversal point (figure 4E). This classification scheme was used in part to identify two main strategies of movement control: co-contraction and reciprocal innervation (used in the biphasic, triphasic, and quadraphasic EMG patterns). In cases where a subject made a corrective submovement on a trial (i.e., the primary movement either overshoot or undershot the target), the pattern of EMG activity was classified according to the EMG burst pattern utilized for the primary movement only. Both the rate of occurrence of each EMG pattern (i.e., the number of trials which utilized a particular EMG pattern within each condition) and the duration of the EMG bursts within each pattern were determined. The movement control strategies were also analyzed in terms of the chronological order in which the co-contraction and the reciprocal innervation patterns occurred.

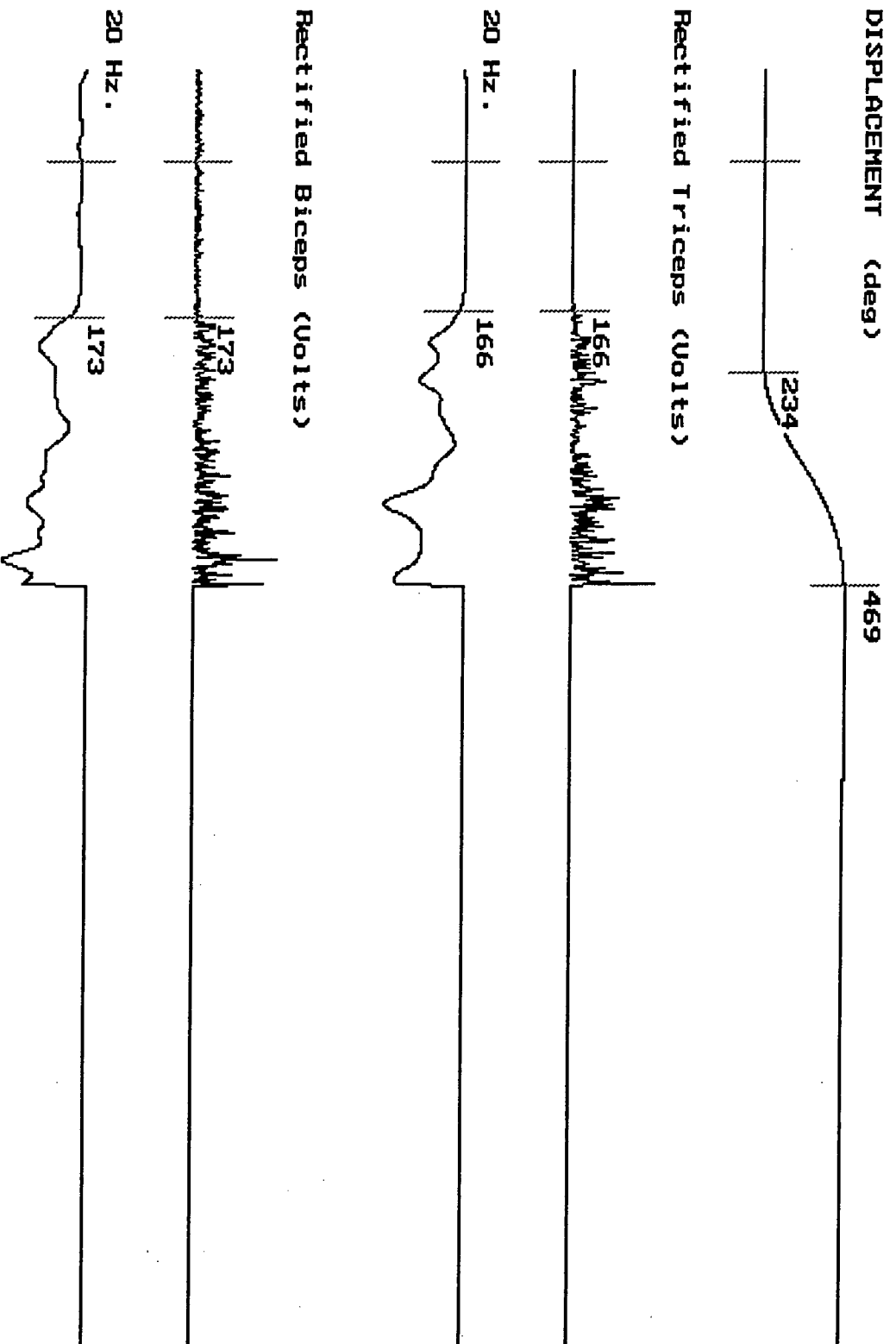
**FIGURE 3C: Co-contraction EMG Pattern, Extension Movement**

FIGURE 4A: Quadrphasic-A EMG pattern, extension-flexion movement

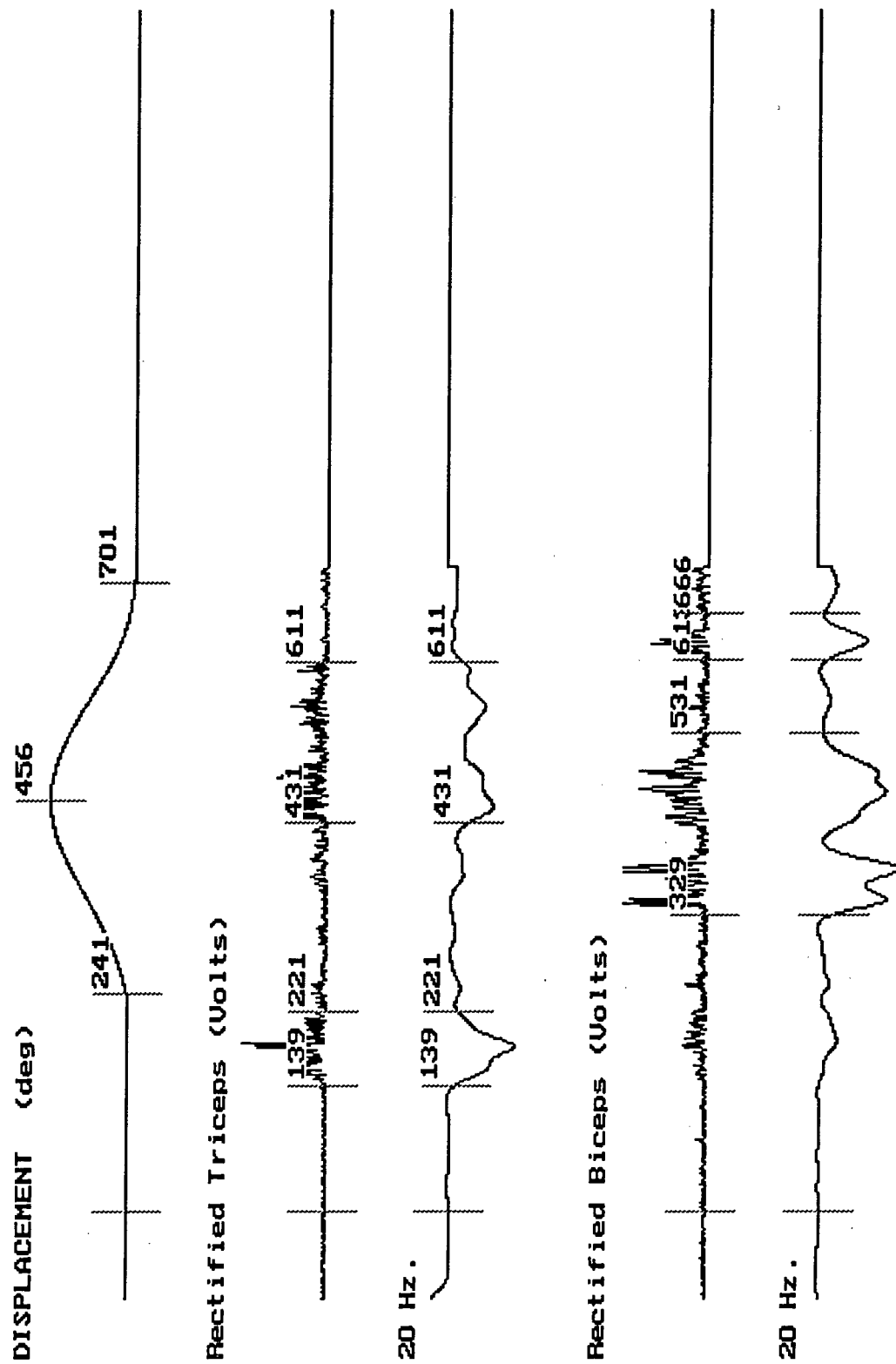




FIGURE 4B: Triphasic-A EMG Pattern, Extension-Flexion Movement

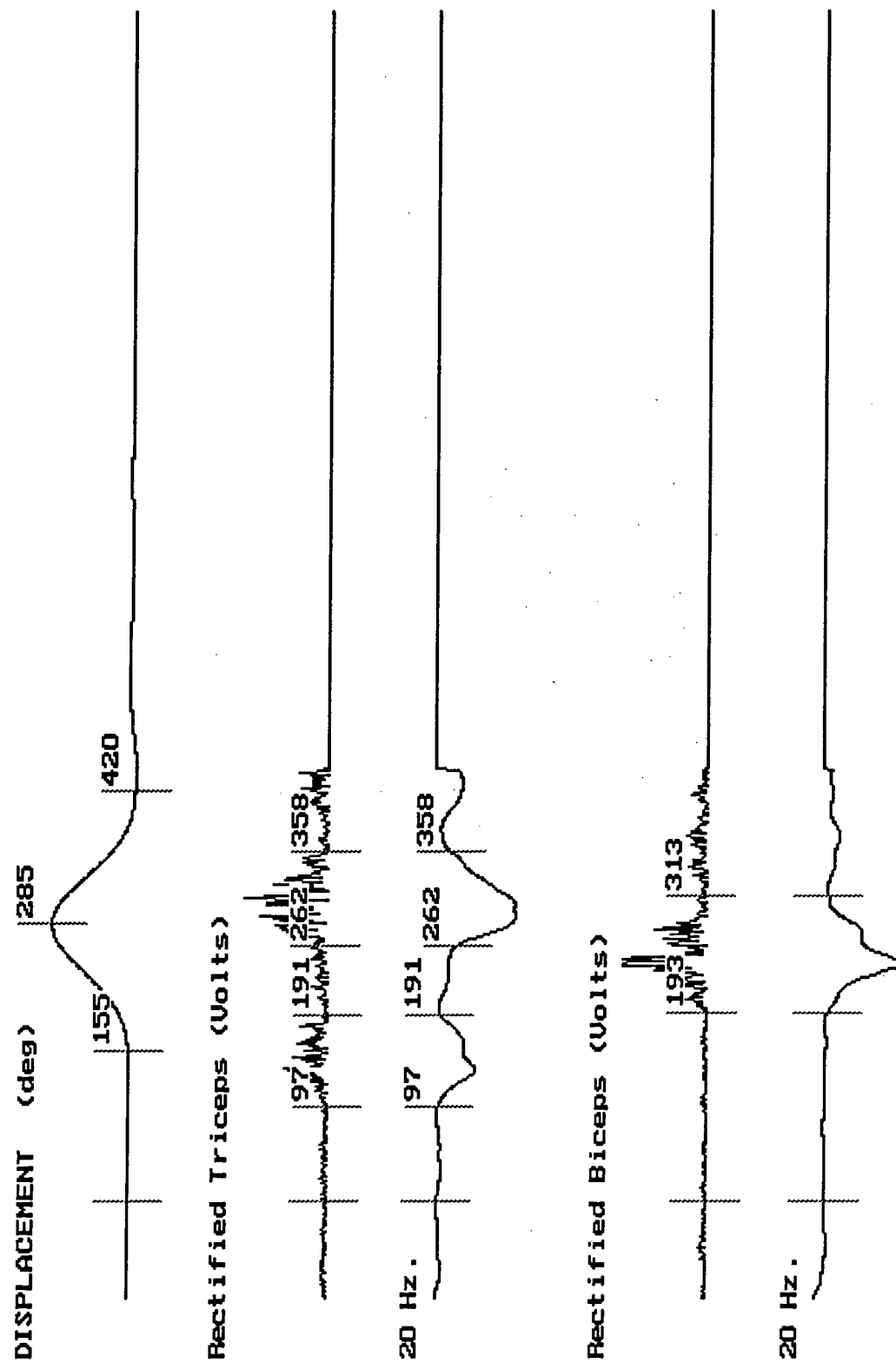


FIGURE 4C: Quadrphasic-B EMG Pattern, Extension-Flexion Movement

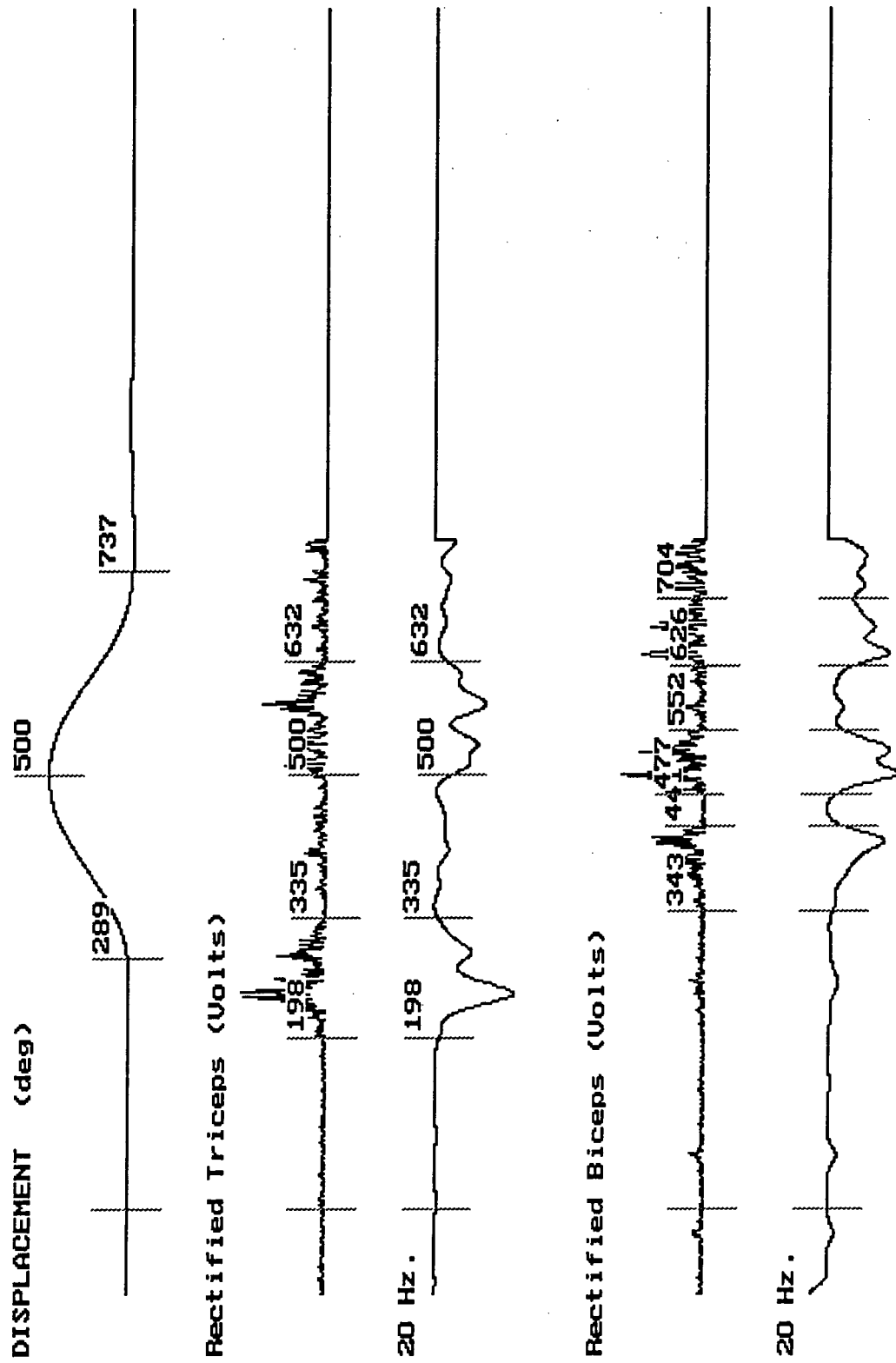


FIGURE 4D: Triphasic-B EMG Pattern, Extension-Flexion Movement

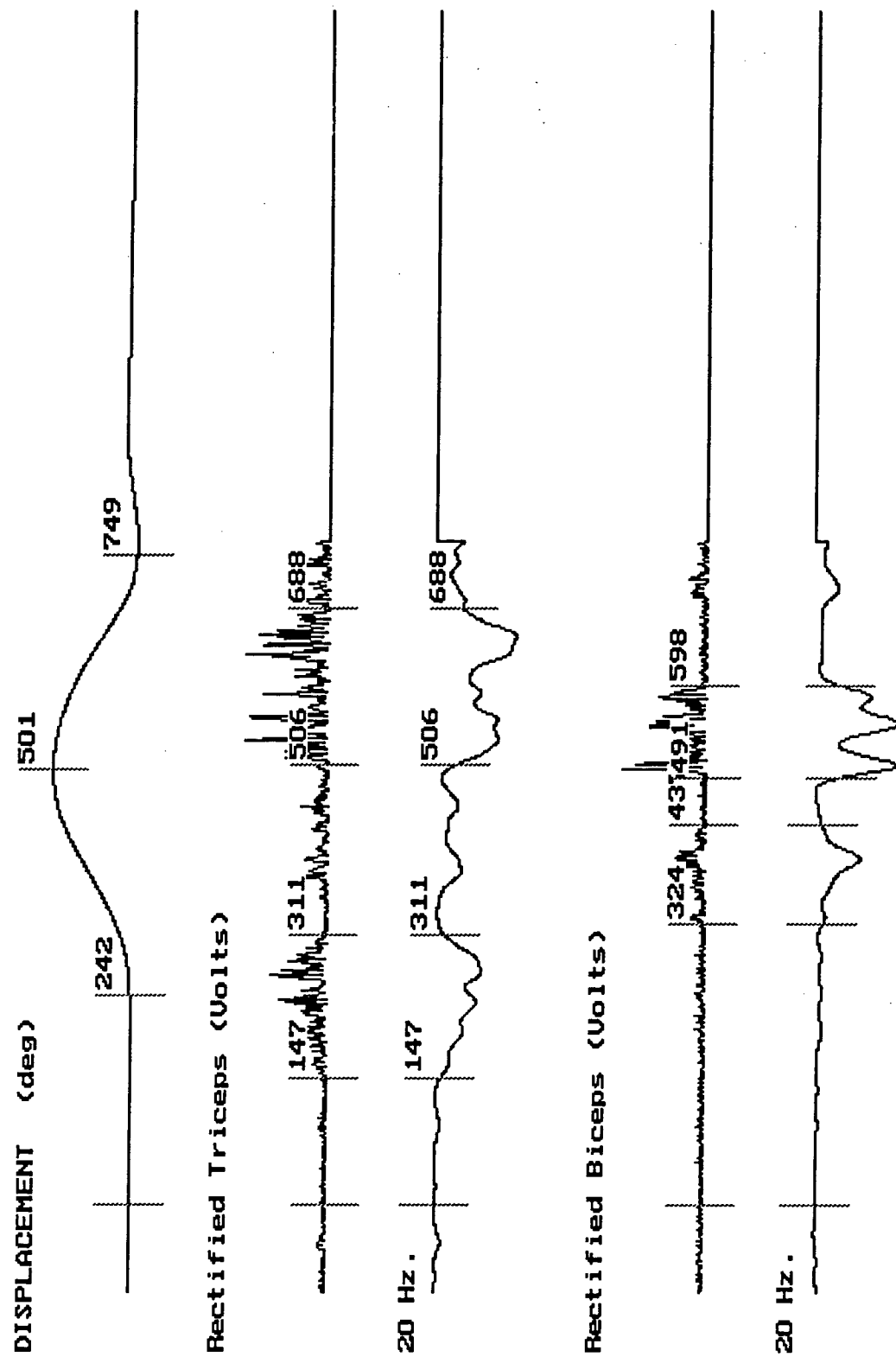
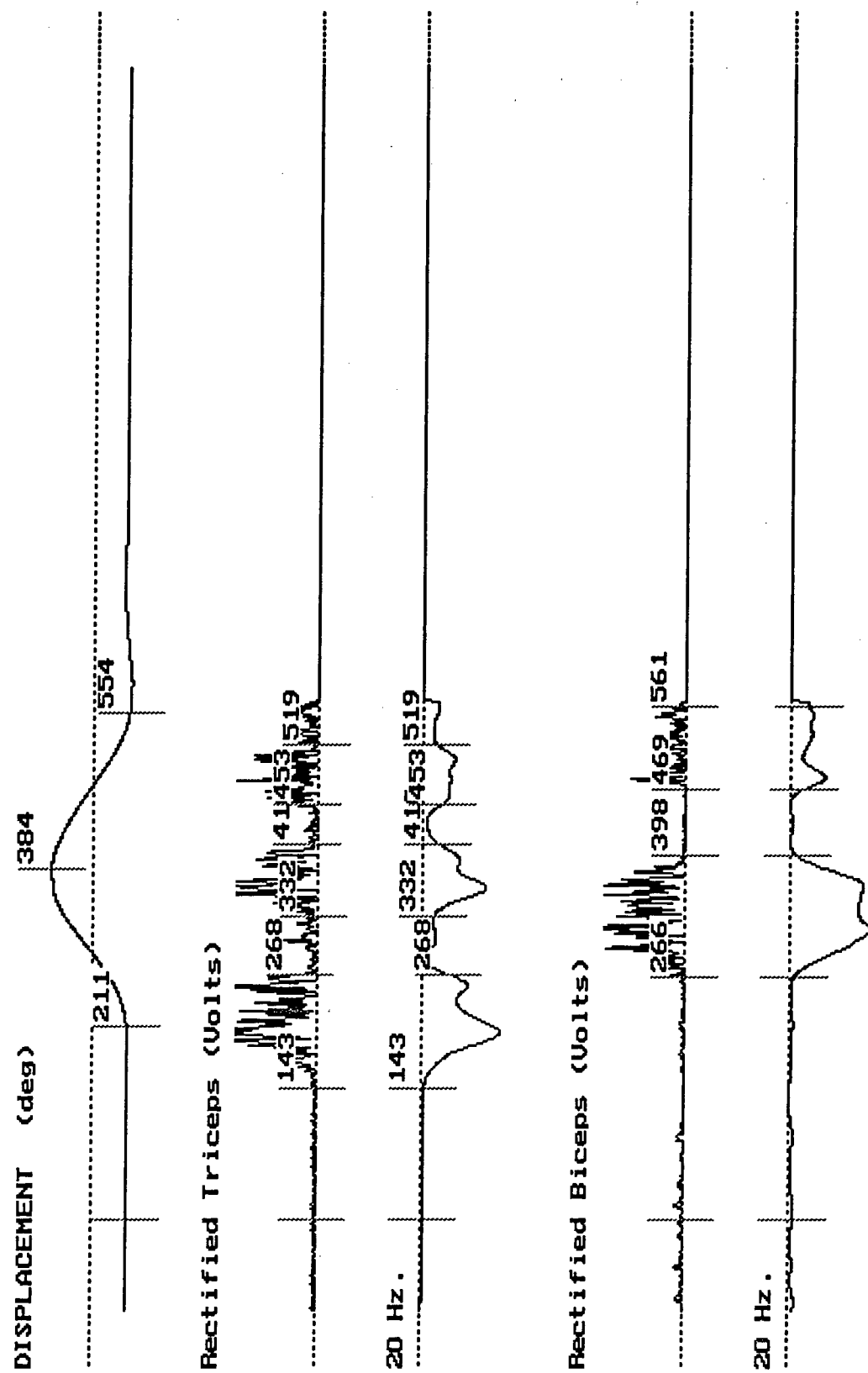


FIGURE 4E: Mid-co-contraction EMG Pattern, Extension-Flexion Movement



Finally, the filtered triceps EMG profile was analyzed in terms of the slope and the height of the initial triceps burst. Specifically, three comparisons of the triceps EMG profile were made between different experimental conditions: the 6° and 12° left target sizes (for movement amplitudes of both 30° and 60° with a 12° right target), the 30° and 60° amplitudes (for right target sizes of 6° and 12° with a 12° left target), and the 6° and 12° right target sizes (for 30° and 60° amplitude movements with a 12° left target). The evaluation of the slope and height comparisons were made visually by the experimenter. Further, these comparisons only included extension movements which used either the co-contraction or the triphasic EMG patterns. In addition, subjects were included in this analysis if they utilized one of these two EMG patterns on at least 5 of the 7 trials in the experimental condition under consideration. As per Gottlieb, a mean EMG profile was then computed from the trials performed by one subject, within one experimental condition. In the present experiment, only those trials which conformed to the EMG pattern used on the majority of the trials (at least 5) were included in the computation of the mean EMG profile. This profile was then compared to the mean EMG profile of a second experimental condition. All comparisons were made independently for each subject and subjects were placed into groups dependent upon whether they used the triphasic or the co-contraction strategy.

A number of kinematic variables were also measured in order to fully describe each movement. The time and distance of each movement was measured from movement initiation to zero velocity for the extension movements and from the point of movement reversal to zero velocity for the flexion movements. The velocity data were derived from the displacement data and the peak velocities of the extension and flexion movements were defined as the greatest positive (E) and negative (F) values on the velocity trace. Peak velocity was then used as the demarcation point between the two phases of the velocity curve. Specifically, the first velocity phase was defined as the time from movement initiation to peak velocity for the extension movements and as the time from the point of reversal to peak velocity for the flexion movements. The second velocity phase was defined as the time from peak velocity to the time

at which velocity equaled zero for each movement.

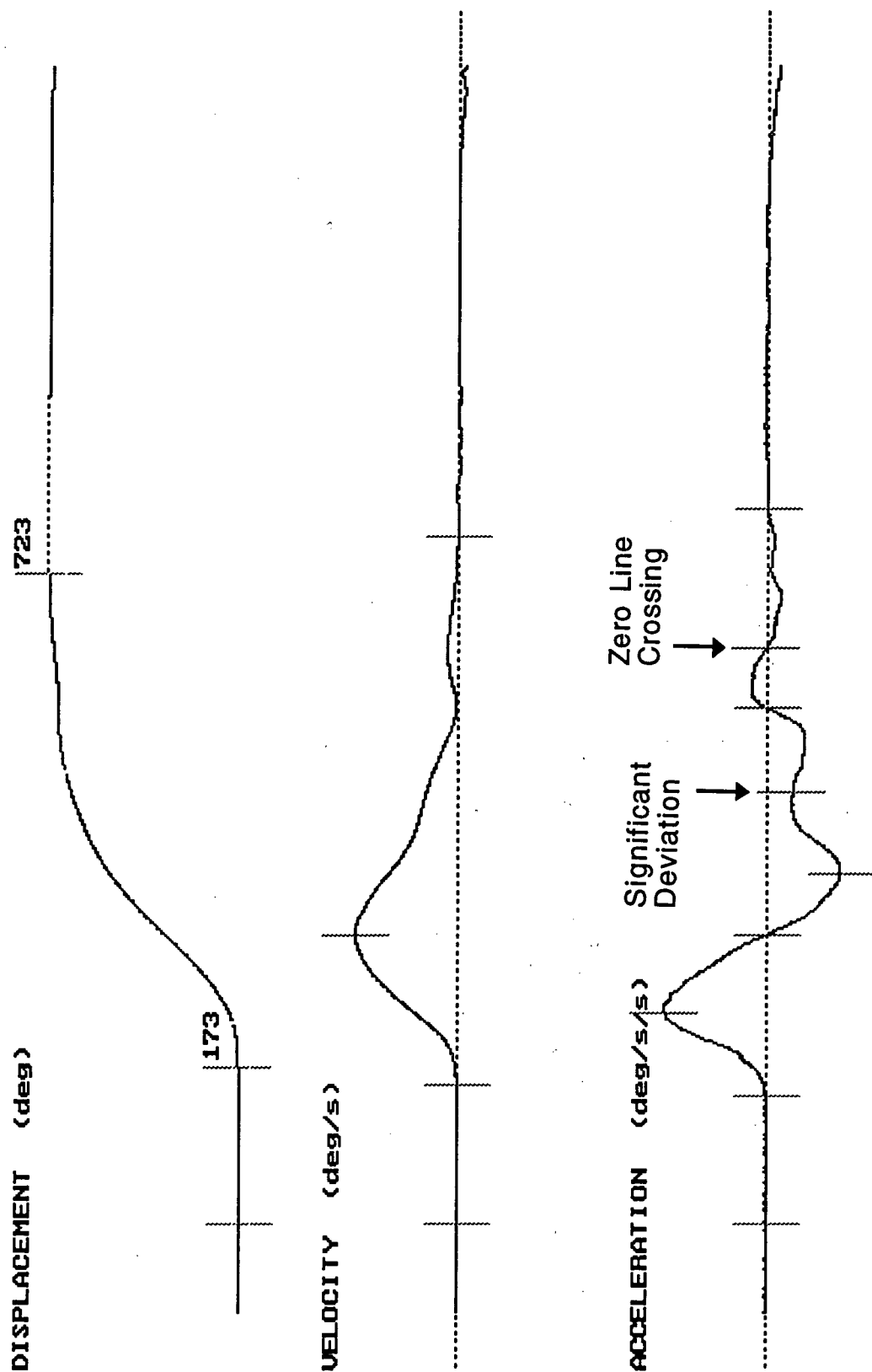
The acceleration data were obtained from the accelerometer and the peak acceleration was defined as the largest positive value on the acceleration curve for both the extension and the flexion movements. The time from movement initiation to peak acceleration was also measured for each movement. In addition, features of the acceleration profile such as zero line crossings and significant deviations were used to indicate the occurrence of on-line control. A zero line crossing was counted each time the acceleration profile crossed the zero line, either from positive to negative acceleration or from negative to positive acceleration (figure 5). Significant deviations were defined as a 'peak' or a 'valley' between consecutive maximum points of positive or negative angular acceleration, preceded and followed by at least 20 data points (20 ms, figure 5). The number of significant deviations and zero line crossings were counted for both the extension and the flexion movements based upon the time frame of the velocity profile. For example, the deviations and zero line crossings of the extension movement were counted from movement initiation to zero velocity, while those of the flexion movement were counted from the point of reversal to zero velocity. Any significant deviations which occurred at the zero line were not included in the deviation data.

Finally, the point of reversal on the first target was analyzed in terms of location and variability. The mean location was expressed as the distance of the reversal point from the center of the target; points of reversal which were to the left of the center were negative, while those which were to the right of the center were positive. The variability of the reversal points was defined as the standard deviation of each subject's mean reversal point distance within each condition.

### *Analysis*

A computer algorithm was used to place markers on the displacement, velocity, and acceleration profiles, according to the definition of each dependent variable (see above). The experimenter viewed all profiles of each trial to verify the marker placement by the computer

FIGURE 5: One Significant Deviation and Multiple Zero Line Crossings  
in an Acceleration Profile



and also placed markers on the EMG data. The data from the extension movements were analyzed with a four-way, movement (2) x amplitude (2) x left target (2) x right target (2) RM ANOVA, while the data from the flexion movements were analyzed with a three-way, amplitude (2) x left target (2) x right target (2) RM ANOVA. The significance level for each analysis was set at 0.05.



## RESULTS

### *Reaction Time*

A 2 x 2 x 2 x 2 RM ANOVA performed on the simple reaction time (SRT) data indicated significant main effects of movement, amplitude, and left target size (see table 1 for ANOVA results). Specifically, SRT was longer in the extension-flexion (EF) condition than it was in the extension (E) condition and longer for the 60° amplitude than it was for the 30° amplitude (figure 6). SRT was also longer in the 6° left target size condition than it was in the 12° left target size condition, while the main effect of right target size was not significant. However, there was a significant amplitude by right target size interaction effect which indicated that the increase in SRT from 30° to 60° was greater for the 12° right target than it was for the 6° right target. All other interaction effects were not significant ( $p > .05$ ). The condition means and standard deviations for all dependent variables are presented in Appendix A.

Based on the onset time of the triceps EMG activity, SRT was broken down into its pre-motor and motor reaction time components (PRT and MRT, respectively). The ANOVA results for PRT (table 1) indicated that the EF and the 60° amplitude conditions had significantly longer PRTs than did the E and the 30° amplitude conditions, respectively (figure 7). In addition, the amplitude by right target size interaction effect was significant; the increase in PRT from 30° to 60° was greater for the 12° right target than it was for the 6° right target. For MRT, a significant main effect of both movement and left target size occurred (table 1); MRT was longer for the EF movement than it was for the E movement and was also longer for the 6° left target than it was for the 12° left target (figure 8). All other effects were not significant ( $p > .05$ ).

In order to provide a direct test of the hypothesis that index of difficulty (ID) is a determiner of reaction time (Fitts & Peterson, 1964; Sidaway et al., 1988), the 16 conditions were organized according to the ID of the first target. Using Fitts' equation,  $ID = \log_2(2A/W)$ ,

**Table 1.** ANOVA results for the dependent variables simple reaction time, pre-motor reaction time, and motor reaction time. All main effects and significant interaction effects are presented.

Effect	F-test	p-value	p < .05
<i>Simple Reaction Time (RT)</i>			
movement	$F(1, 13) = 11.054$	$p = .005$	*
amplitude	$F(1, 13) = 8.069$	$p < .014$	*
left target size	$F(1, 13) = 4.662$	$p = .05$	*
right target size	$F(1, 13) < 0.001$	$p = .985$	
amplitude x right target interaction	$F(1, 13) = 5.836$	$p = .031$	*
<i>Pre-motor Reaction Time (PRT)</i>			
movement	$F(1, 13) = 5.22$	$p = .04$	*
amplitude	$F(1, 13) = 9.13$	$p = .01$	*
left target size	$F(1, 13) = 1.129$	$p = .307$	
right target size	$F(1, 13) = 0.1$	$p = .757$	
amplitude x right target interaction	$F(1, 13) = 5.073$	$p = .042$	*
<i>Motor Reaction Time (MRT)</i>			
movement	$F(1, 13) = 75.398$	$p < .001$	*
amplitude	$F(1, 13) = 0.157$	$p = .698$	
left target size	$F(1, 13) = 11.286$	$p = .005$	*
right target size	$F(1, 13) = 2.707$	$p = .124$	

FIGURE 6: Simple Reaction Time

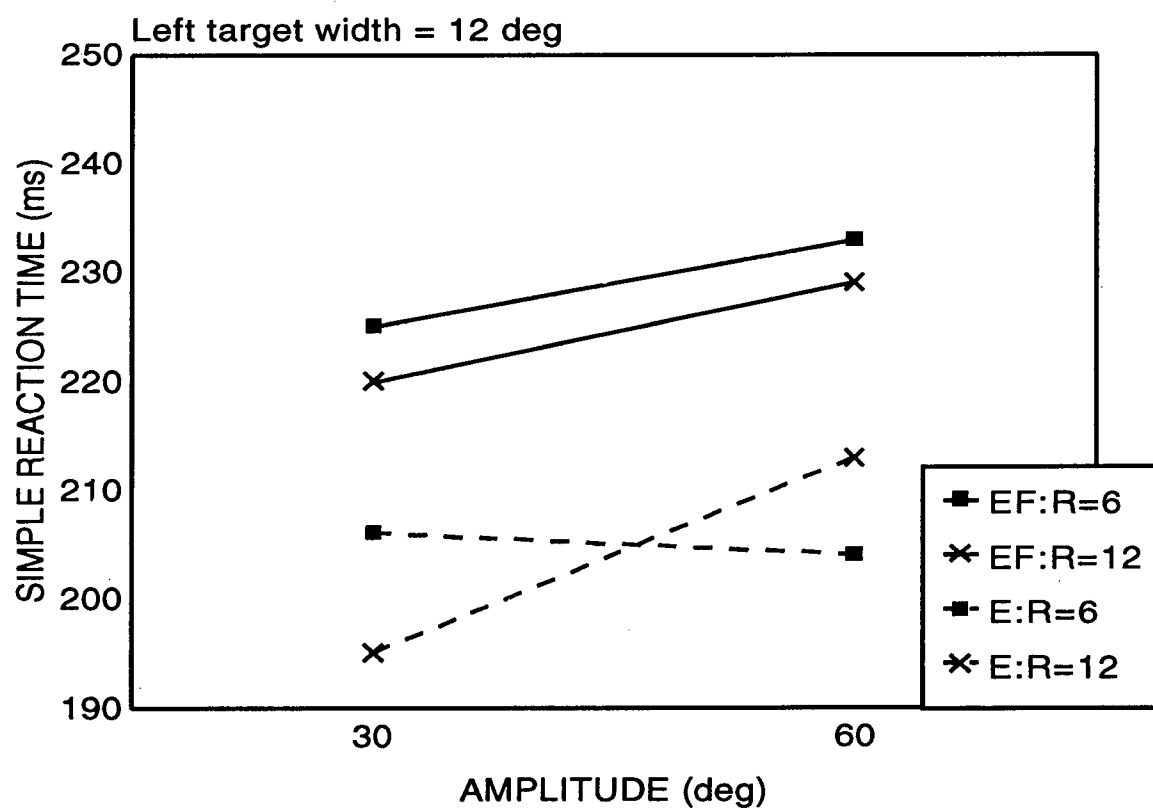
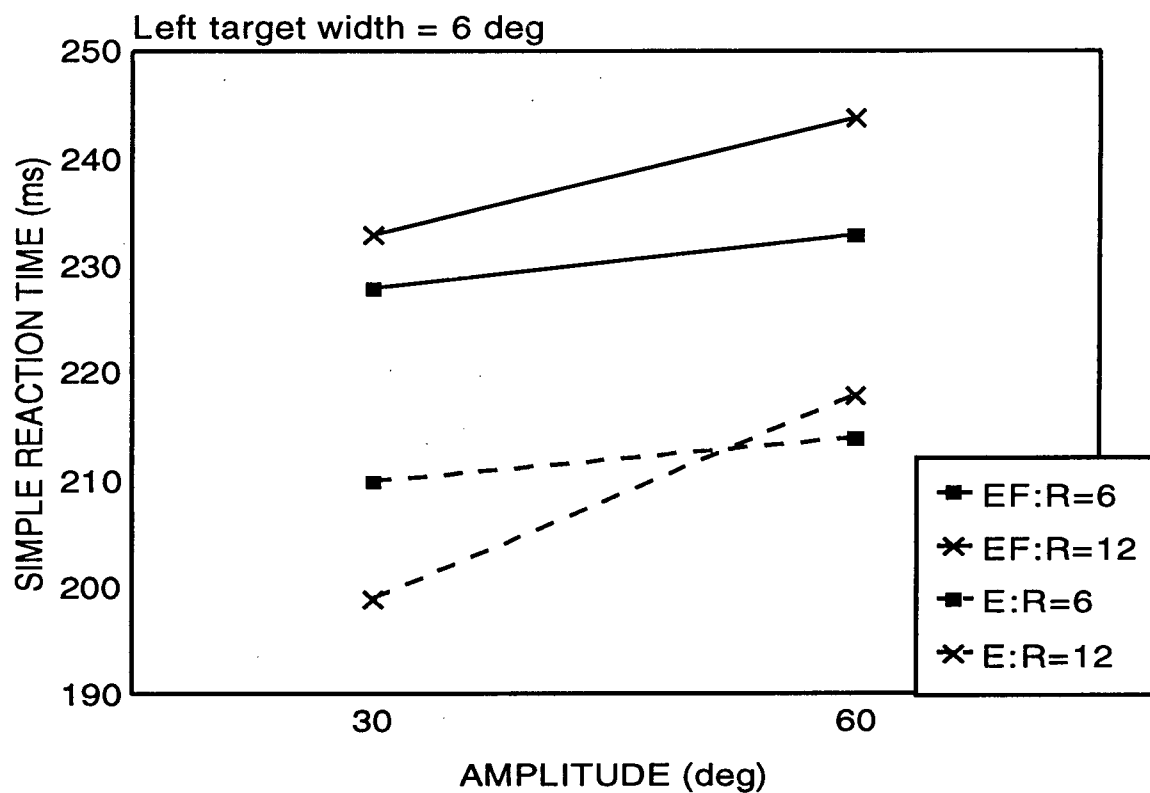


FIGURE 7: Pre-motor Reaction Time

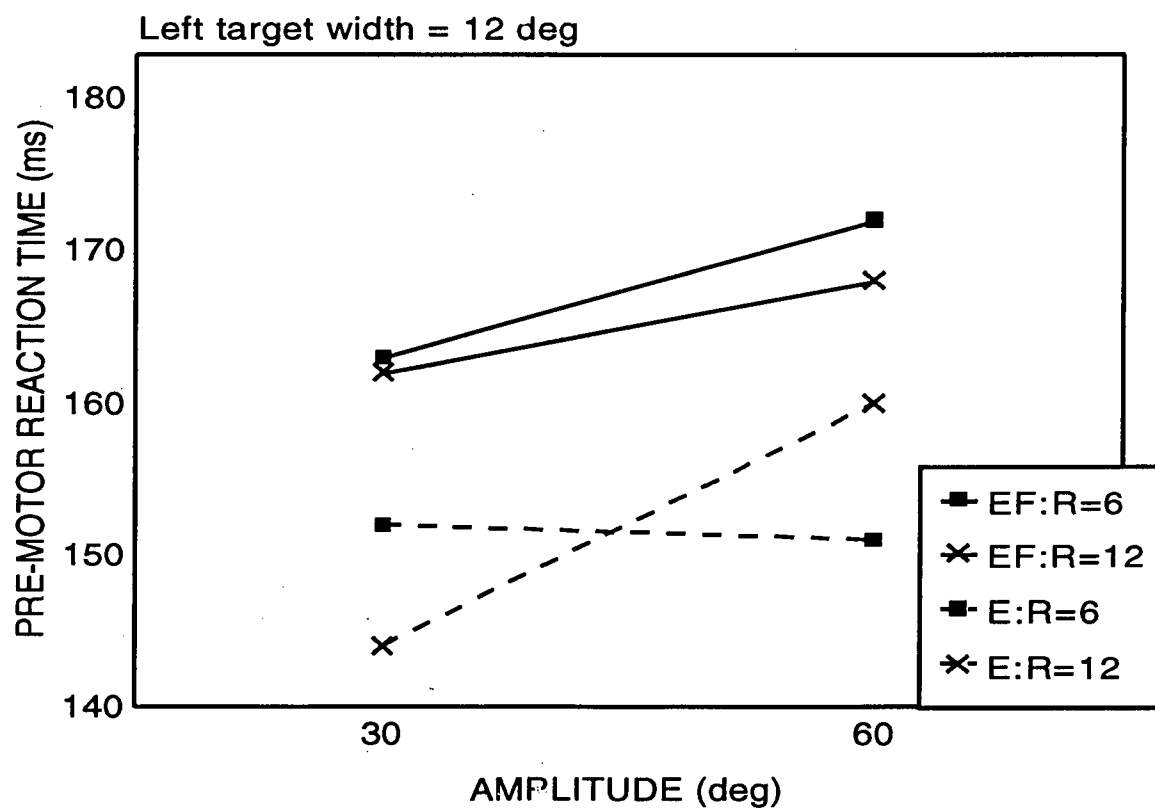
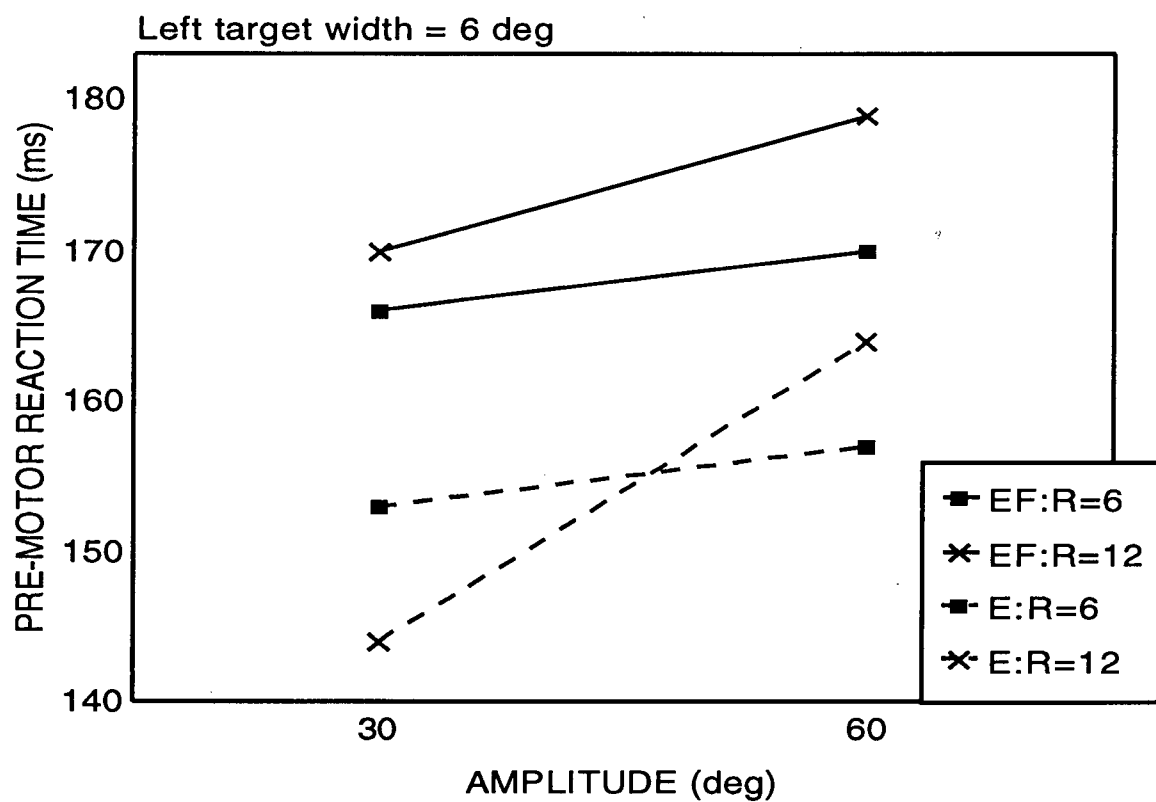
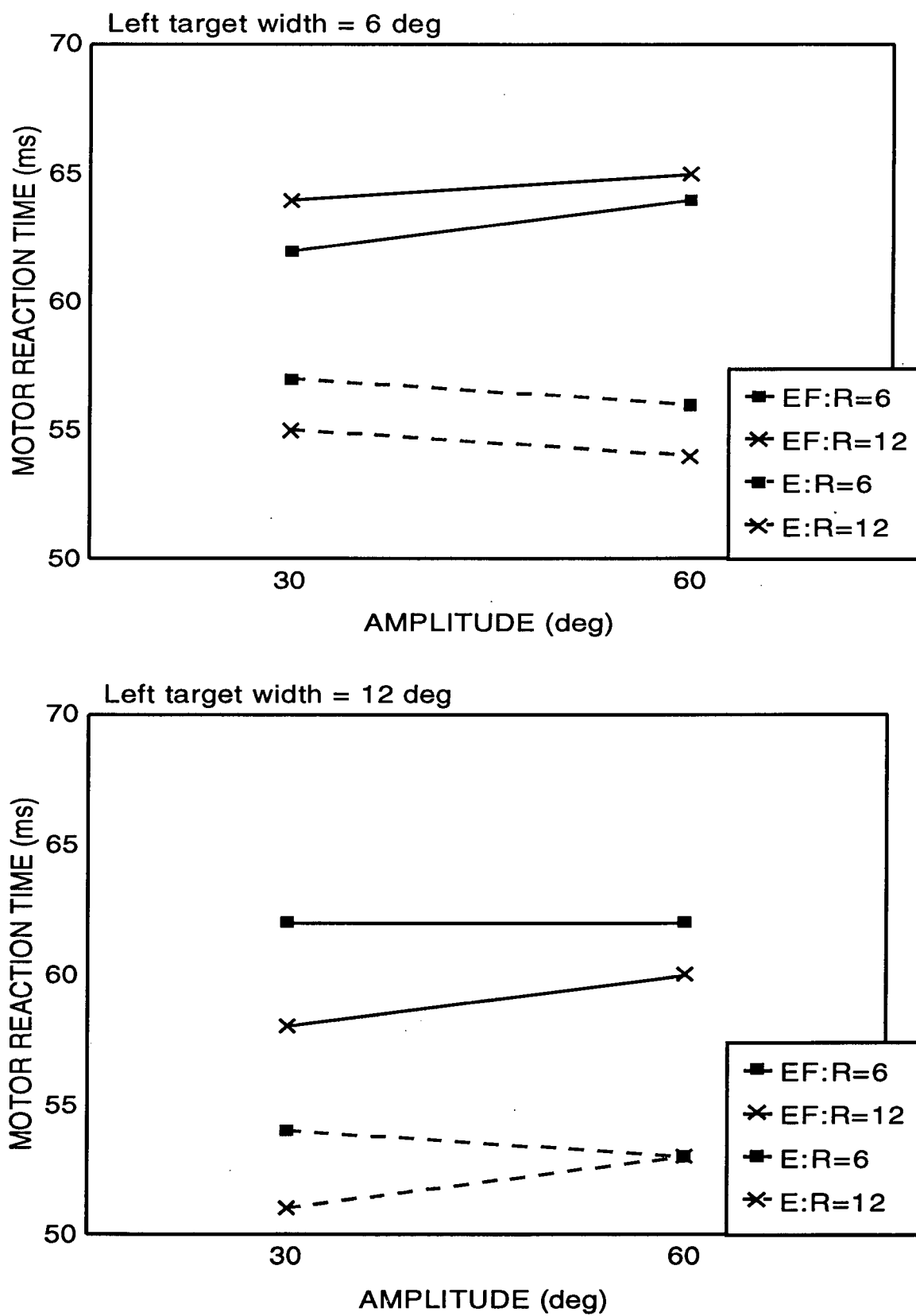


FIGURE 8: Motor Reaction Time



the 30° amplitude yielded an ID of 2.32 for the 12° right target and an ID of 3.32 for the 6° right target. Similarly, the ID for an amplitude of 60° was 3.32 when the right target was 12° and 4.32 when the right target was 6°. These IDs were applied to both the E and the EF movements. A 2 (movement) x 4 (ID) RM ANOVA was performed on both the PRT and the MRT data. A main effect of movement was found for both PRT,  $F(1, 27) = 8.903$ ,  $p = .006$ , and MRT,  $F(1, 27) = 82.866$ ,  $p < .001$ ; the latency was longer for the EF condition than it was for the E condition (figures 9 and 10, respectively). For PRT, a significant main effect of ID was also found,  $F(3, 81) = 3.102$ ,  $p = .031$ , and a Tukey post-hoc test indicated that the ID of 3.32 at 60° was greater than the ID of 2.32 at 30°. Therefore, contrary to the hypothesis that ID determines reaction time, it appears that amplitude had a greater effect on PRT than did ID (since PRT did not consistently increase with the increase in ID). All other effects were not significant ( $p > .05$ ).

Finally, the reaction time data were analyzed to determine whether the reversal component affected the time required to program a response. Movements which did and did not involve a reversal component were compared across constant amplitudes and target widths. Specifically, the 60° E movement was compared to the 30° EF movement at equal left and right target widths of either 6° or 12°. A 2 (movement) x 2 (target size) RM ANOVA was performed on the SRT, PRT, and MRT data. For SRT and PRT, none of the effects were significant ( $p > .05$ ). Therefore, the presence or absence of the reversal component in a movement response did not affect the overall time required to program that response. However, the presence of a reversal component did relate to a small but consistent difference in MRT; the EF movement had a significantly longer MRT than did the E movement,  $F(1, 13) = 17.882$ ,  $p = .001$ . All of the other MRT effects were not significant ( $p > .05$ ).

#### *Extension Movement Distance*

A 2 x 2 x 2 x 2 RM ANOVA performed on the extension movement distance data indicated a significant main effect of amplitude only (table 2). As expected, subjects moved

FIGURE 9: Pre-motor Reaction Time as a Function of Index of Difficulty

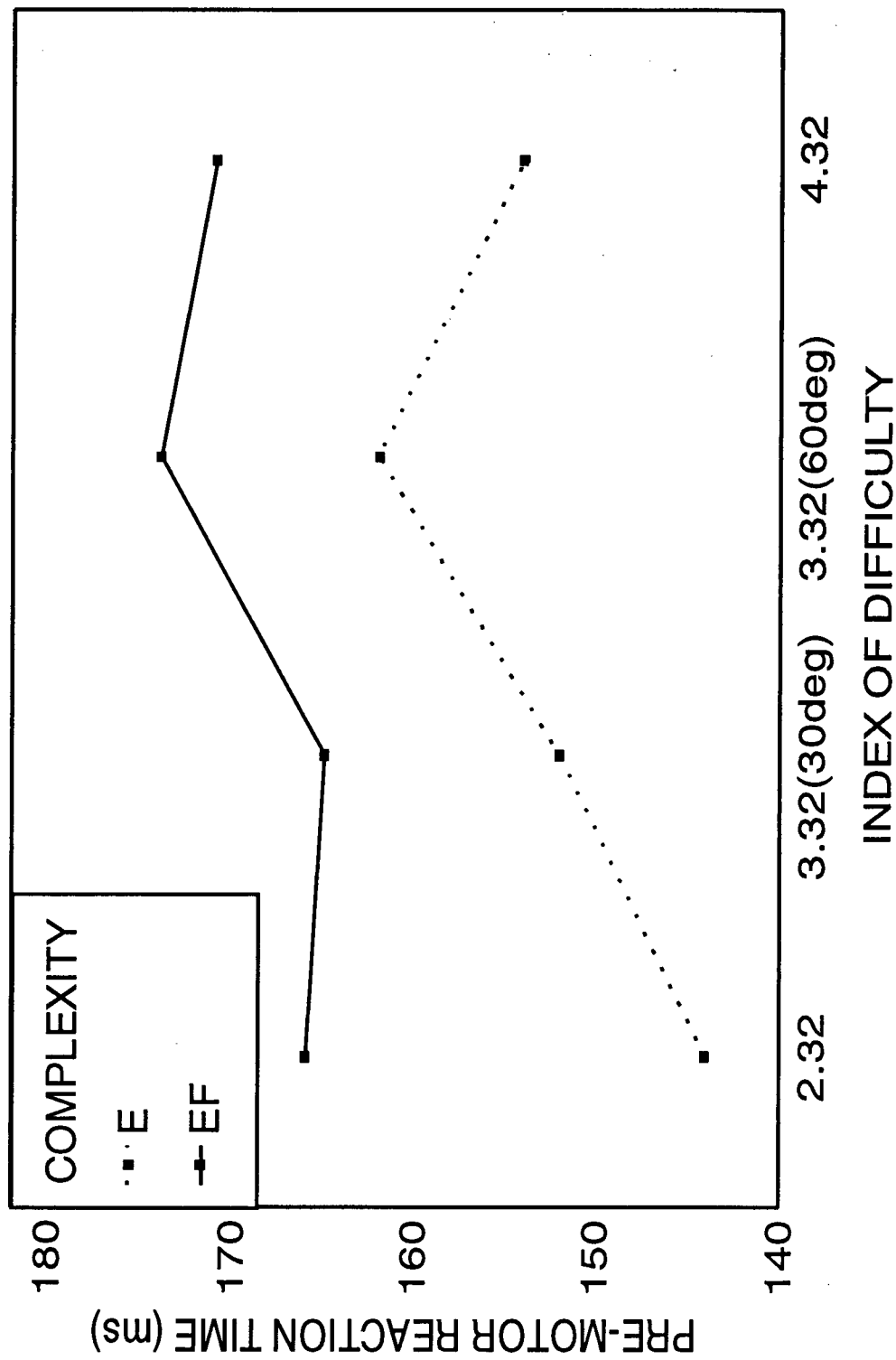
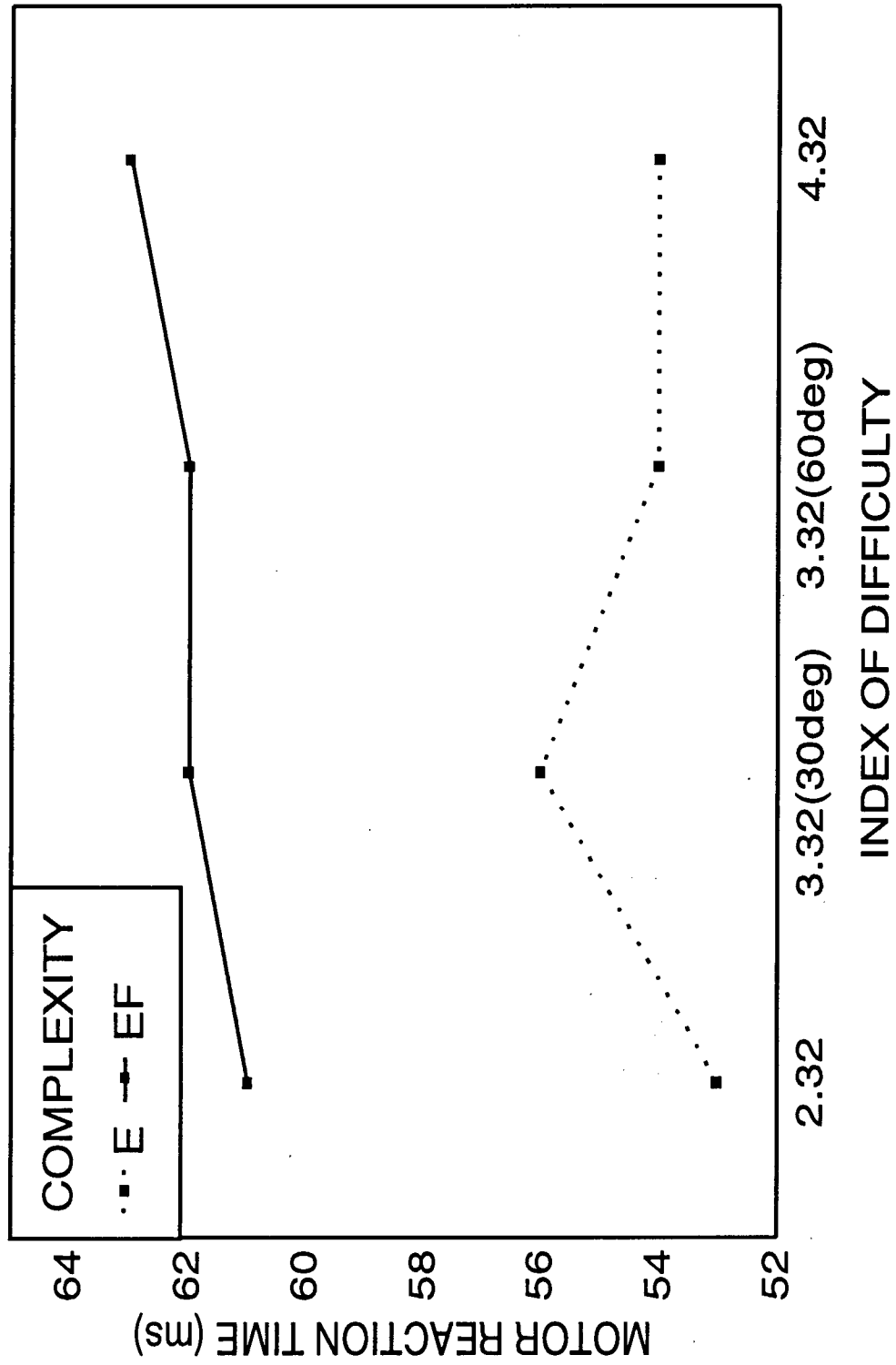


FIGURE 10: Motor Reaction Time as a Function of Index of Difficulty





**Table 2.** ANOVA results for the kinematic dependent variables of the extension movement: movement distance, movement time, velocity time one, velocity time two, peak velocity, acceleration time one, and peak acceleration. All main effects and significant interaction effects are presented.

Effect	F-test	p-value	p < .05
<i>Extension Movement Distance (ED)</i>			
movement	$F(1, 13) = 0.456$	$p = .511$	
amplitude	$F(1, 13) = .432E+5$	$p < .001$	*
left target size	$F(1, 13) = 1.33$	$p = .269$	
right target size	$F(1, 13) = 0.06$	$p = .81$	
<i>Extension Movement Time (ET)</i>			
movement	$F(1, 13) = 34.008$	$p < .001$	*
amplitude	$F(1, 13) = 206.391$	$p < .001$	*
left target size	$F(1, 13) = 2.892$	$p = .113$	
right target size	$F(1, 13) = 45.657$	$p < .001$	*
movement x amplitude interaction	$F(1, 13) = 10.288$	$p = .007$	*
amplitude x right target interaction	$F(1, 13) = 5.167$	$p = .041$	*
<i>Extension Velocity Time One (EV1)</i>			
movement	$F(1, 13) = 14.537$	$p = .002$	*
amplitude	$F(1, 13) = 34.8$	$p < .001$	*
left target size	$F(1, 13) = 1.138$	$p = .306$	
right target size	$F(1, 13) = 14.618$	$p = .002$	*
<i>Extension Velocity Time Two (EV2)</i>			
movement	$F(1, 13) = 48.459$	$p < .001$	*
amplitude	$F(1, 13) = 210.099$	$p < .001$	*
left target size	$F(1, 13) = 1.324$	$p = .271$	
right target size	$F(1, 13) = 39.679$	$p < .001$	*
movement x amplitude interaction	$F(1, 13) = 10.532$	$p = .006$	*
amplitude x right target interaction	$F(1, 13) = 4.828$	$p = .047$	*
<i>Extension Acceleration Time One (EAI)</i>			
movement	$F(1, 13) = 10.435$	$p = .007$	*
amplitude	$F(1, 13) = 6.827$	$p = .021$	*
left target size	$F(1, 13) = 8.878$	$p = .011$	*
right target size	$F(1, 13) = 17.732$	$p = .001$	*

Table 2, continued.

Effect	F-test	p-value	p < .05
<i>Extension Peak Velocity (EPV)</i>			
movement	$F(1, 13) = 2.781$	$p = .119$	
amplitude	$F(1, 13) = 159.982$	$p < .001$	*
left target size	$F(1, 13) = 8.684$	$p = .011$	*
right target size	$F(1, 13) = 11.925$	$p = .004$	*
amplitude x right target interaction	$F(1, 13) = 4.603$	$p = .051$	
<i>Extension Peak Acceleration (EPA)</i>			
movement	$F(1, 13) = 9.875$	$p = .008$	*
amplitude	$F(1, 13) = 36.905$	$p < .001$	*
left target size	$F(1, 13) = 11.014$	$p = .006$	*
right target size	$F(1, 13) = 12.884$	$p = .003$	*

significantly farther when the movement amplitude was 60° ( $\underline{M} = 59.6^\circ$ ) than they did when the amplitude was 30° ( $\underline{M} = 30.1^\circ$ ). All other effects were not significant ( $p > .05$ ).

### *Extension Movement Time*

Significant main effects of movement, amplitude, and right target size were found in the extension movement time data (ET, table 2). The movement time for the E condition was significantly longer than that for the E segment of the EF condition (figure 11). ET was also longer for the 60° amplitude than it was for the 30° amplitude and longer for the 6° right target than it was for the 12° right target. In addition, the movement by amplitude and the amplitude by right target size interaction effects were significant. Thus, the difference between the E and the EF conditions was greater at 60° than it was at 30° and the difference between the 6° right target and the 12° right target was also greater at 60° than it was at 30°. These interaction effects simply represented the trends found in the main effects. For example, ET was longer when the right target was smaller and when the amplitude was longer, but ET was the longest when both these factors were present. None of the other effects were significant ( $p > .05$ ).

In order to test the hypothesis that movement time is dependent upon the ID of a response (Fitts, 1954), the ET data was additionally analyzed in terms of ID. These data were organized the same as those described for the reaction time ID analysis. The results of a 2 (movement) x 4 (ID) RM ANOVA indicated a significant main effect of both movement,  $F(1, 27) = 52.707$ ,  $p < .001$ , and ID,  $F(3, 81) = 93.848$ ,  $p < .001$ . ET was longer for the E condition than it was for the EF condition (figure 12). In addition, the movement by ID interaction effect was significant,  $F(3, 81) = 3.237$ ,  $p = .029$ . A Scheffé post-hoc test for interactions indicated that the difference between the E and the EF conditions was greater for the IDs of 4.32 and 3.32 at 60° than it was for the IDs of 3.32 and 2.32 at 30°. Therefore, ET appears to have been more dependent upon the amplitude of the response than it was upon the ID of the response.

ET was further broken down into the time spent in each of the two velocity phases, the

FIGURE 11: Extension Movement Time

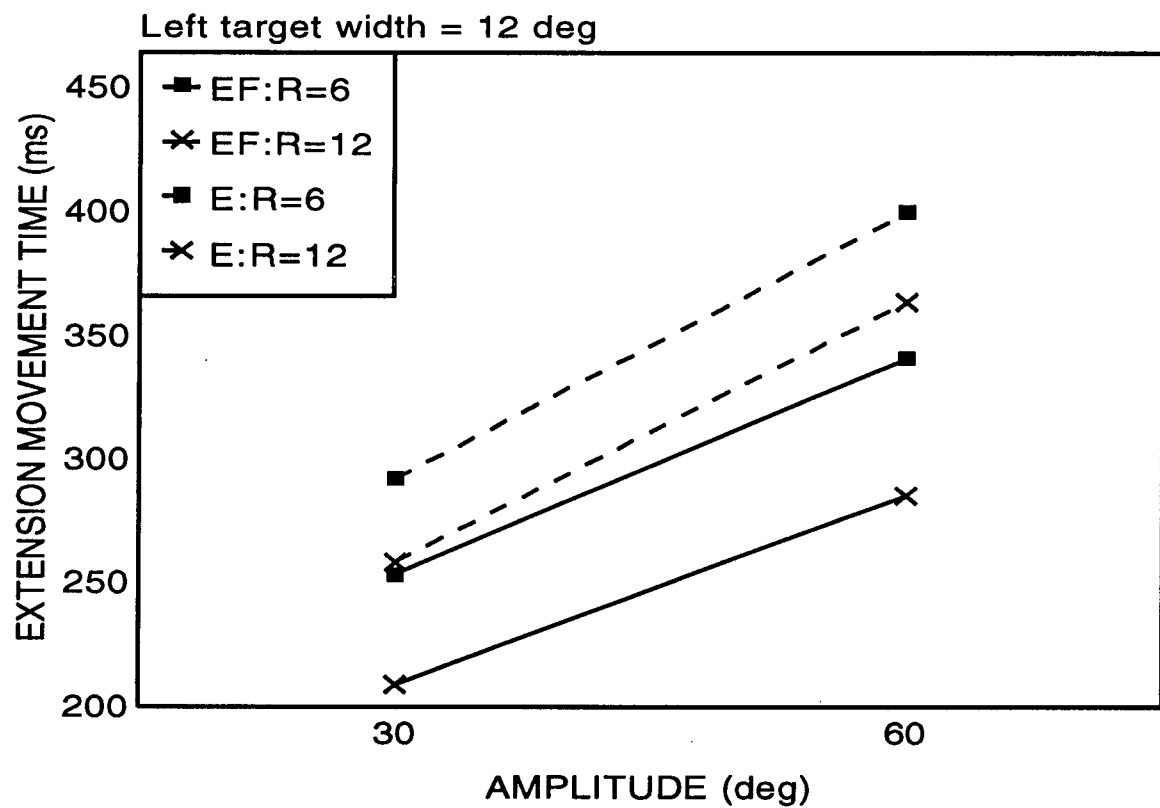
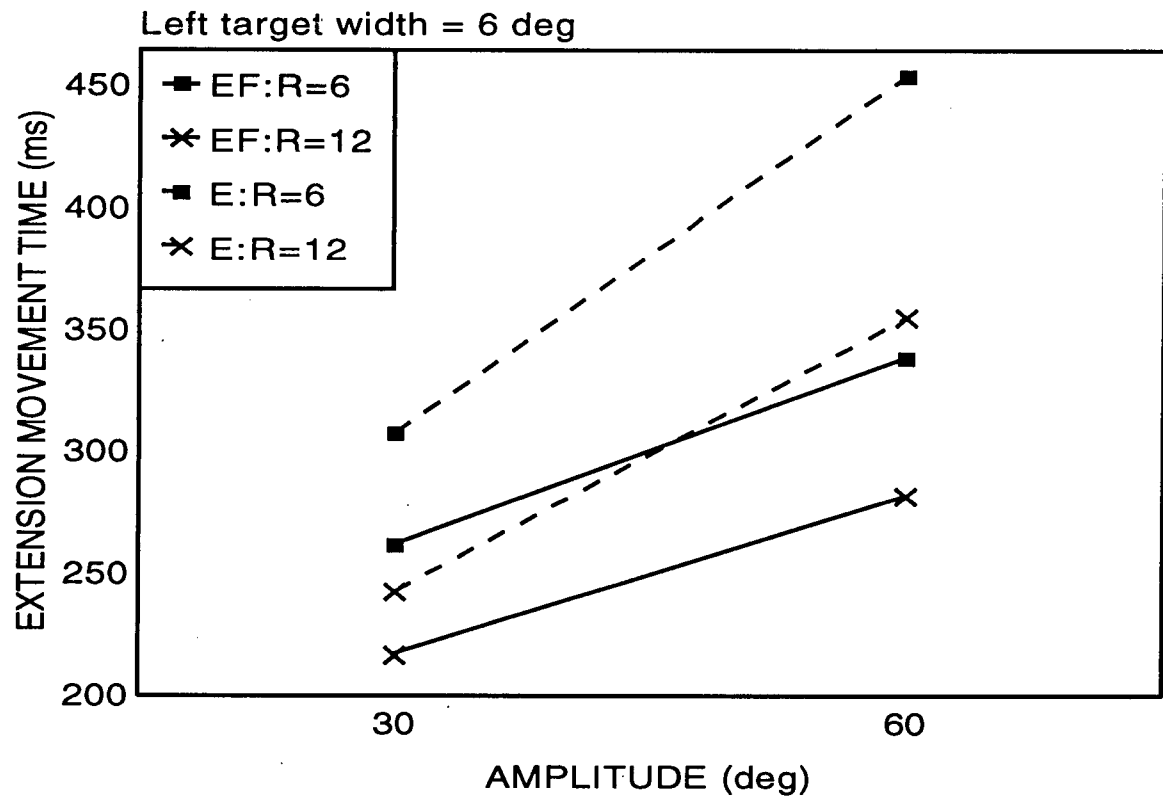
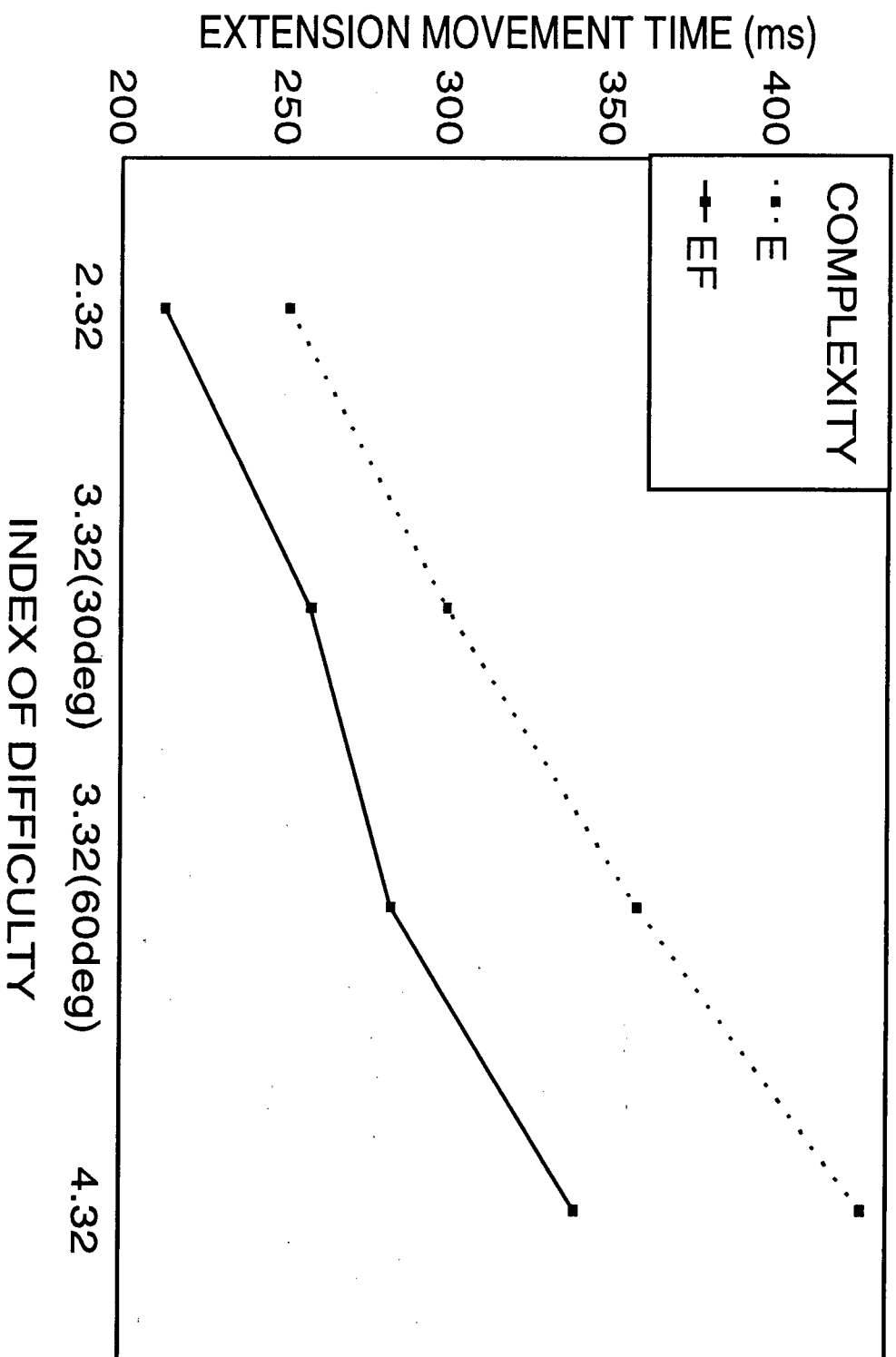


FIGURE 12: Extension Movement Time as a Function of Index of Difficulty



time from movement initiation to peak velocity (EV1) and the time from peak velocity to movement termination (EV2). Similar to ET, the  $2 \times 2 \times 2 \times 2$  RM ANOVA for the dependent variables EV1 and EV2 indicated significant main effects of amplitude and right target size, while the main effect of left target size was not significant (table 2). The time spent in each of these velocity phases was longer for the  $60^\circ$  movement than it was for the  $30^\circ$  movement and was also longer for the  $6^\circ$  right target than it was for the  $12^\circ$  right target. Thus, the increased ET which occurred with an increased amplitude and a decreased right target size was due to an increase in the time spent in both the first and the second velocity phases. In contrast, the main effect of movement differed for EV1 and EV2. While both dependent variables had a significant main effect of movement, the time spent in the first velocity phase was longer for the EF condition than it was for the E condition (figure 13), while the time spent in the second velocity phase was longer for the E condition than it was for the EF condition (figure 14). Therefore, the greater ET for the E condition, as compared to the EF condition, occurred due to an increase in the time spent in the second velocity phase only. In addition, EV2 had two significant interaction effects: movement by amplitude and amplitude by right target size. These interactions indicated the same trends as were seen in the ET data; the difference between the E and the EF conditions was greater at  $60^\circ$  than it was at  $30^\circ$  and the difference between the  $6^\circ$  right target and the  $12^\circ$  right target was also greater at  $60^\circ$  than it was at  $30^\circ$ . Since none of the other interaction effects were significant ( $p > .05$ ), the ET interaction effects were due to interactions which occurred in the second velocity phase only.

To determine any differences in movement time that occurred in the initial portion of each movement, the time from movement initiation to peak acceleration (EA1) was also analyzed. Significant main effects were found for movement, amplitude, left target size, and right target size (table 2). Similar to EV1, EA1 was longer in the EF condition than it was in the E condition, longer for the  $60^\circ$  amplitude than it was for the  $30^\circ$  amplitude, and longer for the  $6^\circ$  right target than it was for the  $12^\circ$  right target (figure 15). In addition, EA1 was also longer when the left target was  $6^\circ$ , as compared to  $12^\circ$ . Moving out of a small target therefore

FIGURE 13: Velocity Time One, Extension Movement

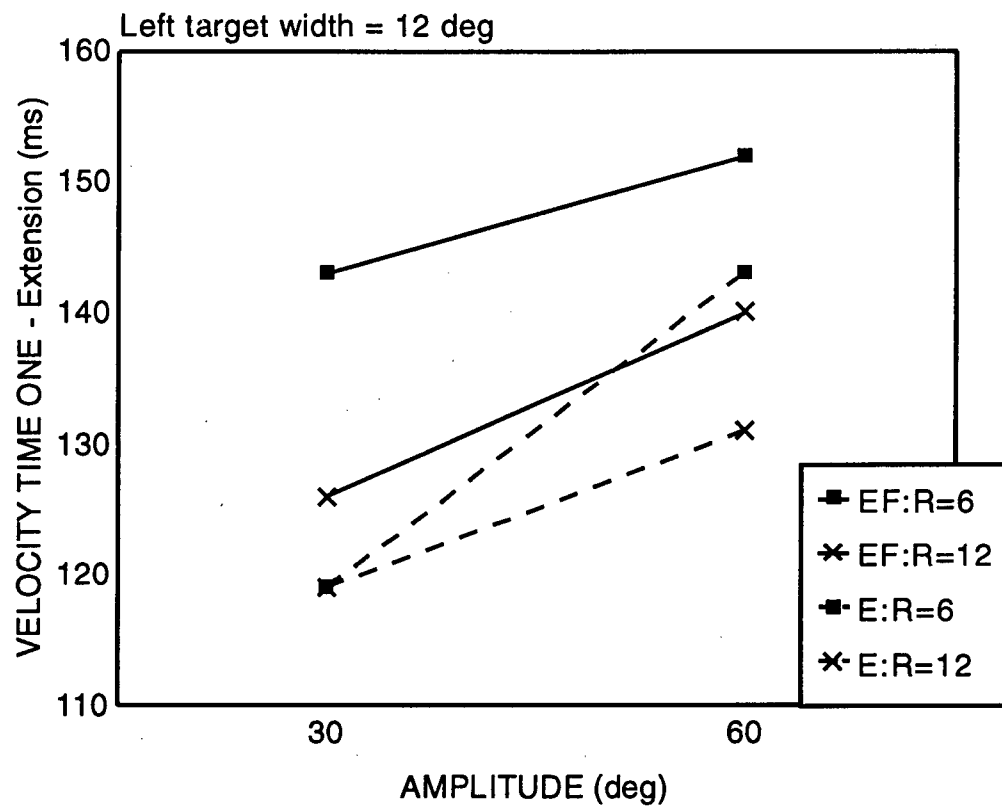
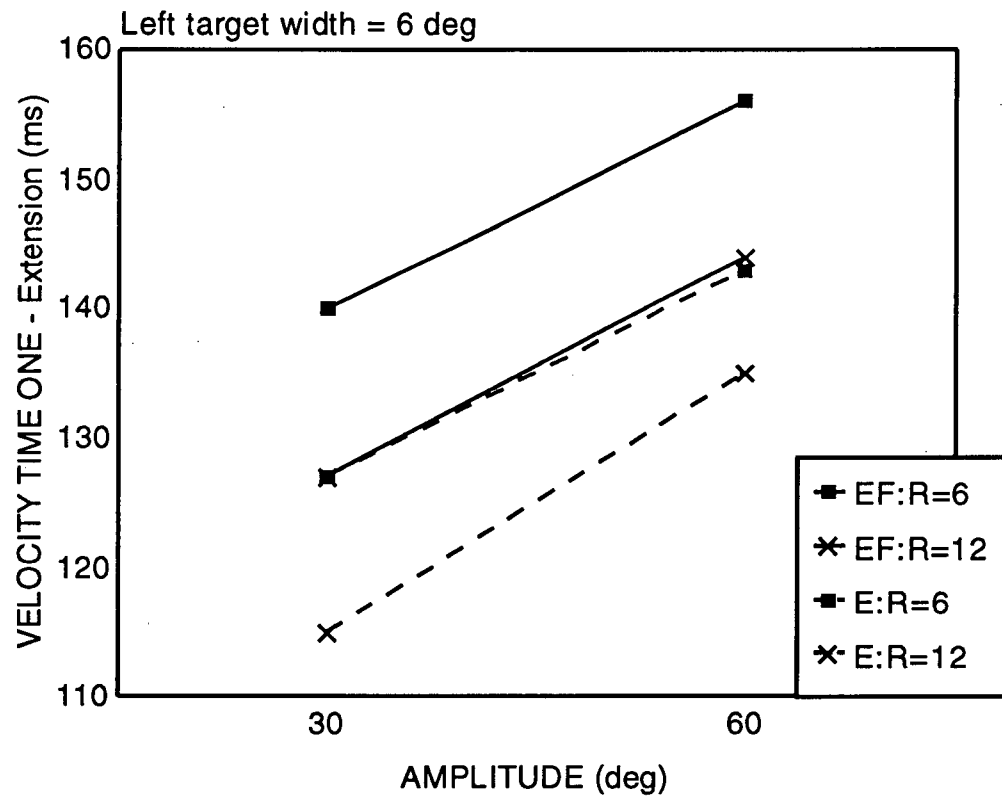


FIGURE 14: Velocity Time Two, Extension Movement

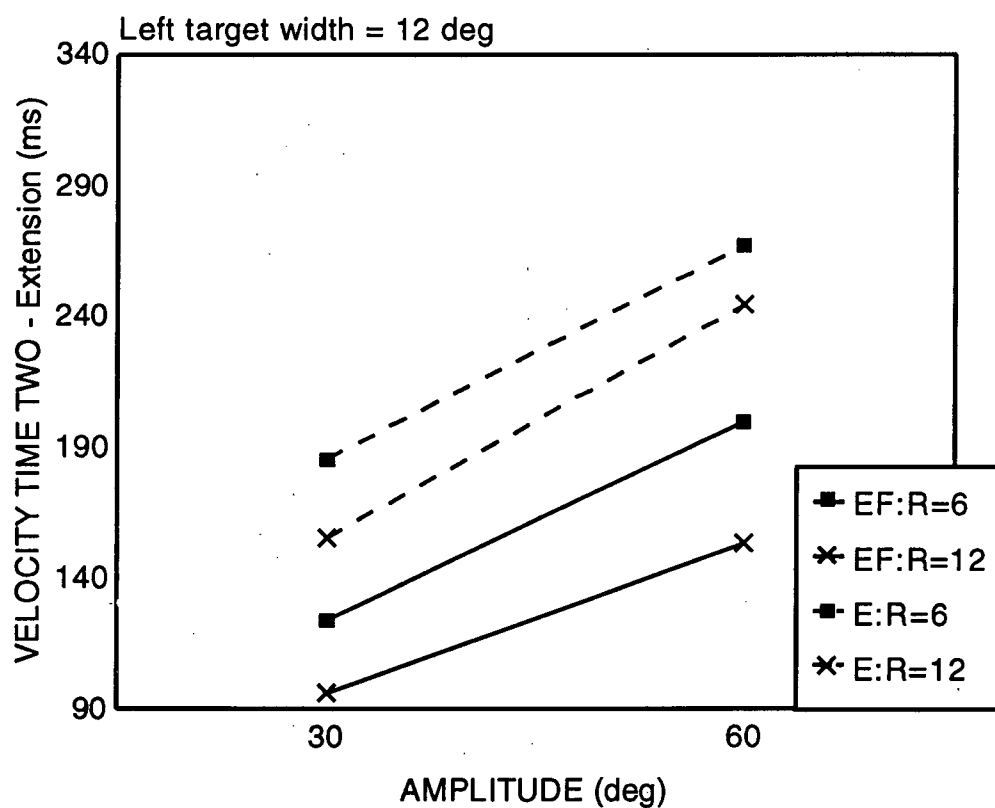
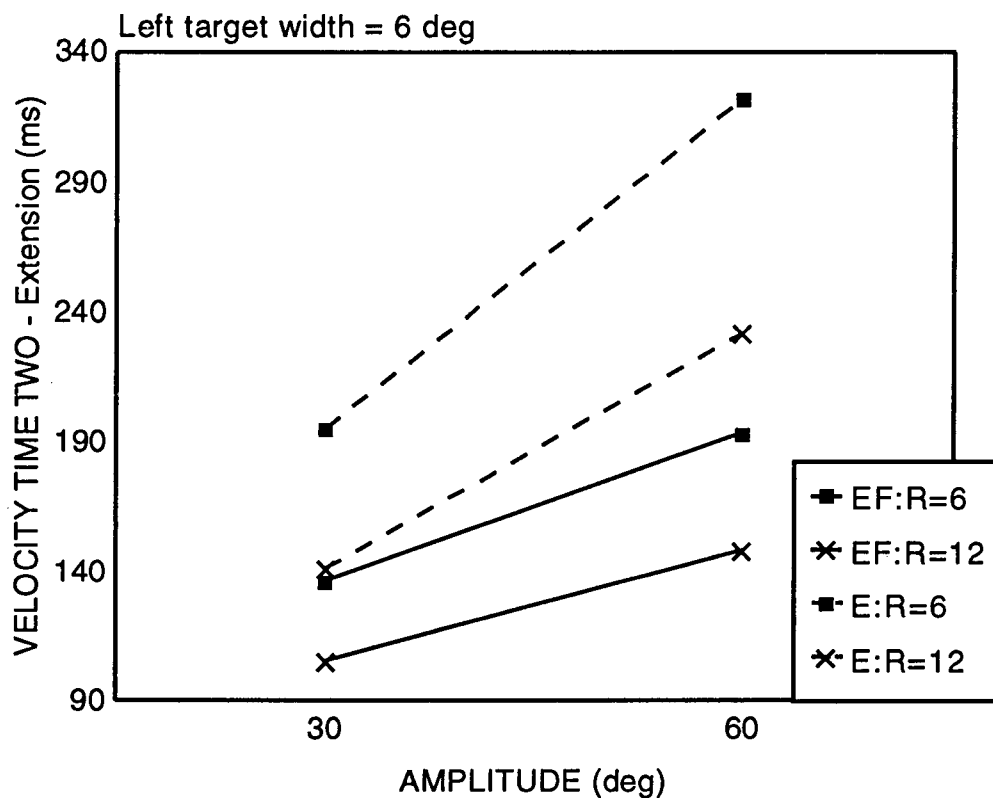
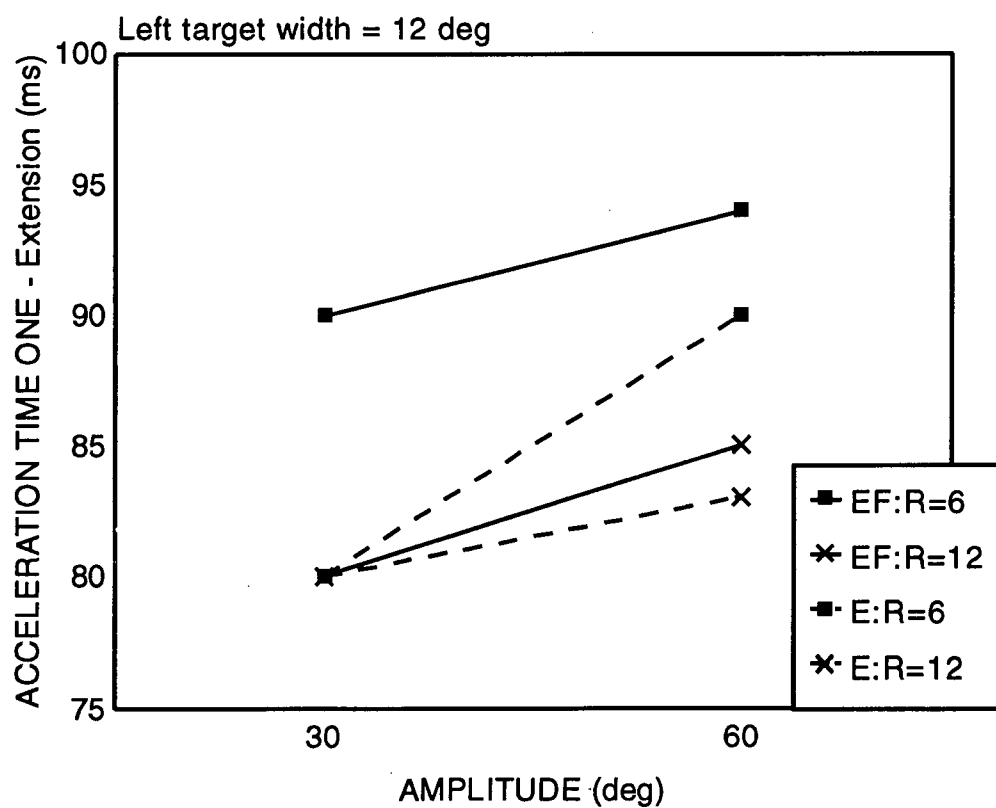
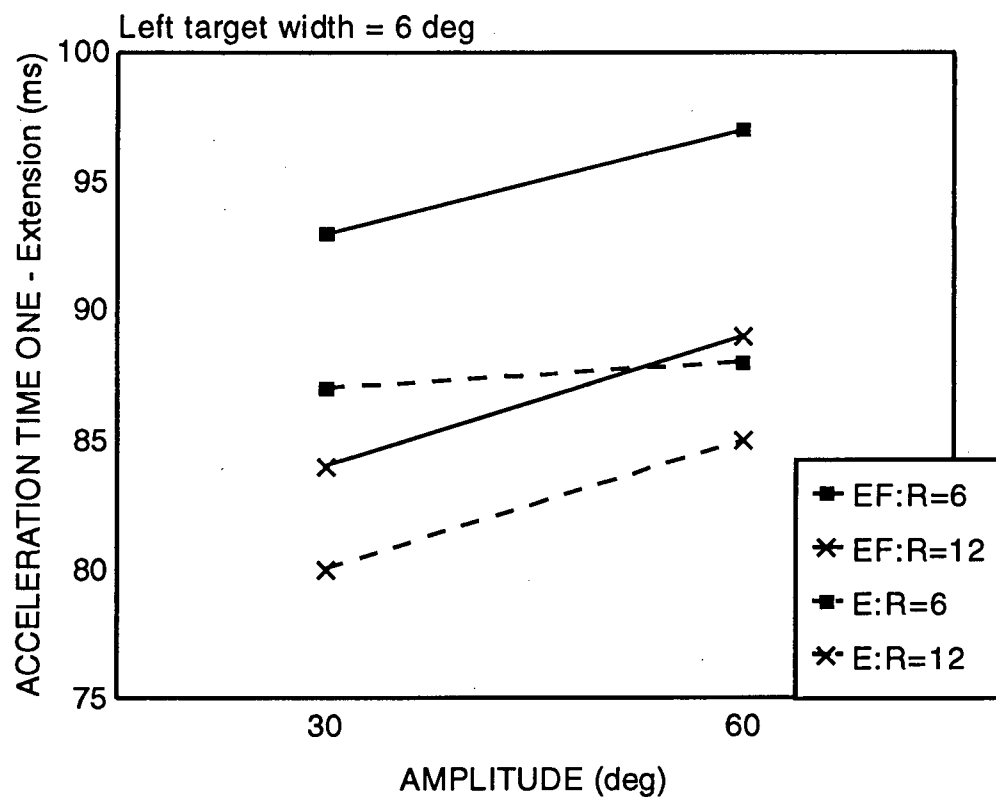




FIGURE 15: Acceleration Time One, Extension Movement



appears to have only affected the time spent in the initial portion of the movement, as there were no significant left target size differences for EV1 or ET. None of the interaction effects were significant ( $p > .05$ ).

#### *Extension Peak Velocity*

Significant main effects of amplitude, left target size, and right target size were found in the peak velocity data of the extension movement (EPV, table 2). EPV was greater for the 60° movement than it was for the 30° movement, and was also greater when the left and right targets were 12°, as opposed to 6° (figure 16). In addition, the amplitude by right target size interaction effect approached significance ( $p = .051$ ), and indicated that the difference in EPV between the 6° and the 12° right targets was greater at 60° than it was at 30°. All other effects were not significant ( $p > .05$ ).

#### *Extension Peak Acceleration*

All main effects from the EPA data were found to be significant (table 2). EPA was greater for the E condition than it was for the EF condition, greater for the 60° movement than it was for the 30° movement, and was also greater for 12° left and right targets, as compared to the 6° targets (figure 17). No interaction effects were significant ( $p > .05$ ).

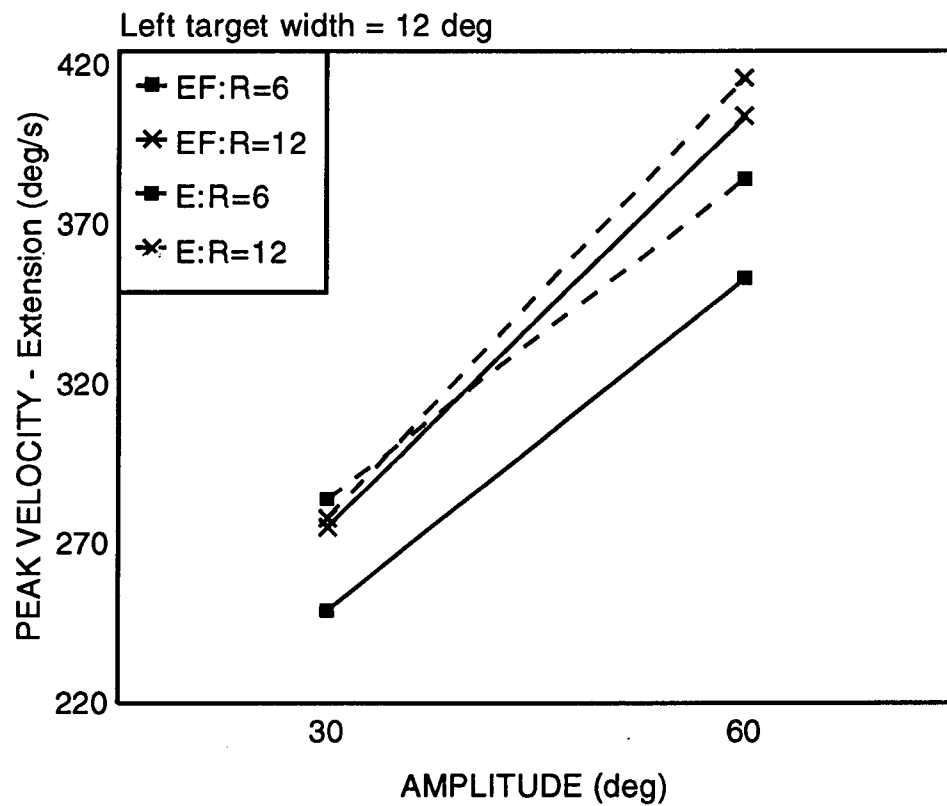
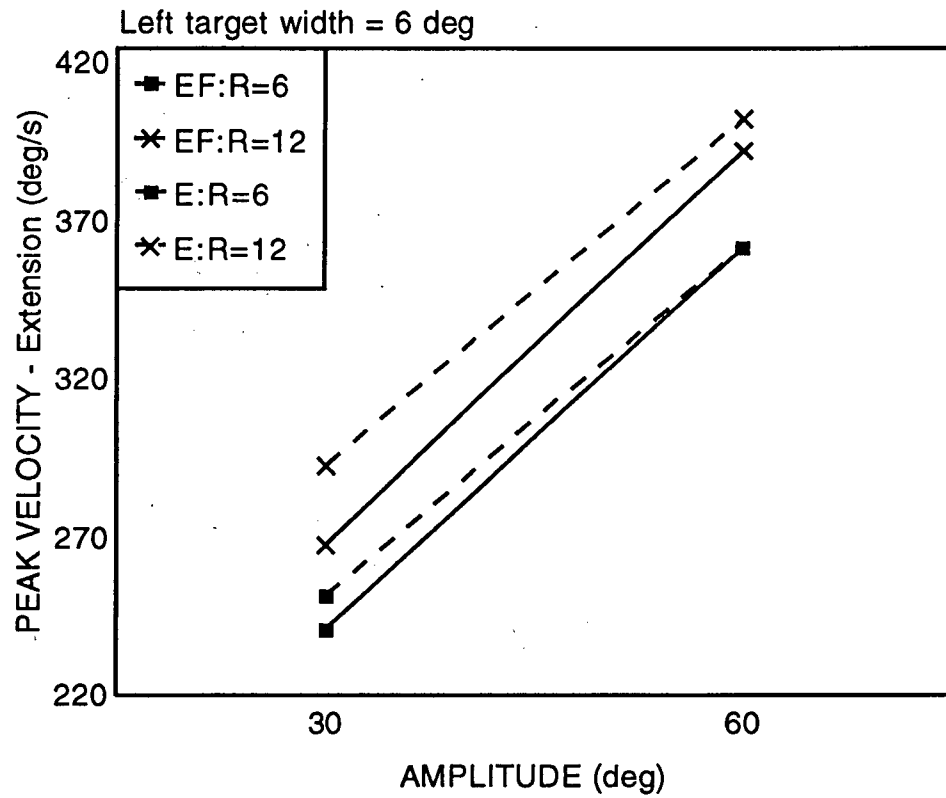
#### *Flexion Movement Distance*

A 2 x 2 x 2 RM ANOVA was performed on all data from the flexion movements. For flexion movement distance, the main effect of amplitude was significant, as subjects moved farther in the 60° ( $\bar{M} = 59.8^\circ$ ) amplitude condition than they did in the 30° ( $\bar{M} = 30.7^\circ$ ) amplitude condition (table 3). None of the other effects were significant ( $p > .05$ ).

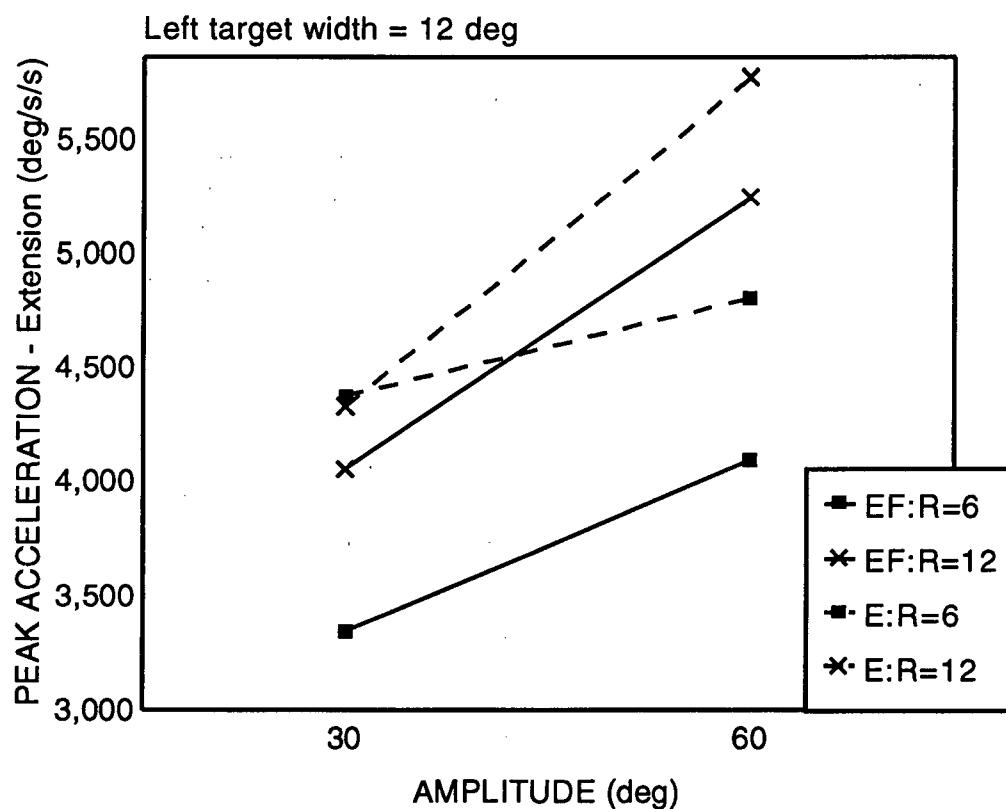
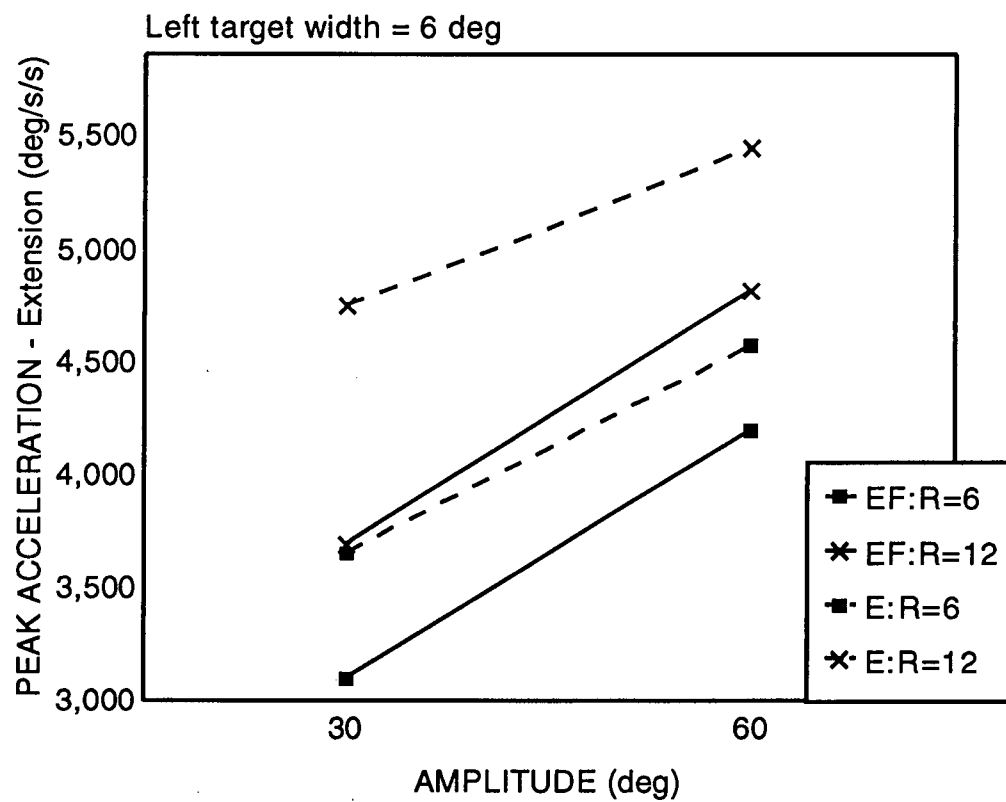
#### *Flexion Movement Time*

Significant main effects of amplitude, left target size, and right target size occurred in

FIGURE 16: Peak Velocity,  
Extension Movement



# FIGURE 17: Peak Acceleration, Extension Movement



**Table 3.** ANOVA results for the kinematic dependent variables of the flexion movement: movement distance, movement time, velocity time one, velocity time two, peak velocity, acceleration time one, and peak acceleration. All main effects and significant interaction effects are presented.

Effect	F-test	p-value	p <.05
<i>Flexion Movement Distance (FD)</i>			
amplitude	$F(1, 13) = 8957.39$	$p < .001$	*
left target size	$F(1, 13) = 0.115$	$p = .74$	
right target size	$F(1, 13) < 0.001$	$p = 1.000$	
<i>Flexion Movement Time (FT)</i>			
amplitude	$F(1, 13) = 114.547$	$p < .001$	*
left target size	$F(1, 13) = 17.458$	$p = .001$	*
right target size	$F(1, 13) = 7.03$	$p = .02$	*
<i>Flexion Velocity Time One (FV1)</i>			
amplitude	$F(1, 13) = 46.971$	$p < .001$	*
left target size	$F(1, 13) = 0.622$	$p = .444$	
right target size	$F(1, 13) = 19.023$	$p = .001$	*
amplitude x right target interaction	$F(1, 13) = 6.888$	$p = .021$	*
<i>Flexion Velocity Time Two (FV2)</i>			
amplitude	$F(1, 13) = 73.369$	$p < .001$	*
left target size	$F(1, 13) = 26.463$	$p < .001$	*
right target size	$F(1, 13) = 0.077$	$p = .343$	
<i>Flexion Acceleration Time One (FA1)</i>			
amplitude	$F(1, 13) = 41.209$	$p < .001$	*
left target size	$F(1, 13) = 0.037$	$p = .851$	
right target size	$F(1, 13) = 7.866$	$p = .015$	*
<i>Flexion Peak Velocity (FPV)</i>			
amplitude	$F(1, 13) = 116.364$	$p < .001$	*
left target size	$F(1, 13) = 0.032$	$p = .86$	
right target size	$F(1, 13) = 11.121$	$p = .005$	*
<i>Flexion Peak Acceleration (FPA)</i>			
amplitude	$F(1, 13) = 7.632$	$p = .016$	*
left target size	$F(1, 13) = 0.015$	$p = .905$	
right target size	$F(1, 13) = 8.901$	$p = .011$	*

the flexion movement time data (FT, table 3). FT was longer for the 60° movement than it was for the 30° movement, and was also longer for the 6° left and right targets, as compared to the 12° targets (figure 18). There were no significant interaction effects ( $p > .05$ ).

FT was further broken down into the time spent in the first and second velocity phases (FV1 and FV2, respectively). The main effect of amplitude was significant for both FV1 and FV2 (table 3), such that the time spent in each of these velocity phases was greater for the 60° movement than it was for the 30° movement. However, the main effects of left and right target size differed for FV1 and FV2. While the main effect of right target size was significant for FV1, it was not for FV2. FV1 was longer when the right target was 6° than it was when the right target was 12° (figure 19). Thus, the increased FT which occurred with the decreased right target size was due to an increased time spent in the first velocity phase only. In contrast, the main effect of left target size was not significant for FV1, but FV2 was significantly longer for the 6° left target than it was for the 12° left target (figure 20). The increase in FT from the large to the small left target was therefore attributed to an increase in the time spent in the second velocity phase. In addition, FV1 had a significant amplitude by right target interaction effect which indicated that the difference in FV1 between the 6° and the 12° right target sizes was greater at the 60° amplitude than it was at the 30° amplitude. All other interaction effects were not significant ( $p > .05$ ).

The time from movement initiation to peak acceleration (FA1) was also analyzed to determine any differences which may have occurred during the initial portion of each flexion movement. The main effects of amplitude and right target size were significant as FA1 was greater for the 60° movement than it was for the 30° movement and was also greater for the 6° right target than it was for the 12° right target (figure 21, table 3). All other effects were not significant ( $p > .05$ ).

#### *Total Movement Time: Effects of Varying Amplitude with ID Held Constant*

In the present experiment, two instances occurred where both the amplitude and target

## FLEXION 18: Flexion Movement Time

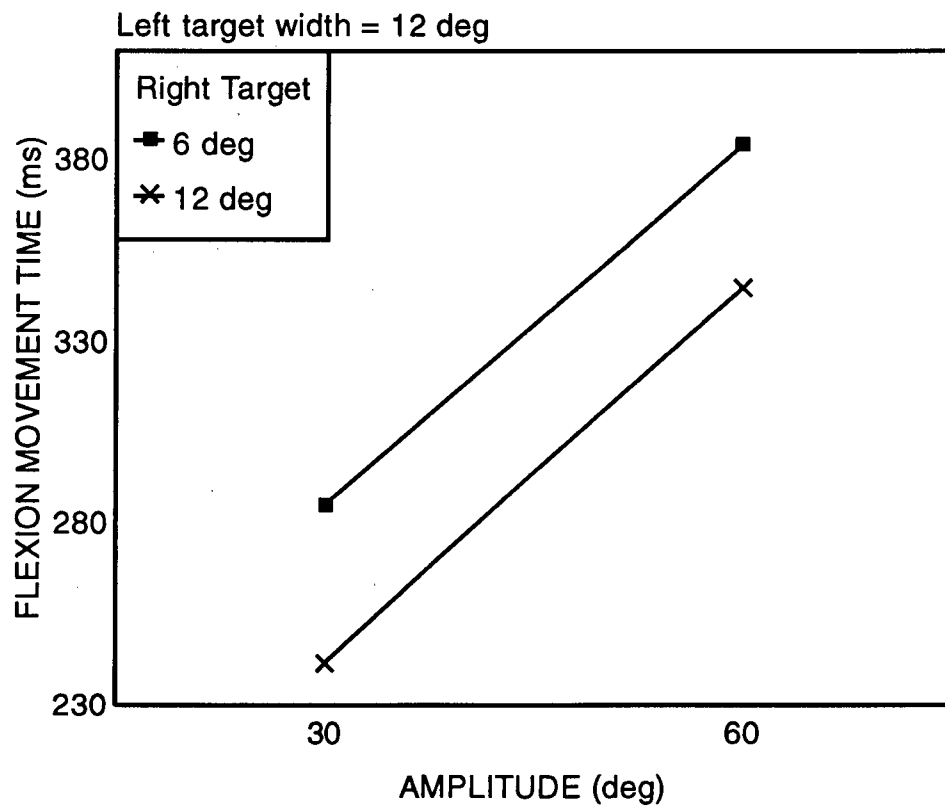
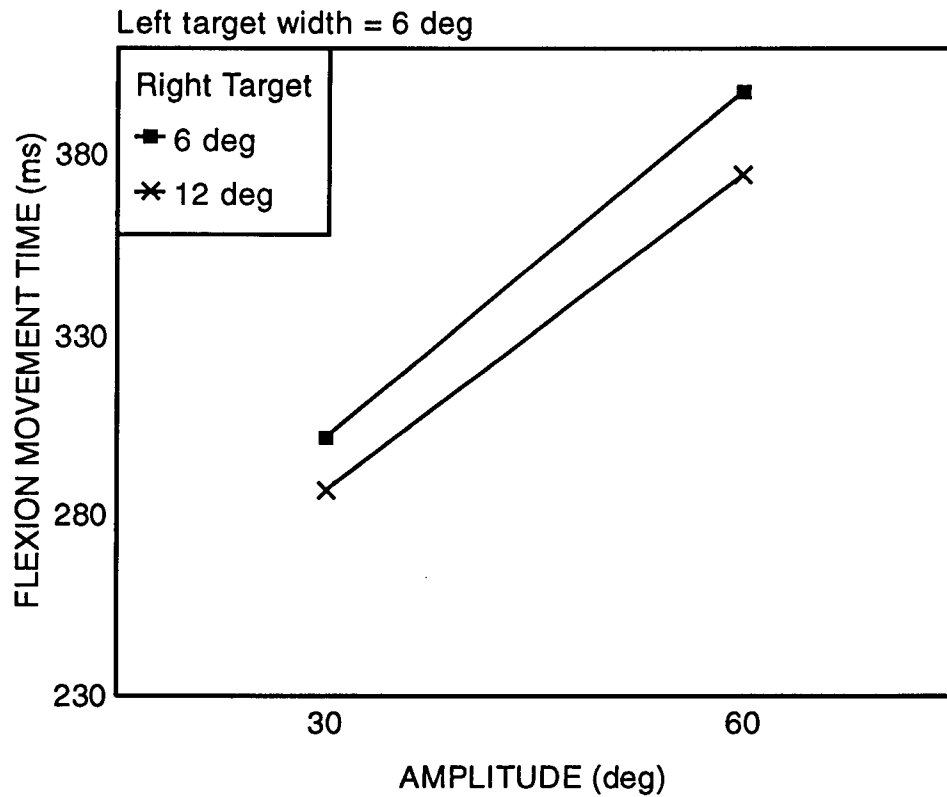


FIGURE 19: Velocity Time One Flexion Movement

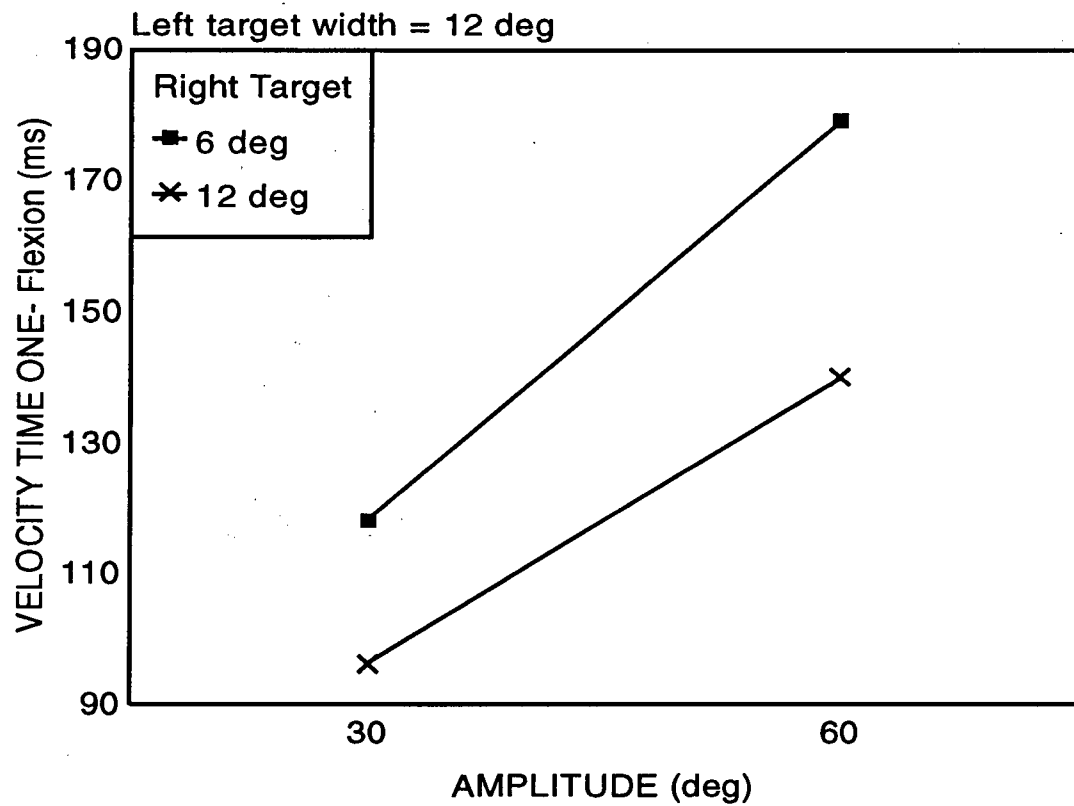
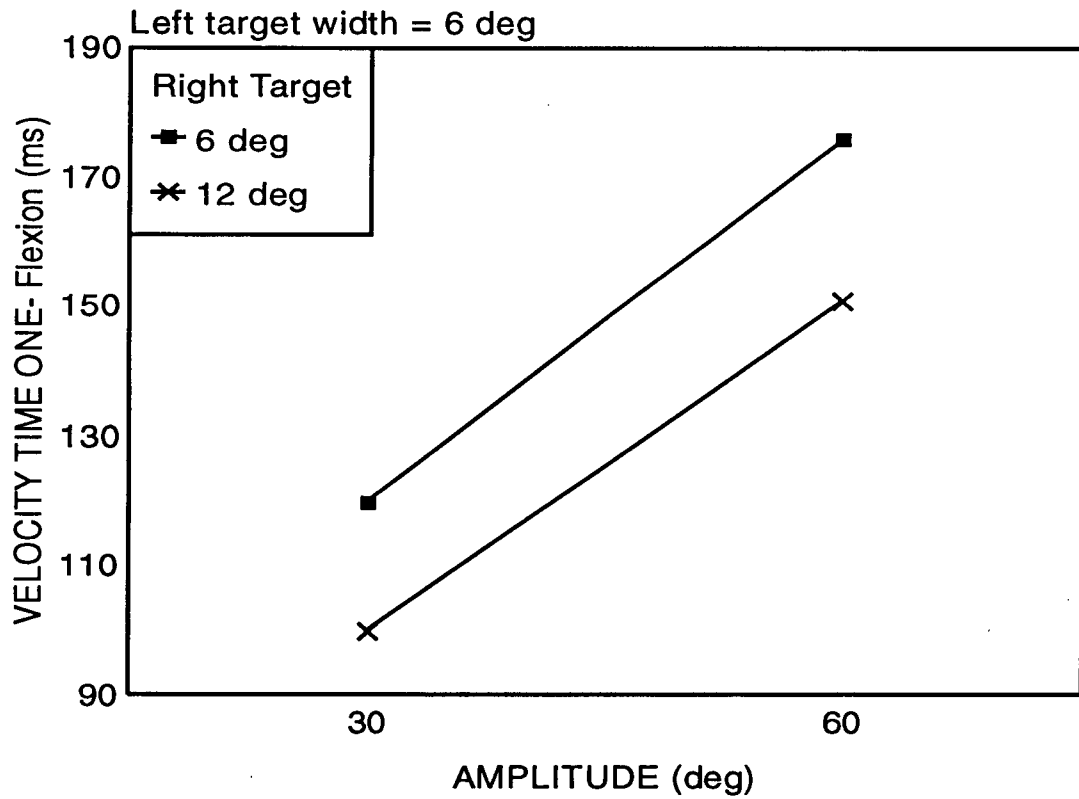




FIGURE 20: Velocity Time Two, Flexion Movement

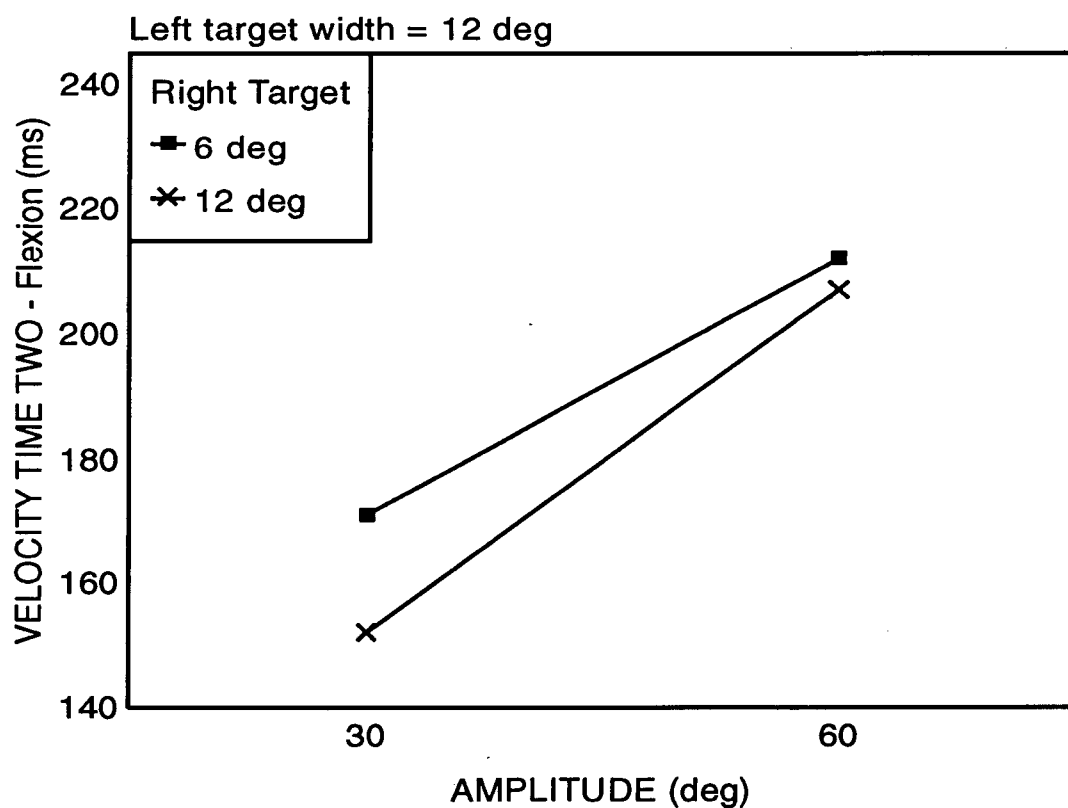
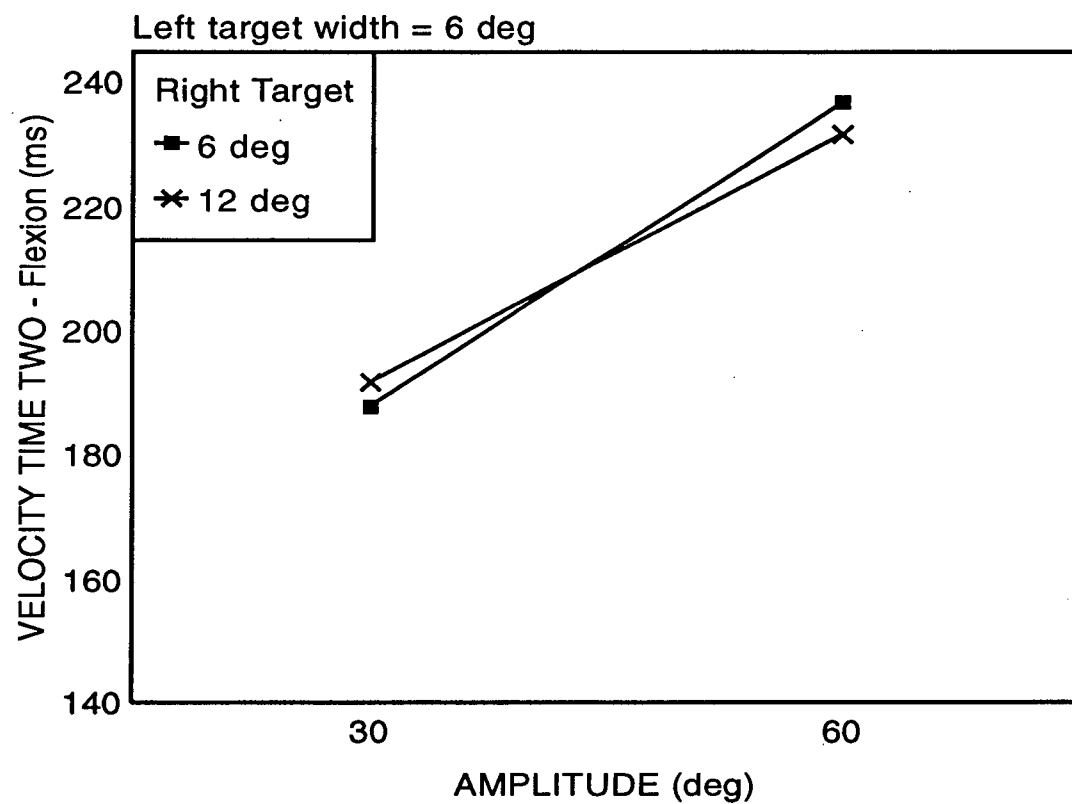
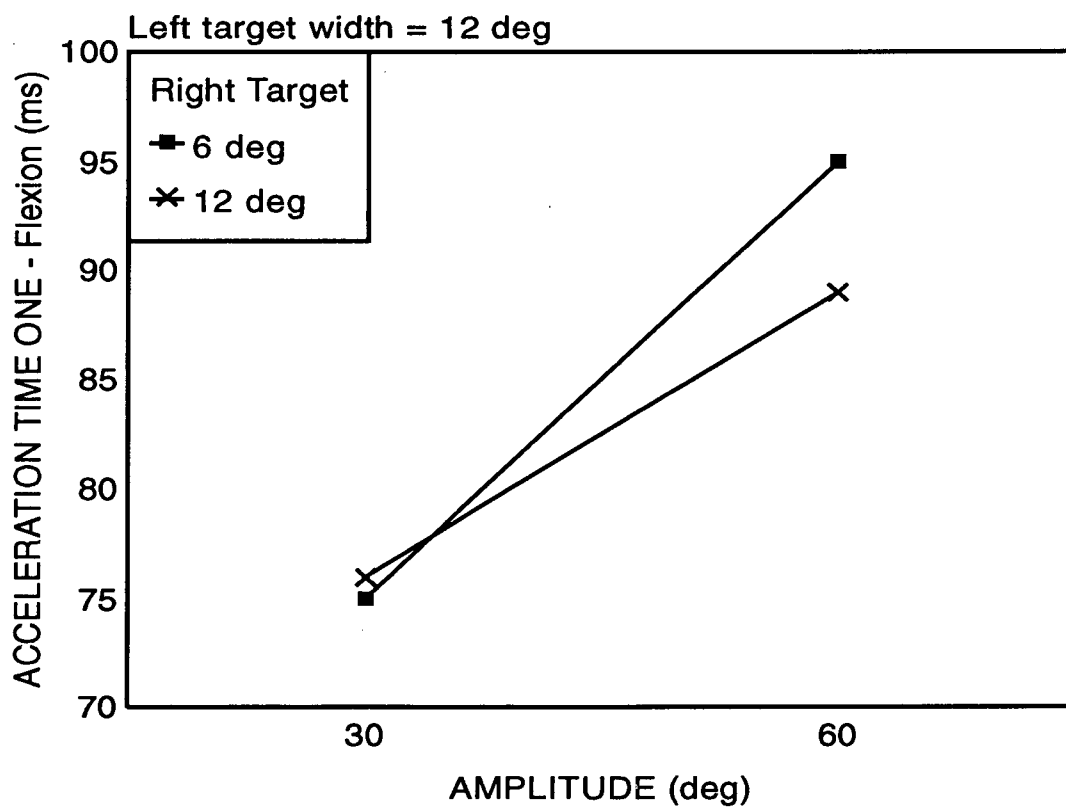
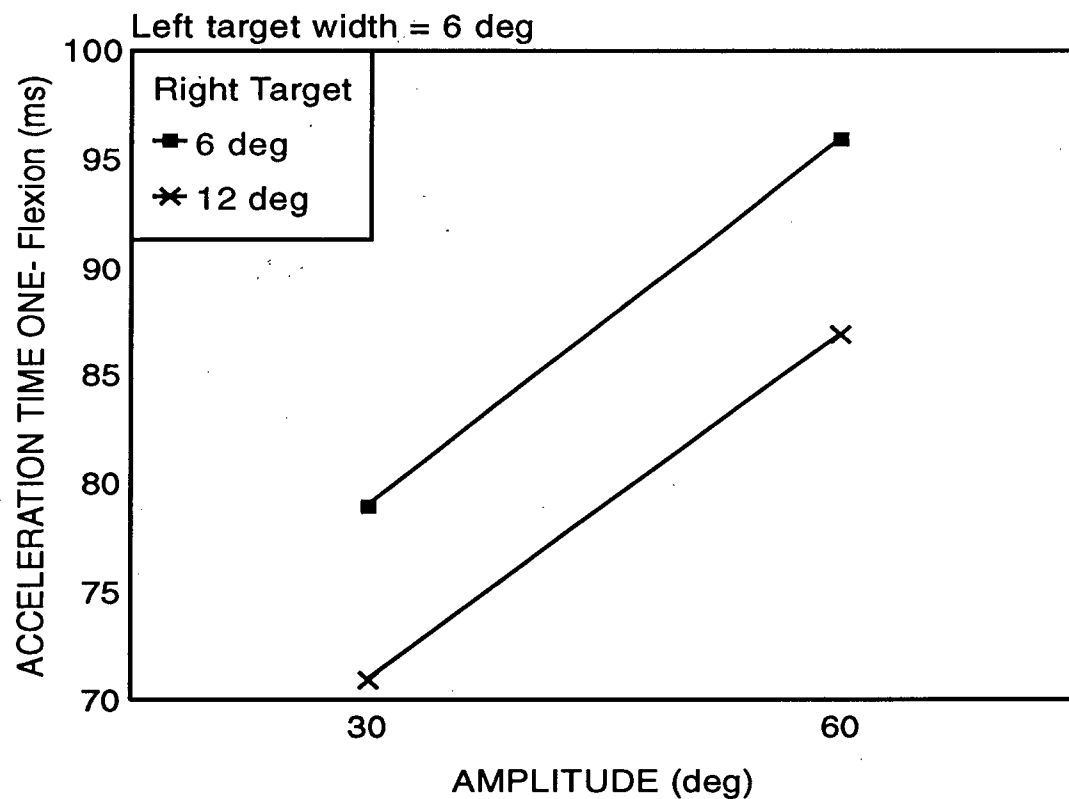


FIGURE 21: Acceleration Time One, Flexion Movement



width were doubled. Since the ID remains constant in this case, Fitts law would predict an invariant movement time. To test this hypothesis, the total movement time of 30° E and EF movements with equal left and right target widths of 6° were compared to similar movements with a 60° amplitude and 12° target widths. The results of a 2 (movement) by 2 (amplitude/target size) RM ANOVA indicated significant main effects of both movement,  $F(1, 13) = 83.565$ ,  $p < .001$ , and amplitude/target size,  $F(1, 13) = 5.547$ ,  $p = .035$ . The total movement time of the EF movements was greater than that of the E movements which was expected due to the increased amplitude of the EF movement. However, contrary to the prediction provided by Fitts law, movement time significantly increased when the amplitude and target size were doubled (figure 22). The interaction effect was not significant ( $p > .05$ ).

#### *Flexion Peak Velocity and Flexion Peak Acceleration*

The results of a 2 x 2 x 2 RM ANOVA on the peak velocity and the peak acceleration data of the flexion movements (FPV and FPA, respectively) indicated significant main effects for amplitude and right target size (table 3). Both FPV and FPA were greater for the 60° movement than they were for the 30° movement, and were also greater for the 12° right target than they were for the 6° right target (figures 23 and 24, respectively). All other effects were not significant ( $p > .05$ ).

#### *Indications of On-Line Control: Extension Movement*

The number of significant deviations and the number of zero line crossings in the acceleration profile were used as indications of on-line control in the present experiment. For the number of significant deviations in the extension movement (EDEV), the 2 x 2 x 2 x 2 RM ANOVA revealed significant main effects of both amplitude and right target size (table 4). Specifically, EDEV was greater for the 60° movement than it was for the 30° movement, and was also greater for the 6° right target than it was for the 12° right target (figure 25). None of the other effects were significant ( $p > .05$ ).

FIGURE 22: Total Movement Time as a Function of Complexity, Amplitude, and Target Width

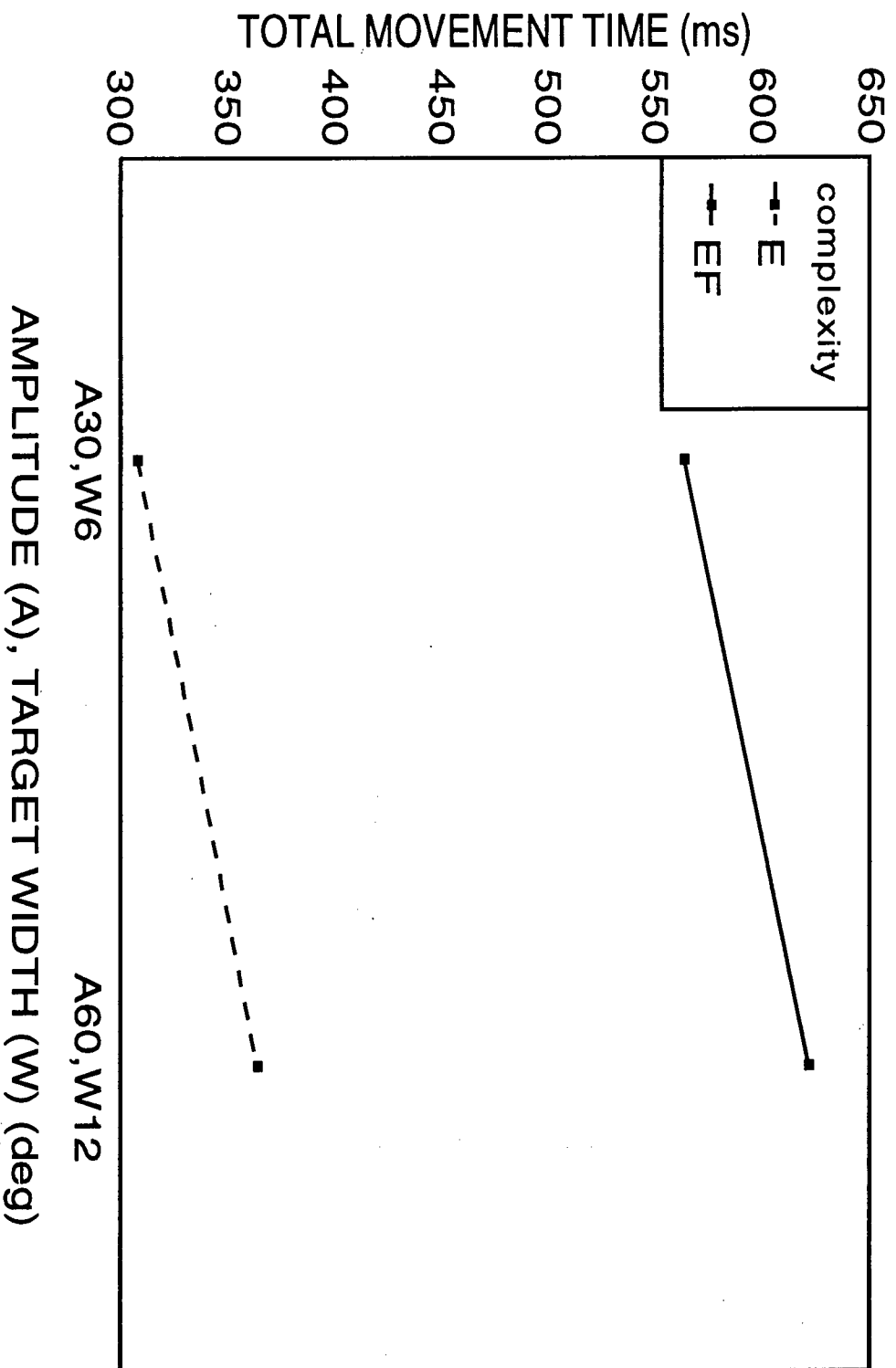


Figure 23: Peak Velocity,  
Flexion Movement

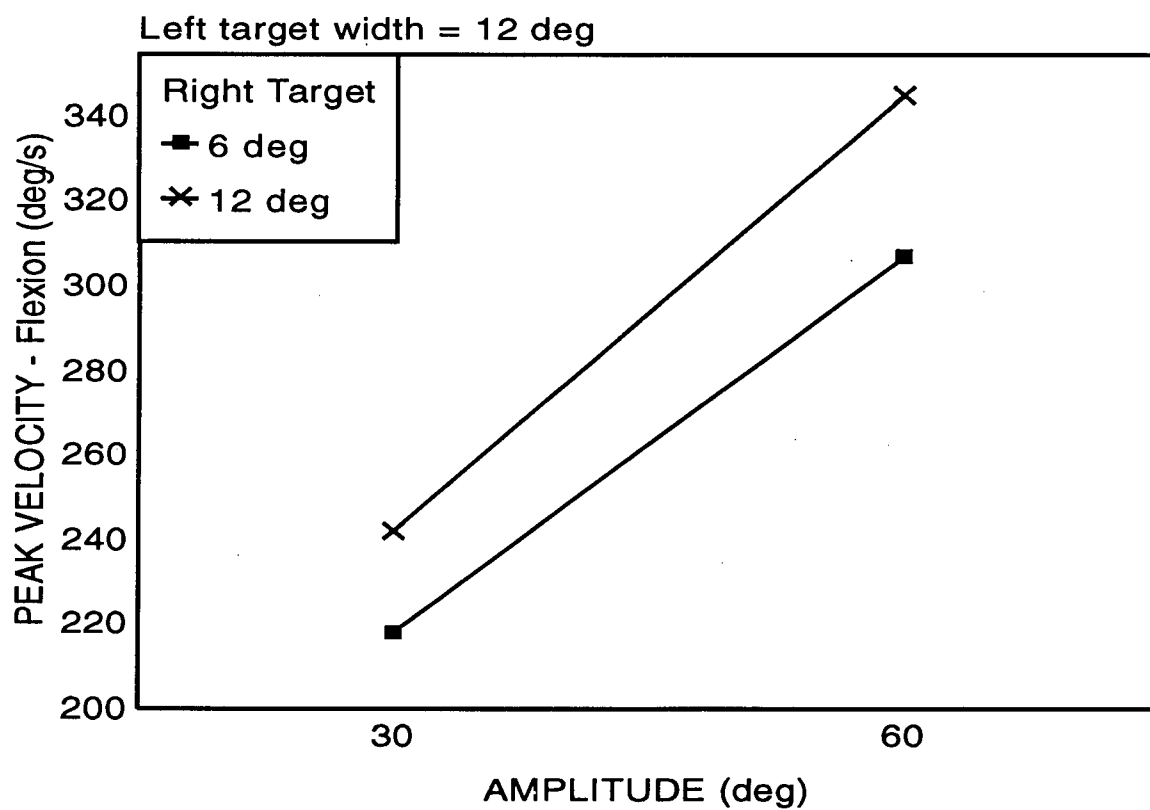
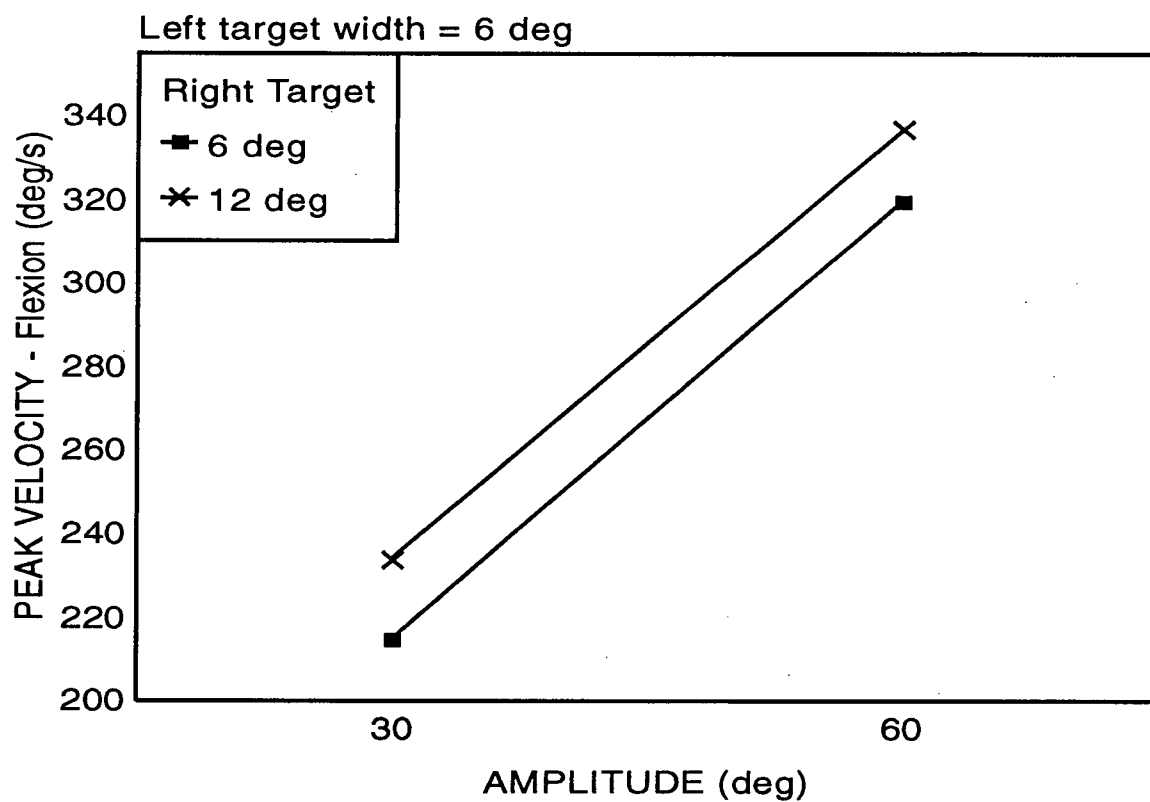
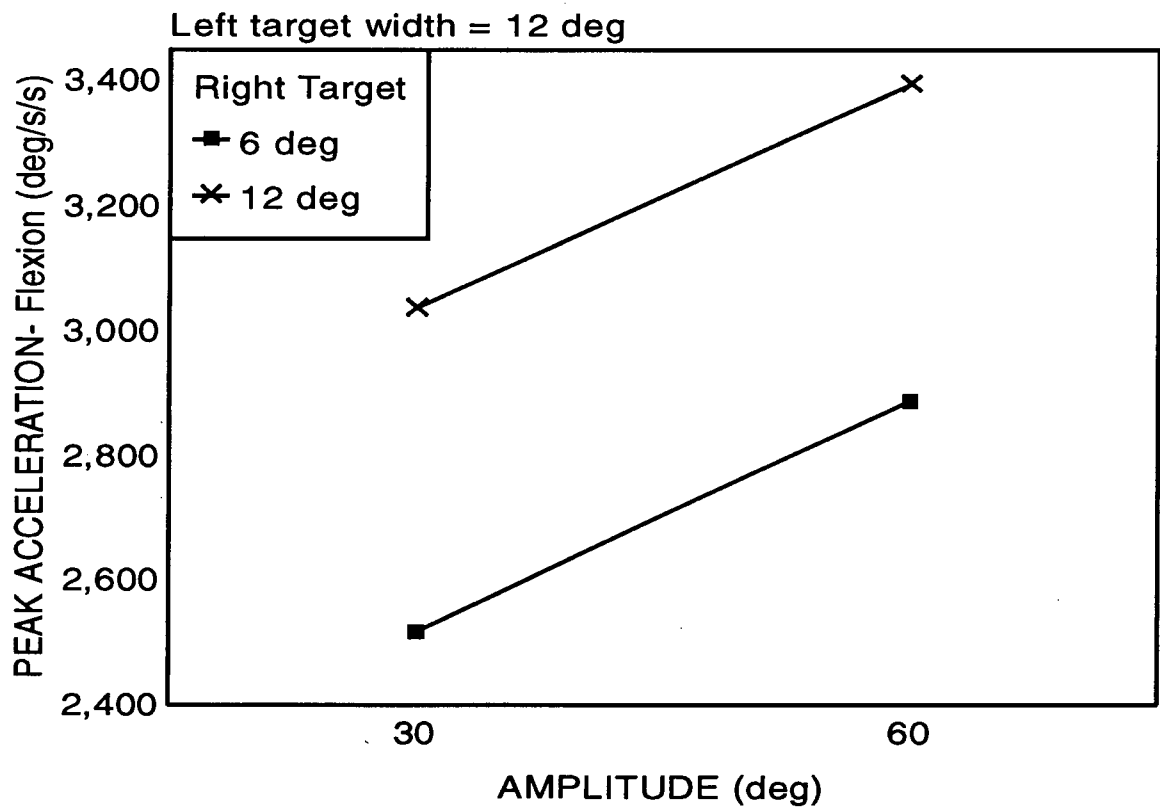
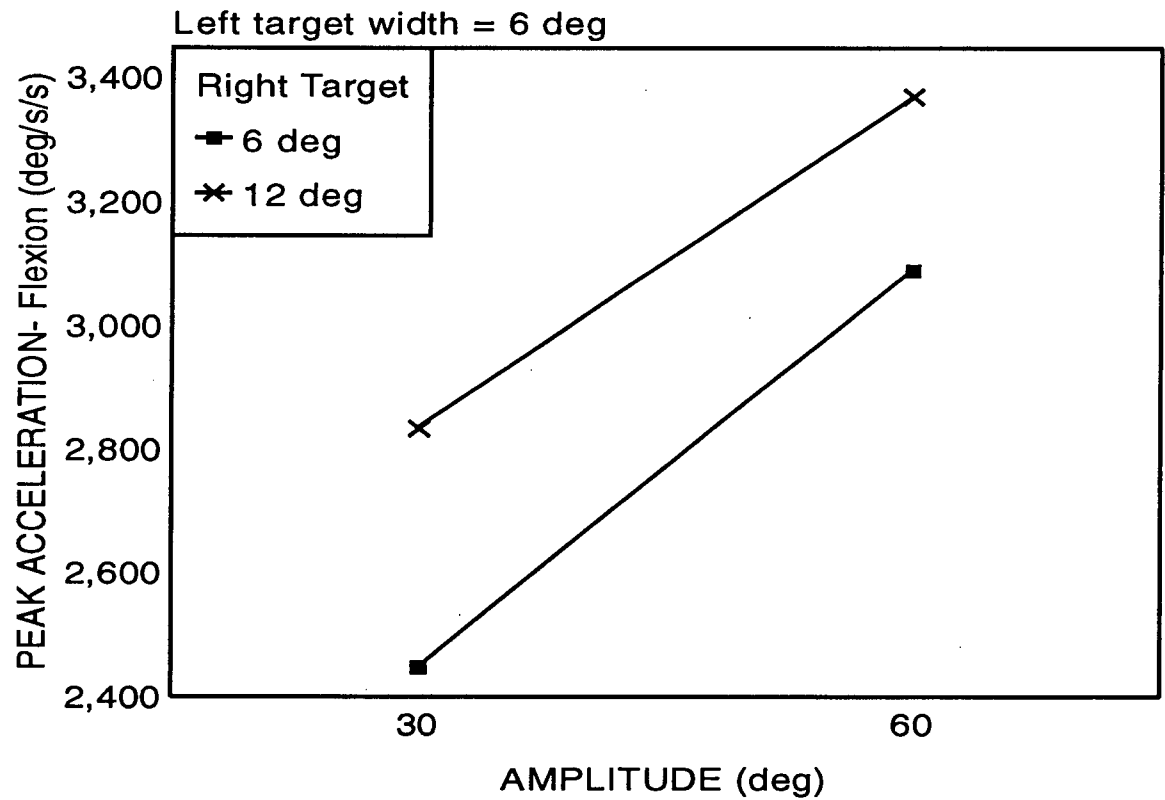


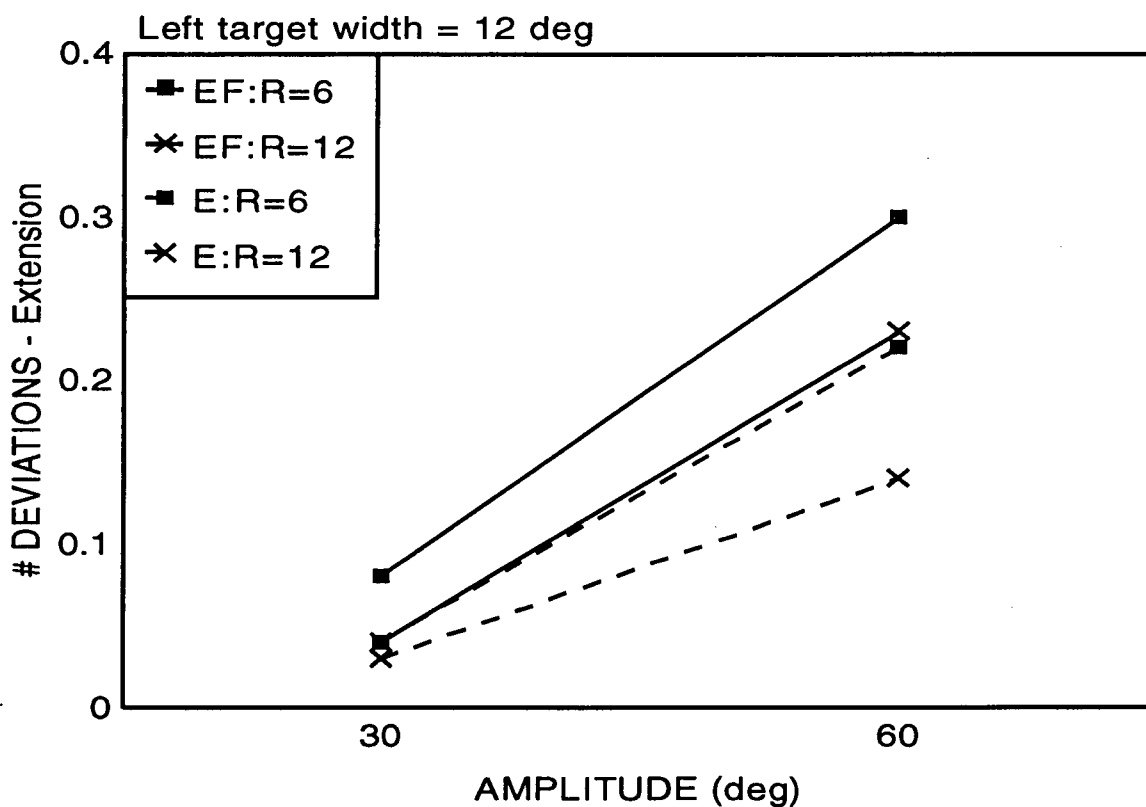
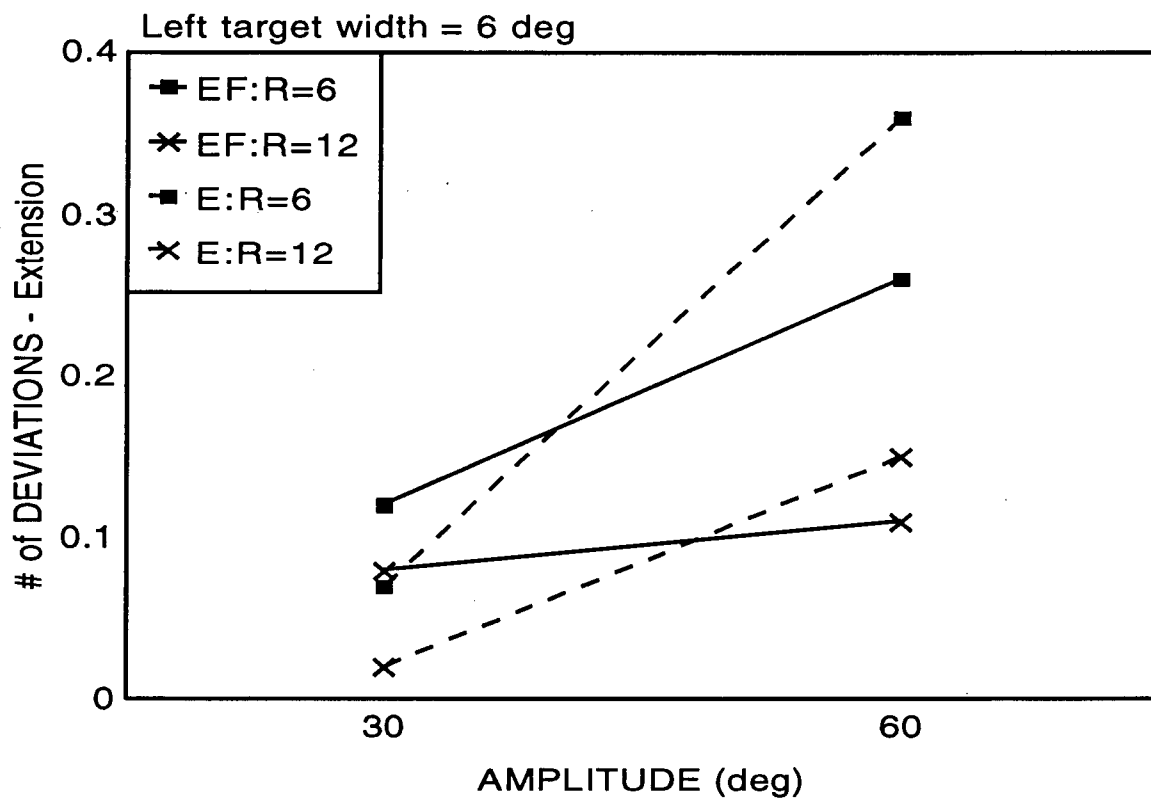
FIGURE 24: Peak Acceleration,  
Flexion Movement



**Table 4.** ANOVA results for the dependent variables number of significant deviations and number of zero line crossings for the extension and flexion movements. All main effects and significant interaction effects are presented.

Effect	F-test	p-value	p <.05
<i>Extension # of Deviations (EDEV)</i>			
movement	$F(1, 13) = 0.306$	$p = .59$	
amplitude	$F(1, 13) = 25.276$	$p < .001$	*
left target size	$F(1, 13) = 0.472$	$p = .504$	
right target size	$F(1, 13) = 7.552$	$p = .017$	*
<i>Extension # of Zero Line Crossings (EZLC)</i>			
movement	$F(1, 13) = 53.538$	$p < .001$	*
amplitude	$F(1, 13) = 8.906$	$p = .011$	*
left target size	$F(1, 13) = 0.003$	$p = .957$	
right target size	$F(1, 13) = 24.546$	$p < .001$	*
movement x right target interaction	$F(1, 13) = 4.757$	$p = .048$	*
<i>Flexion # of Deviations (FDEV)</i>			
amplitude	$F(1, 13) = 8.743$	$p = .011$	*
left target size	$F(1, 13) = 0.832$	$p = .378$	
right target size	$F(1, 13) = 4.322$	$p = .058$	
<i>Flexion # of Zero Line Crossings (FZLC)</i>			
amplitude	$F(1, 13) = 0.228$	$p = .641$	
left target size	$F(1, 13) = 7.289$	$p = .018$	*
right target size	$F(1, 13) = 0.013$	$p = .911$	

FIGURE 25: Number of Significant Deviations, Extension Movement





For the number of extension movement zero line crossings (EZLC), the main effects of movement, amplitude, and right target size were significant (table 4). EZLC was greater for the E condition than it was for the EF condition, greater for the 60° movement than it was for the 30° movement, and greater for the 6° right target, as compared to the 12° right target (figure 26). In addition, a significant movement by right target size interaction effect indicated that the difference between the 6° right target and the 12° right target was greater at 60° than it was at 30°. All other effects were not significant ( $p > .05$ ). These EZLC differences were further analyzed by investigating the number of trials per condition (out of a total of 7) which had more than the minimal number of zero line crossings. On a trial with no additional zero line crossings, an extension movement was defined to have one zero line crossing. For the main effect of amplitude, a discrepancy occurred between the EZLC data and the data from the number of trials with more than one zero line crossing; the main effect of amplitude for the data from the number of trials was not significant ( $p > .05$ ). Thus, the increase in EZLC from 30° to 60° was due to an increase in the number of zero line crossings which occurred within each trial, as the number of trials with more than one zero line crossing remained constant. To summarize, if both EDEV and EZLC are used to indicate the occurrence of on-line control, it appears that subjects adopted on-line movement control during extension movements when the amplitude was larger and when the right target size was smaller. In addition, subjects utilized on-line control in the extension movement more than they did in the extension segment of the EF movement.

#### *Indications of On-Line Control: Flexion Movement*

The 2 x 2 x 2 RM ANOVA for the number of significant deviations which occurred during the flexion movement (FDEV) indicated a significant main effect of amplitude and that of right target size approached significance ( $p = .058$ , table 4). FDEV was greater for the 60° movement than it was for the 30° movement and was also greater for the 6° right target than it was for the 12° right target (figure 27). All other effects were not significant ( $p > .05$ ).

FIGURE 26: Number of Zero Line Crossings, Extension Movement

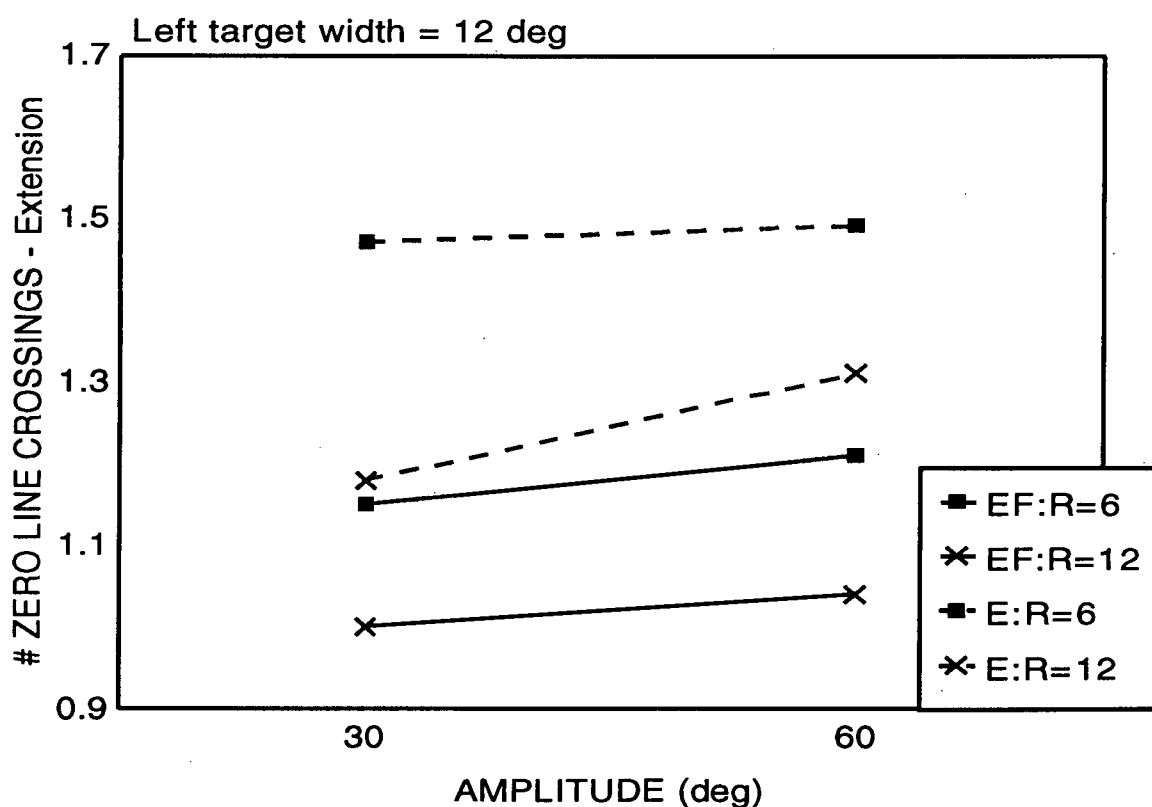
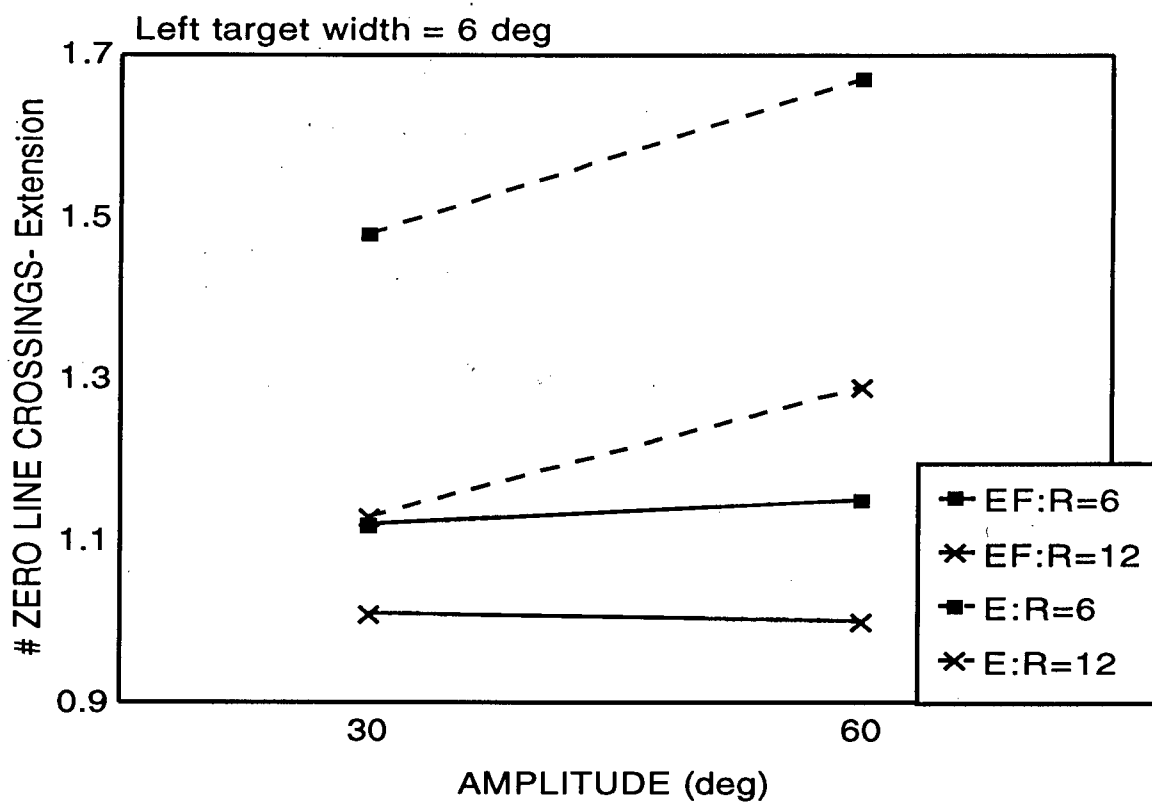
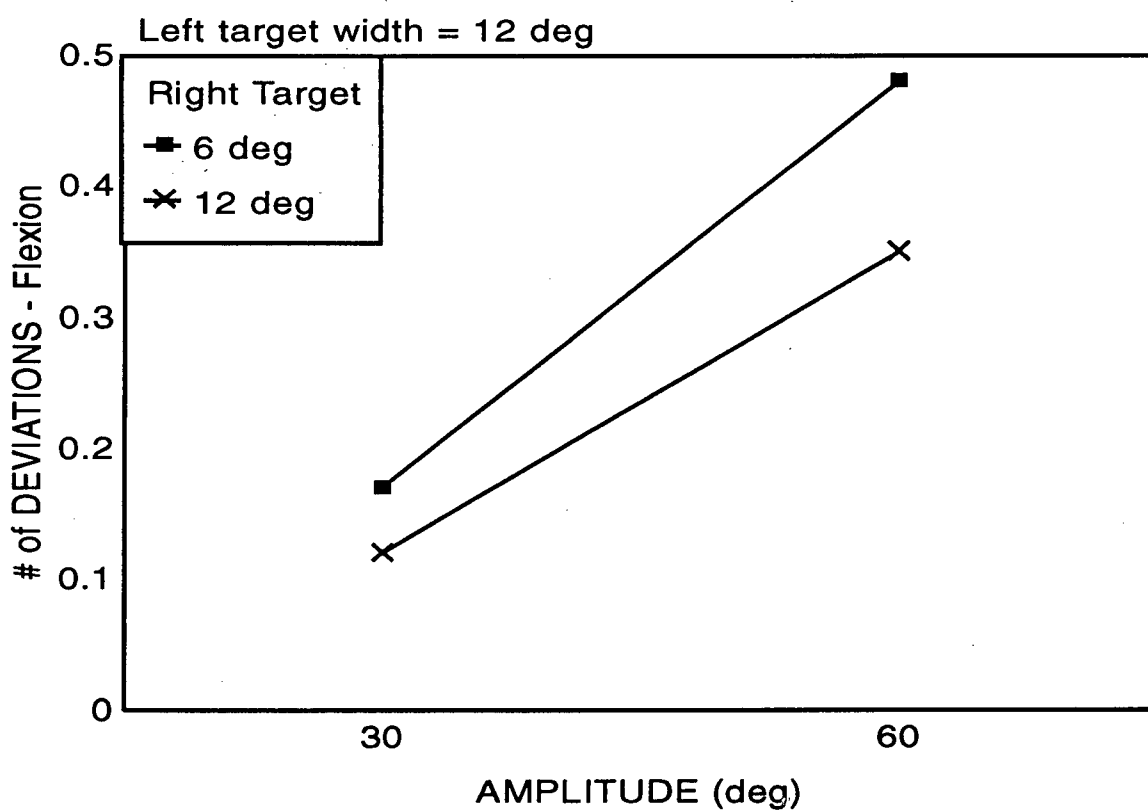
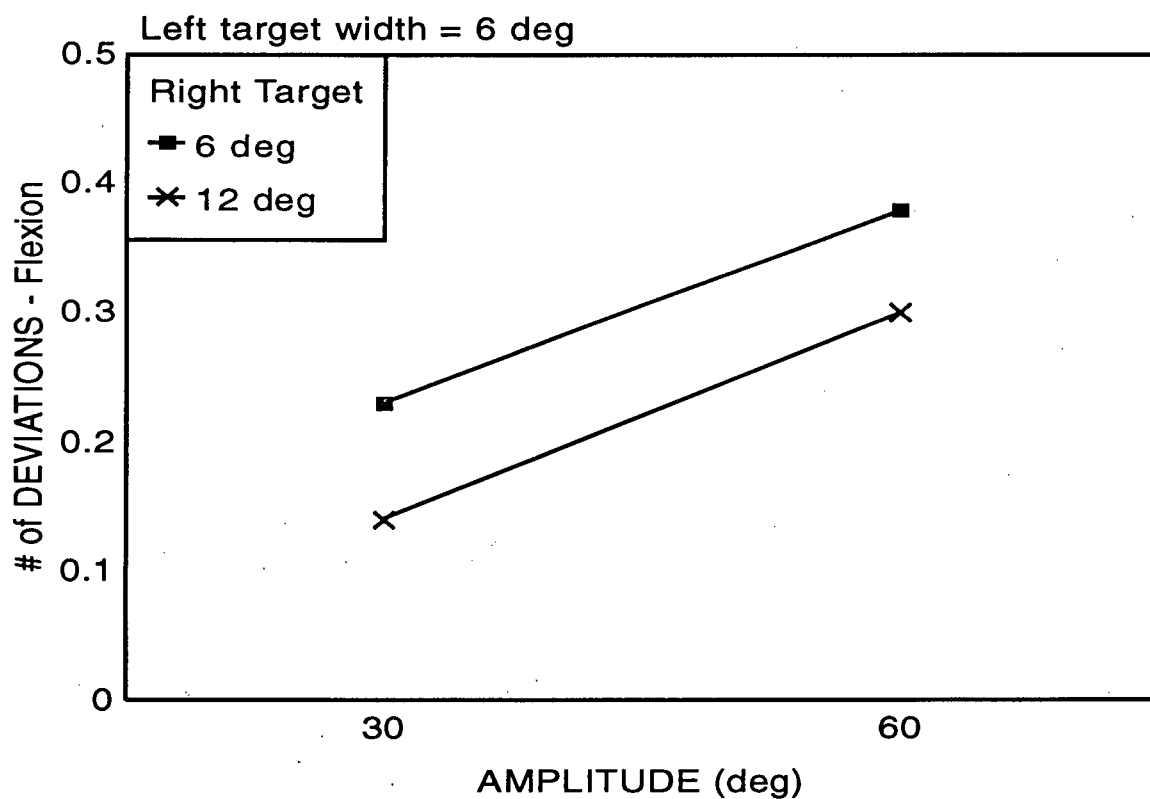


FIGURE 27: Number of Significant Deviations, Flexion Movement



The number of flexion movement zero line crossings (FZLC) was found to be significantly greater for the 6° left target than it was for the 12° left target (table 4, figure 28). However, a RM ANOVA on the number of trials (out of 7) which had more than the minimal number of zero line crossings (2 for the flexion movement) indicated that the main effect of left target size was not significant,  $F(1, 13) = 2.586$ ,  $p = .132$ . Thus, the increase in FZLC which occurred with a decreased left target size was due to an increase in the number of zero line crossings within each trial, rather than to an increase in the number of trials which had more than the minimal number of zero line crossings. None of the other effects were significant ( $p > .05$ ). Summarizing the results of both FDEV and FZLC, it appears that subjects utilized on-line control during the flexion movements when the amplitude was larger and when the left target was smaller.

#### *Reversal Point Distance and Variability*

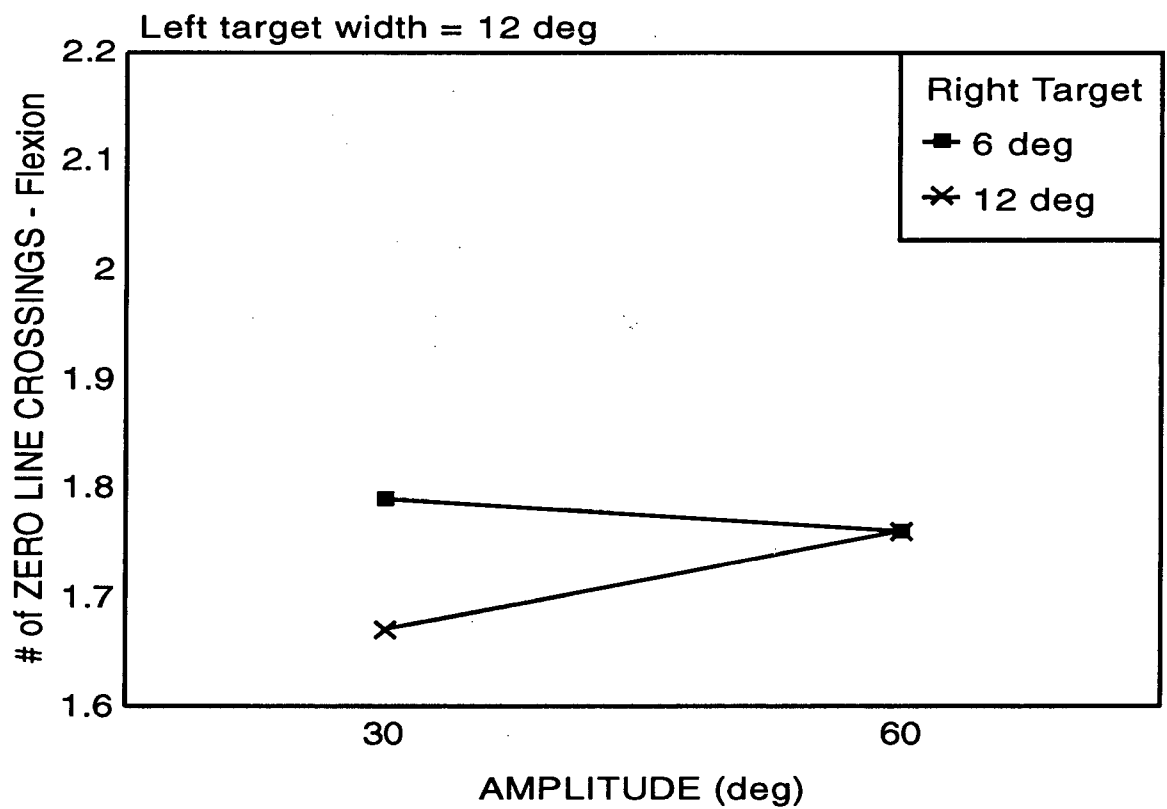
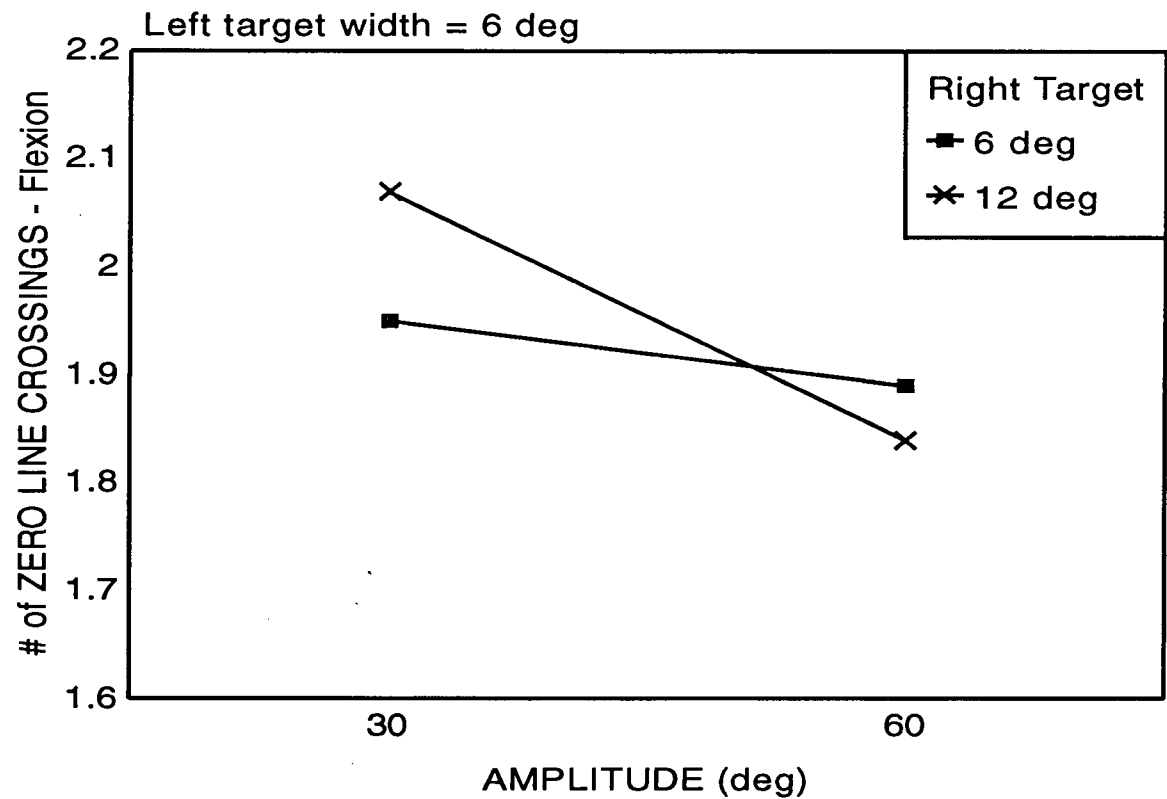
For the flexion movements, the point of reversal on the right target was analyzed in terms of location (distance from the center of the target) and variability (RPD and RPV, respectively). The 2 x 2 x 2 RM ANOVA for RPD indicated a significant main effect for amplitude (table 5); subjects reversed direction to the left of target center in the 60° amplitude condition, but reversed direction to the right of target center in the 30° amplitude condition (figure 29). All other effects were not significant ( $p > .05$ ).

Significant main effects of both amplitude and right target size were found for RPV (table 5). The point at which subjects reversed their movement was more variable for the 60° movement than it was for the 30° movement and was also more variable for the 12° right target than it was for the 6° right target (figure 30). None of the other effects were significant ( $p > .05$ ).

#### *EMG Patterns*

The EMG data were classified according to patterns of agonist and antagonist burst

FIGURE 28: Number of Zero Line Crossings, Flexion Movement



**Table 5.** ANOVA results for the dependent variables reversal point distance and reversal point variability. All main effects are presented (there were no significant interaction effects).

Effect	F-test	p-value	p < .05
<i>Reversal Point Distance (RPD)</i>			
amplitude	$F(1, 13) = 7.725$	$p = .016$	*
left	$F(1, 13) = 0.026$	$p = .875$	
right	$F(1, 13) = 0.142$	$p = .713$	
<i>Reversal Point Variability (RPV)</i>			
amplitude	$F(1, 13) = 14.428$	$p = .002$	*
left target size	$F(1, 13) = 0.07$	$p = .795$	
right target size	$F(1, 13) = 106.503$	$p < .001$	*

FIGURE 29: Reversal Point Distance

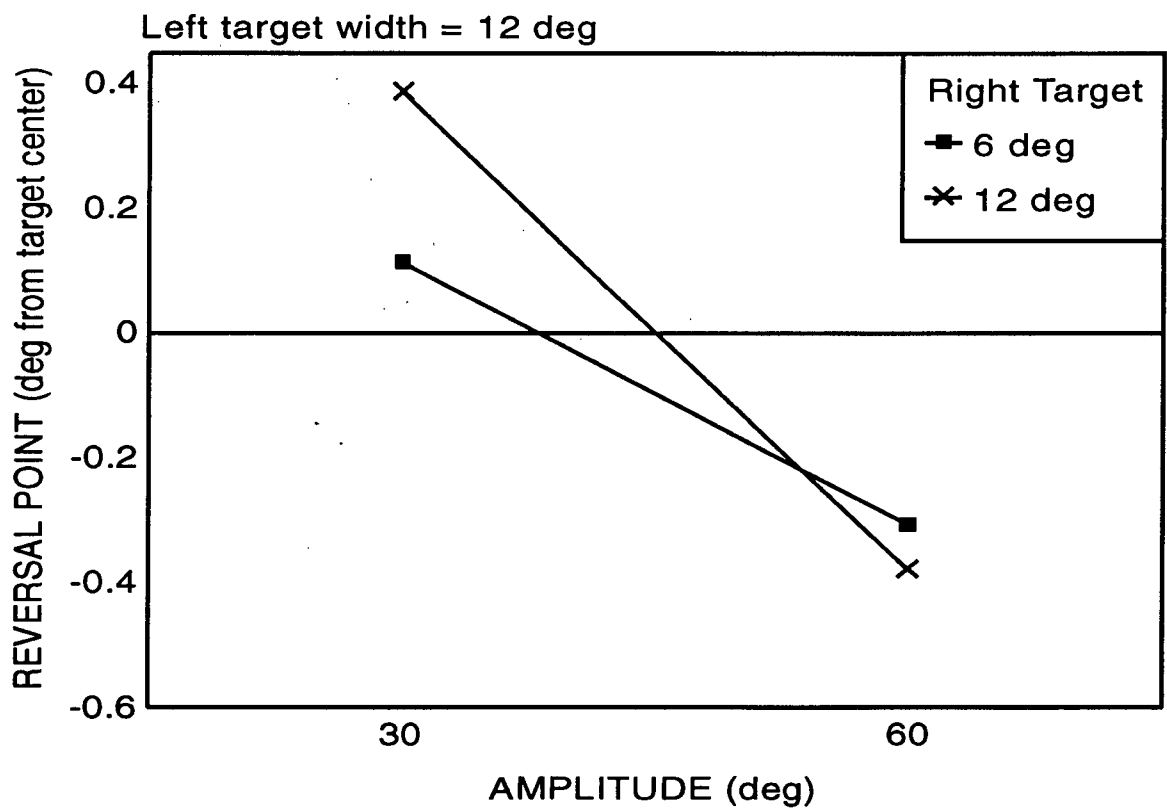
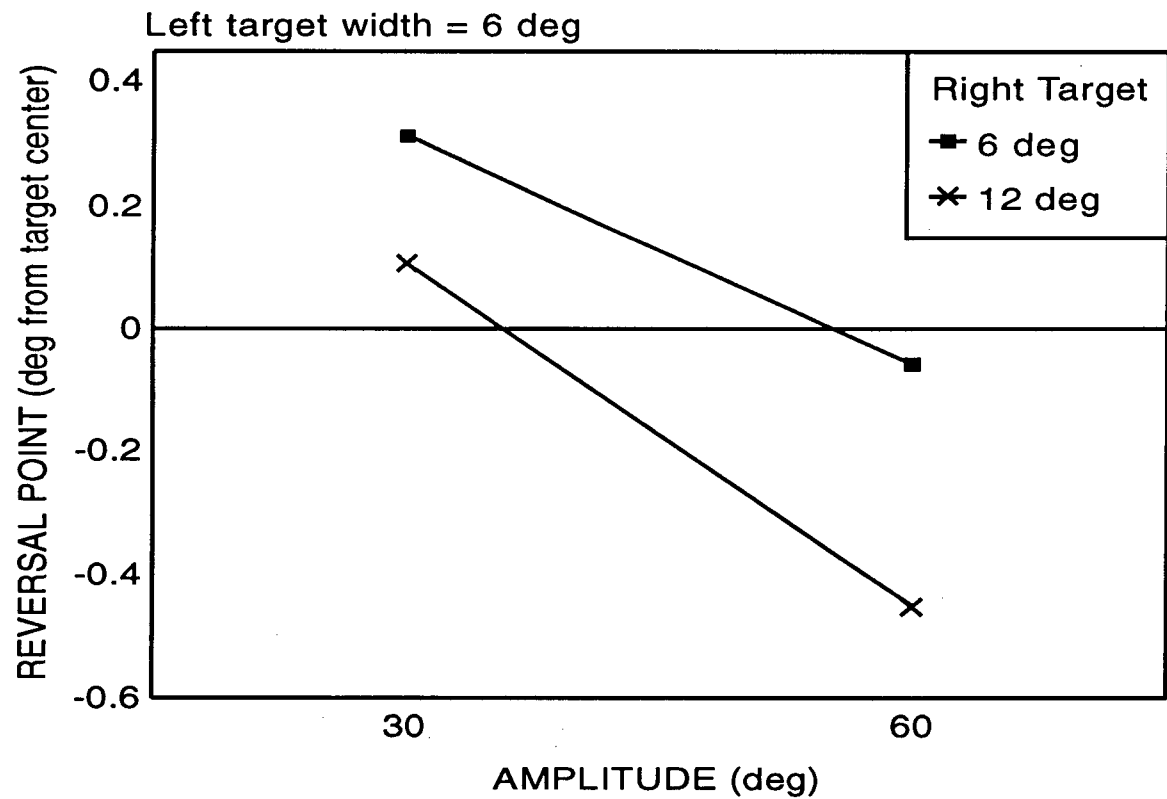
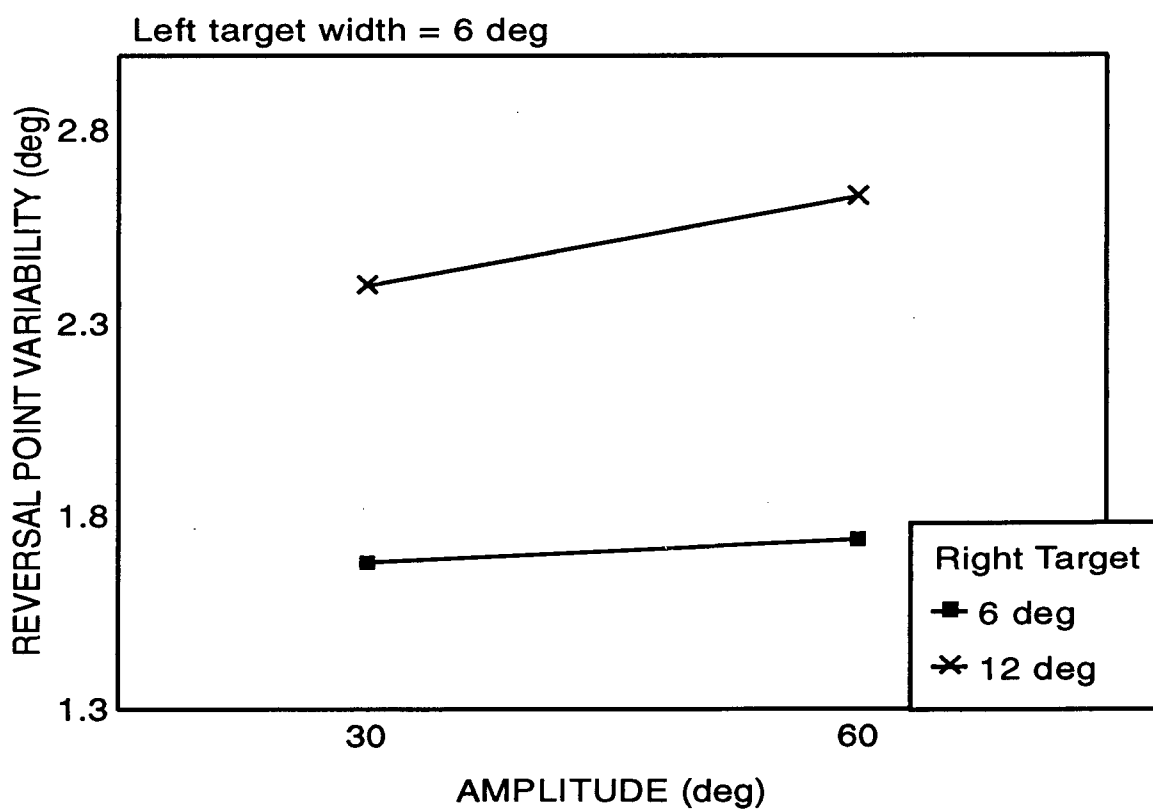
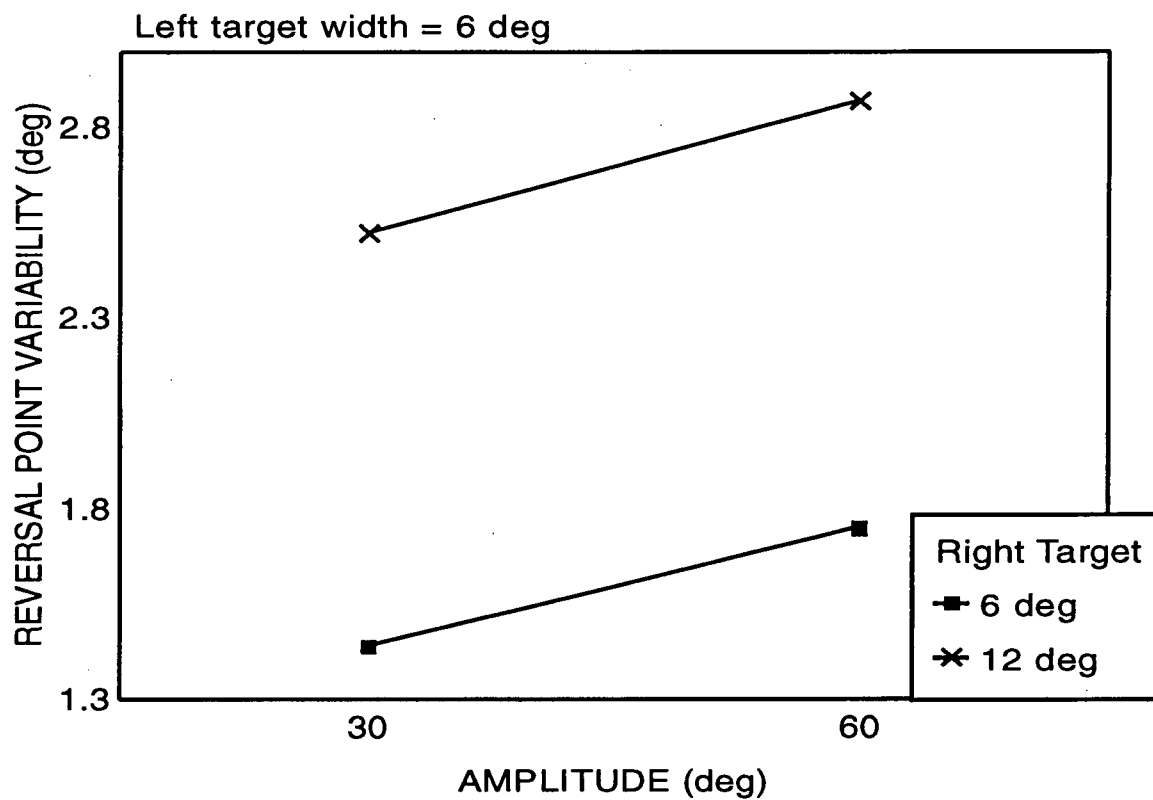


FIGURE 30: Reversal Point Variability





activity: triphasic, biphasic and co-contraction patterns for the E movements and quadruphasic, triphasic, and co-contraction patterns for the EF movements. The rate of occurrence of each of these patterns (i.e., the number of trials on which a particular pattern occurred, within each experimental condition) was described averaged across subjects as well as averaged across experimental conditions. For the extension movements, subjects appeared to use similar EMG patterns regardless of amplitude or target size (table 6A). Further, subjects tended to use either the co-contraction EMG pattern or the triphasic pattern consistently (table 6B). Therefore, the similarity between the number of trials per condition which used these two patterns was in fact due to the relatively equal number of subjects who chose to use each of these patterns in a consistent manner. For the EF movements, subjects also used similar EMG patterns regardless of amplitude or target size (tables 7A and 7B).

The EMG patterns were further analyzed in terms of the chronological order with which they occurred. Specifically, all testing trials which met the acceptable trial criteria and occurred subsequent to a previous discarded trial (due to a missed target or a non-continuous movement, within one experimental condition) were classified according to whether the subject utilized a co-contraction or a reciprocal innervation EMG pattern. Subjects were found to use a strategy of co-contraction on 61.5% of the trials which immediately followed a discarded trial, while they utilized a strategy of reciprocal innervation 38.5% of the time. On average, this event (acceptable trial following a discarded trial) was found to occur 21 times per subject. In addition, the EMG patterns were investigated in terms of whether or not a subject would continue to utilize a strategy of co-contraction if they had already performed at least two consecutive successful trials which utilized this strategy. Subjects were defined to have switched strategies if reciprocal innervation occurred on a consecutive trial (following at least two co-contraction trials) prior to the end of the experimental condition or the occurrence of a discarded trial. These circumstances occurred an average of 10 times for each subject and subjects were found to switch from a strategy of co-contraction to one of reciprocal innervation 23% of the time, while they maintained the co-contraction strategy 77% of the time.

**Table 6.** Rate of occurrence for each EMG pattern of the extension movement.

A) Described by condition, averaged over subjects. B) Described by subject, averaged over condition.

**A)**

Condition	Extension EMG Pattern		
	Triphasic	Biphasic	Co-Contraction
A30°, L6°, R6°	2.9	0.1	4.0
A30°, L6°, R12°	3.4	0.1	3.6
A30°, L12°, R6°	2.9	0.4	3.7
A30°, L12°, R12°	3.0	0.1	3.8
A60°, L6°, R6°	2.6	0.4	3.7
A60°, L6°, R12°	3.4	0.1	3.6
A60°, L12°, R6°	3.1	0.3	3.5
A60°, L12°, R12°	3.0	0.1	3.9
mean (sd)	3.0 (0.3)	0.2 (0.1)	3.7 (0.2)

**B)**

Subject	Extension EMG Pattern		
	Triphasic	Biphasic	Co-Contraction
1	0.0	0.0	7.0
2	6.1	0.4	0.5
3	0.0	0.0	7.0
4	4.8	1.0	1.3
5	2.5	0.8	3.8
6	1.6	0.1	5.3
7	2.4	0.3	4.1
8	5.0	0.1	1.9
9	1.4	0.0	5.5
10	5.9	0.1	0.6
11	6.9	0.0	0.1
12	0.1	0.0	6.8
13	1.1	0.1	5.6
14	4.4	0.2	2.6
mean (sd)	3.0 (2.4)	0.2 (0.3)	3.7 (2.5)

**Table 7.** Rate of occurrence of each EMG pattern of the extension-flexion movement.

A) Described by condition, averaged over subjects. B) Described by subject, averaged over condition. 'Quad' refers to the quadraphasic EMG pattern, 'Tri' refers to the triphasic EMG pattern, and 'Co-C' refers to the co-contraction EMG pattern.

**A)**

	Extension-Flexion EMG Pattern					
Condition	Quad-A	Quad-B	Tri-A	Tri-B	Co-C	Mid-Co-C
A30°, L6°, R6°	1.0	0.9	0.5	0.5	1.6	2.5
A30°, L6°, R12°	1.4	0.6	0.4	0.1	1.8	2.6
A30°, L12°, R6°	1.1	0.4	0.3	0.4	1.4	3.4
A30°, L12°, R12°	1.3	0.4	0.7	0.2	2.3	2.0
A60°, L6°, R6°	0.3	0.4	0.6	0.7	2.1	2.6
A60°, L6°, R12°	0.7	0.4	1.1	0.3	2.4	2.2
A60°, L12°, R6°	0.1	0.2	0.6	0.8	2.0	3.1
A60°, L12°, R12°	0.9	0.3	0.5	0.4	2.0	2.7
mean (sd)	0.9 (0.5)	0.4 (0.2)	0.6 (0.2)	0.4 (0.2)	2.0 (0.3)	2.7 (0.5)
total mean (sd)	1.3 (0.6)		1.0 (1.0)		4.7 (0.3)	

**B)**

	Extension-Flexion EMG Pattern					
Subject	Quad-A	Quad-B	Tri-A	Tri-B	Co-C	Mid-Co-C
1	0.0	0.0	0.0	0.0	7.0	0.0
2	0.5	1.5	0.3	1.1	0.0	3.3
3	0.0	0.0	0.0	0.0	7.0	0.0
4	3.6	1.3	2.4	0.1	0.5	0.1
5	0.3	0.9	0.1	0.5	3.0	2.3
6	2.1	0.3	0.0	0.0	4.0	0.5
7	0.1	0.0	0.3	0.3	1.3	5.1
8	0.1	0.4	0.1	0.1	0.3	6.0
9	0.0	1.1	0.0	0.1	1.5	4.0
10	1.3	0.0	0.3	0.0	0.1	5.4
11	0.5	0.5	1.5	1.0	0.1	3.3
12	1.5	0.6	1.0	0.3	0.4	2.3
13	0.9	0.3	1.1	0.4	1.9	2.5
14	1.3	0.4	1.4	1.0	0.4	2.6
	0.9 (1.0)	0.4 (0.5)	0.6 (0.7)	0.4 (0.5)	2.0 (2.5)	2.7 (2.0)
total mean (sd)	1.3 (1.1)		1.0 (1.0)		4.6 (1.9)	

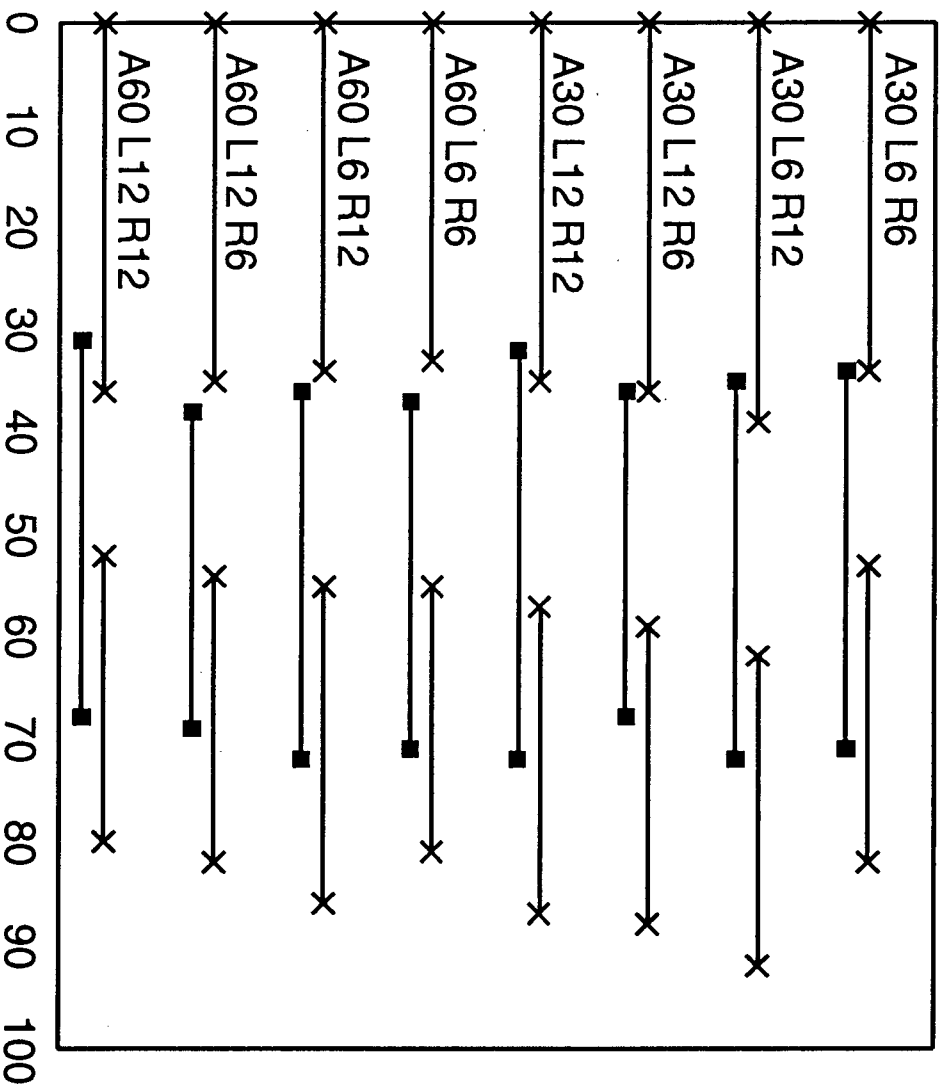
### *EMG Burst Durations*

For the extension movements, the durations of the triceps and biceps EMG bursts were described in terms of a percentage of the extension movement time for each trial. The percentage durations in both the triphasic and the biphasic patterns (figures 31 and 32, respectively) remained consistent regardless of the amplitude or target size. The percentage durations of the triceps and biceps EMG bursts of the extension-flexion movements (in relation to the total movement time) also remained consistent regardless of the amplitude or target size. This trend held for the quadruphasic-A, quadruphasic-B, triphasic-A, triphasic-B, and mid-co-contraction patterns (figures 33, 34, 35, 36, and 37, respectively).

### *Slope of Initial Triceps Burst*

The variation in the slope and the height of the initial triceps burst was evaluated for the following comparisons: small and large left target size, small and large amplitude, and small and large right target size (tables 8A, 8B, and 8C, respectively). Subjects were included in the comparison if they utilized the same EMG pattern on at least five trials within an experimental condition. The comparisons were evaluated individually for each subject and the results often differed between subjects. For example, the comparison of the triceps EMG slope between the large and small amplitudes could yield three possible results: the slope could be steeper for the large amplitude than it was for the small amplitude, the slope could be steeper for the small amplitude than it was for the large amplitude, or the slope of both amplitudes could be similar. The result of a comparison was only considered to be consistent if the majority of the subjects who qualified for each comparison had similar results. Comparing the EMG profiles for the small and large left target sizes, the slope of the initial triceps burst increased when the left target was larger, but only for the 60° movement amplitude (figure 38). In addition, for the co-contraction movements, the height of the triceps EMG profile increased as the left target size increased (figure 39). The comparison of the EMG profiles of the small and large movement amplitudes indicated that the height increased as the amplitude of the movement increased,

FIGURE 31: Percent Duration of EMG Bursts, Extend Triphasic



\* Triceps  
■ Biceps

FIGURE 32: Percent Duration of EMG Bursts, Extend Biphasic

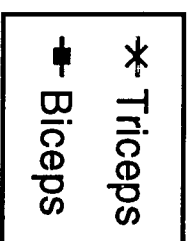
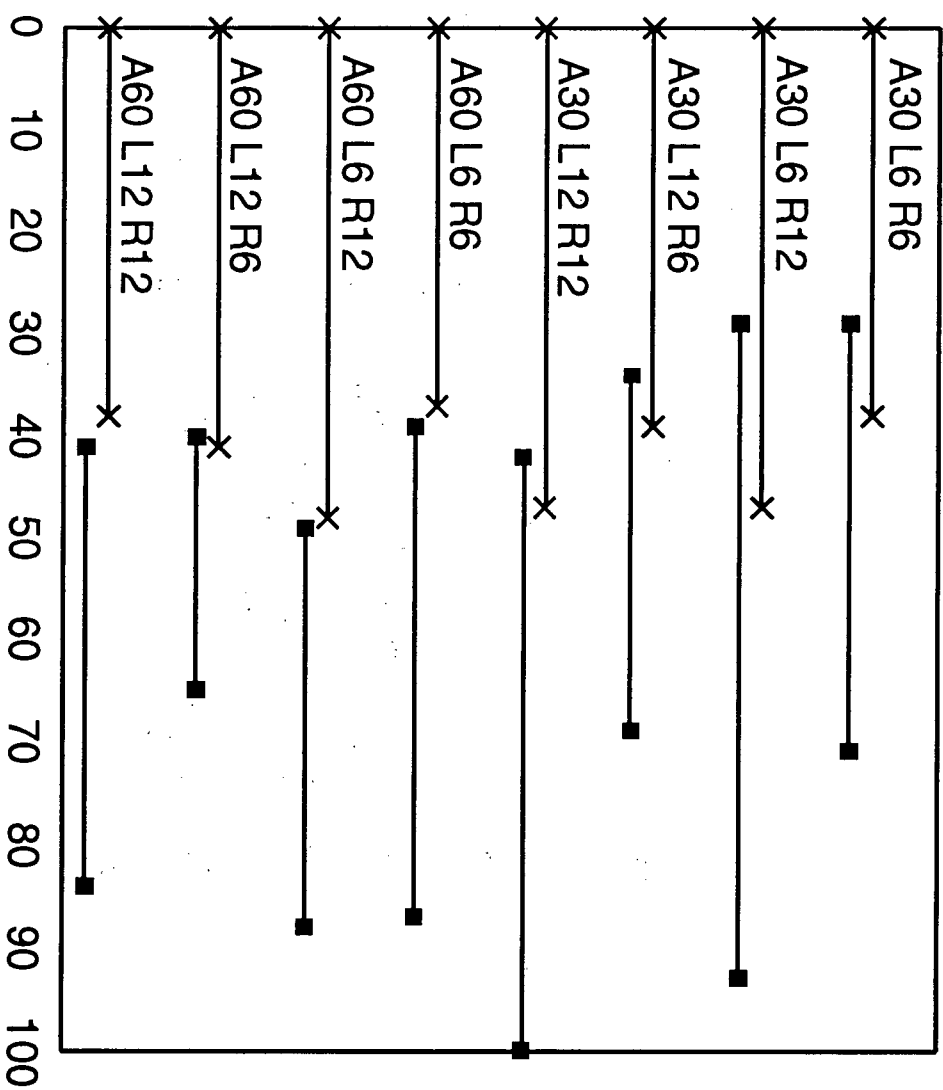
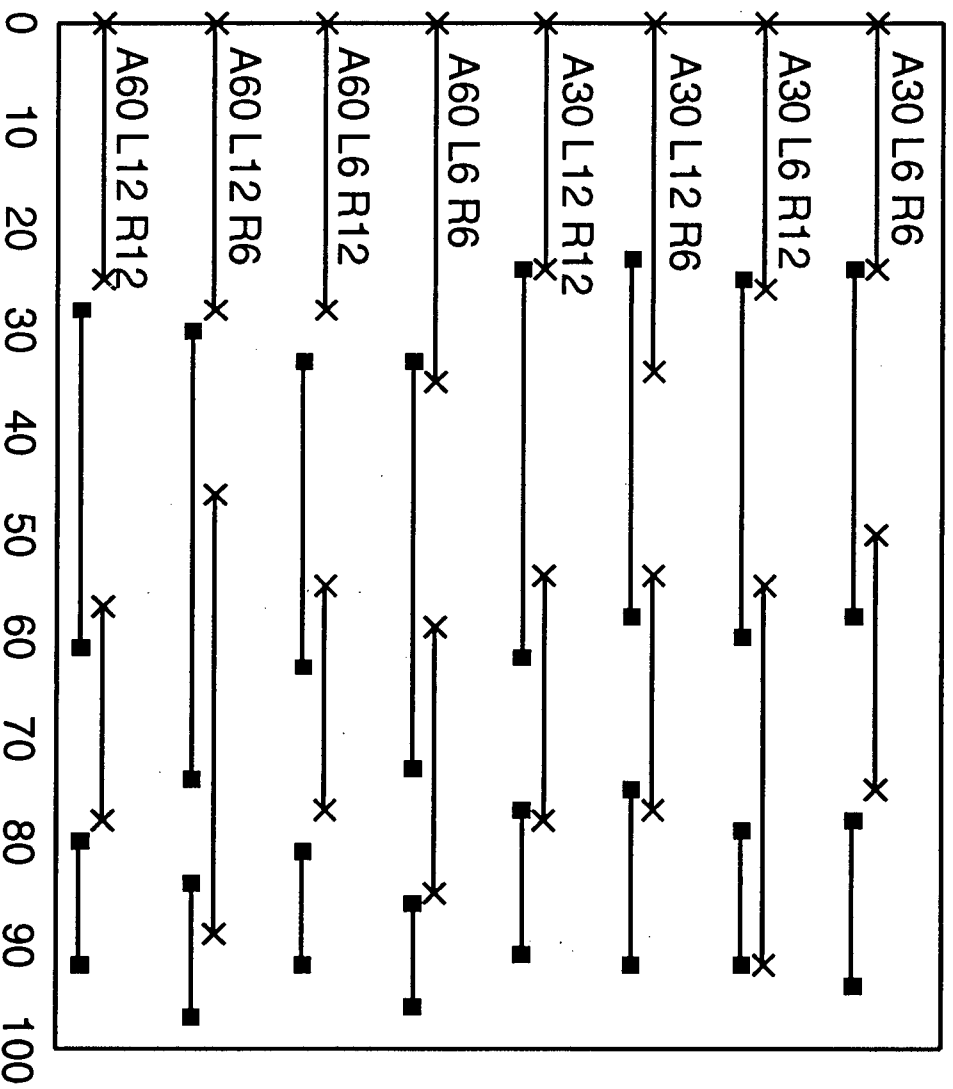
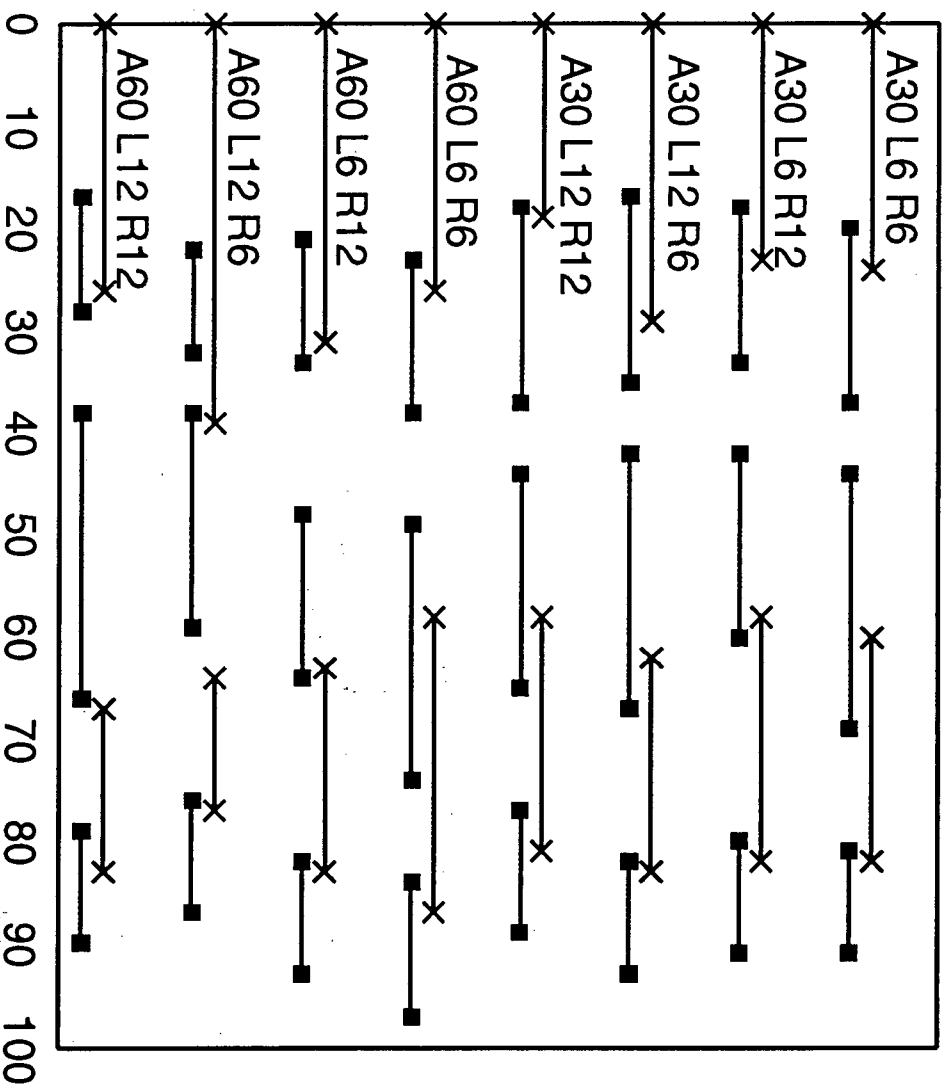


FIGURE 33: Percent Duration of EMG Bursts, Extend-Flex Quadraphasic-A



\* Triceps  
■ Biceps

FIGURE 34: Percent Duration of EMG Bursts, Extend-Flex Quadraphasic-B



x Triceps  
 ■ Biceps



FIGURE 35: Percent Duration of EMG Bursts, Extend-Flex Triphasic-A

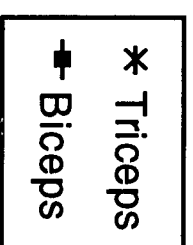
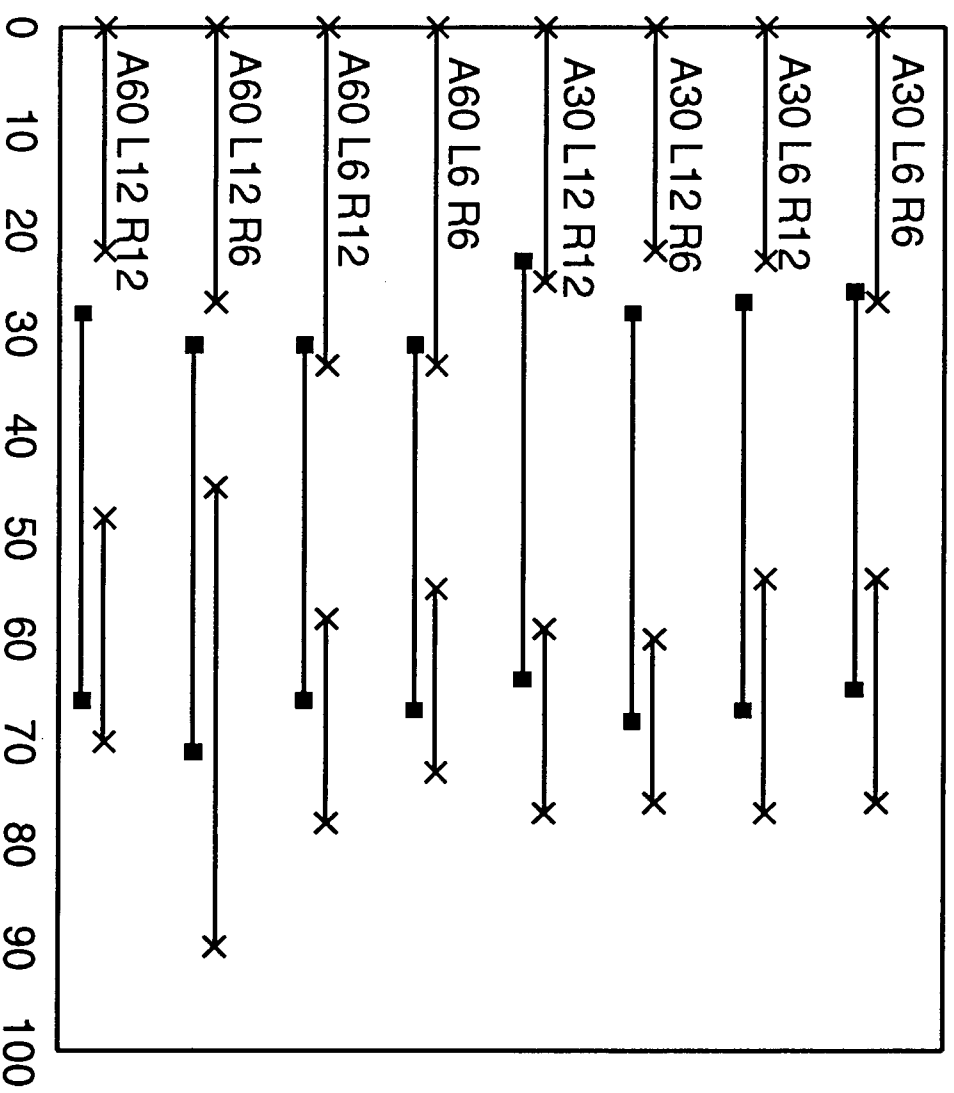


FIGURE 36: Percent Duration of EMG Bursts, Extend-Flex Triphasic-B

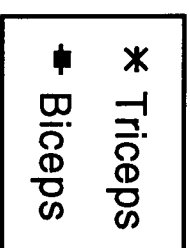
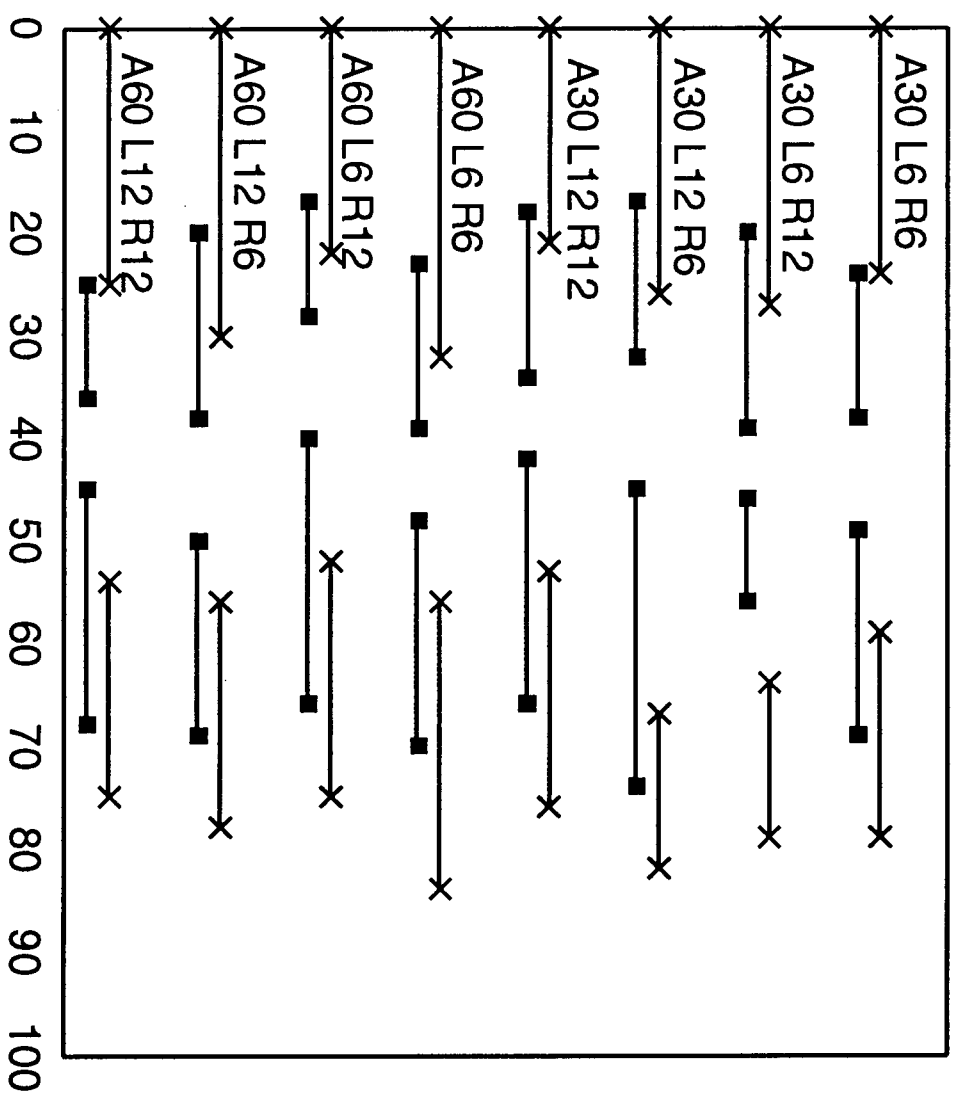
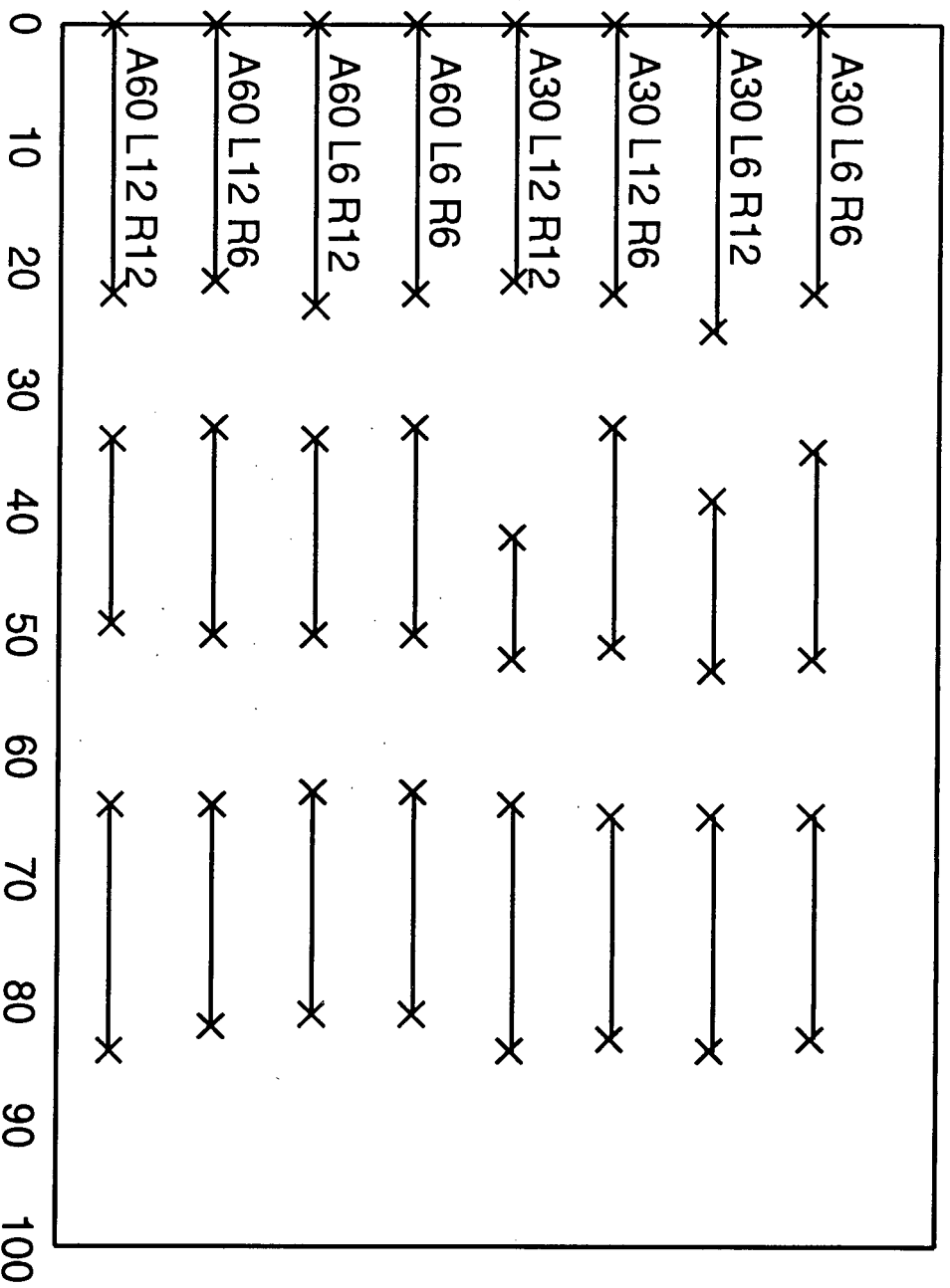


FIGURE 37: Percent Duration of Triceps Bursts,  
Extend-Flex Mid-co-contraction



**Table 8A.** Slope and height comparison of the initial triceps burst for the 6° and 12° left target sizes. Comparison includes extension movements only and is described in terms of the number of subjects which could be categorized according to the result of each comparison. 'A' refers to amplitude, 'R' refers to right target size, 'tri' refers to the triphasic EMG pattern, 'co-c' refers to the co-contraction EMG pattern, and 'L' refers to left target size.

amplitude & right target size	EMG pattern	total # subjects	slope or height comparison	# subjects
A30°, R12°	tri	4	slope: L6° > L12°	1
			slope: L12° > L6°	1
			similar slope	2
	co-c	5	height: L6° > L12°	1
			height: L12° > L6°	2
			similar height	1
A60°, R12°	tri	5	slope: L12° > L6°	1
			similar slope	4
			height: L6° > L12°	3
			similar height	2
	co-c	7	slope: L6° > L12°	1
			slope: L12° > L6°	3
			similar slope	3
			height: L12° > L6°	5
			similar height	2

**Table 8B.** Slope and height comparison of the initial triceps burst for the 30° and 60° amplitudes. Comparison includes extension movements only and is described in terms of the number of subjects which could be categorized according to the result of each comparison. 'L' refers to left target size, 'R' refers to right target size, 'tri' refers to the triphasic EMG pattern, 'co-c' refers to the co-contraction EMG pattern, and 'A' refers to the amplitude.

amplitude & right target size	EMG pattern	total # subjects	slope or height comparison	# subjects
L12°, R12°	tri	4	slope: A30° > A60°	1
			slope: A60° > A30°	1
	co-c	6	similar slope	2
			height: A60° > A30°	3
			similar height	1
			slope: A30° > A60°	2
L 12°, R6°	tri	2	slope: A60° > A30°	1
			similar slope	1
			height: A30° > A60°	1
	co-c	5	height: A60° > A30°	1
			slope: A30° > A60°	3
			slope: A60° > A30°	1
			similar slope	1
			height: A30° > A60°	2
			height: A60° > A30°	2
			similar height	1

**Table 8C.** Slope and height comparison of the initial triceps burst for the 6° and 12° right target sizes. Comparison includes extension movements only and is described in terms of the number of subjects which could be categorized according to the result of each comparison. 'A' refers to amplitude, 'L' refers to left target size, 'tri' refers to the triphasic EMG pattern, 'co-c' refers to the co-contraction EMG pattern, and 'R' refers to the right target size.

amplitude & right target size	EMG pattern	total # subjects	slope or height comparison	# subjects
A30°, L12°	tri	4	slope: R6° > R12°	1
			slope: R12° > R6°	2
			similar slope	1
	co-c	6	height: R6° > R12°	2
			height: R12° > R6°	2
			similar slope	4
A60°, L12°	tri	5	slope: R12° > R6°	1
			similar slope	4
			height: R6° > R12°	2
	co-c	6	height: R12° > R6°	1
			similar height	3
			similar height	3
A60°, L12°	tri	5	slope: R6° > R12°	2
			slope: R12° > R6°	3
			height: R12° > R6°	5
	co-c	6	slope: R12° > R6°	3
			similar slope	3
			height: R12° > R6°	5
A60°, L12°	tri	5	similar height	1
			similar height	1
			similar height	1
	co-c	6	similar height	1
			similar height	1
			similar height	1

FIGURE 38: Small vs. Large Left Target  
(60 deg amplitude, 12 deg right target)

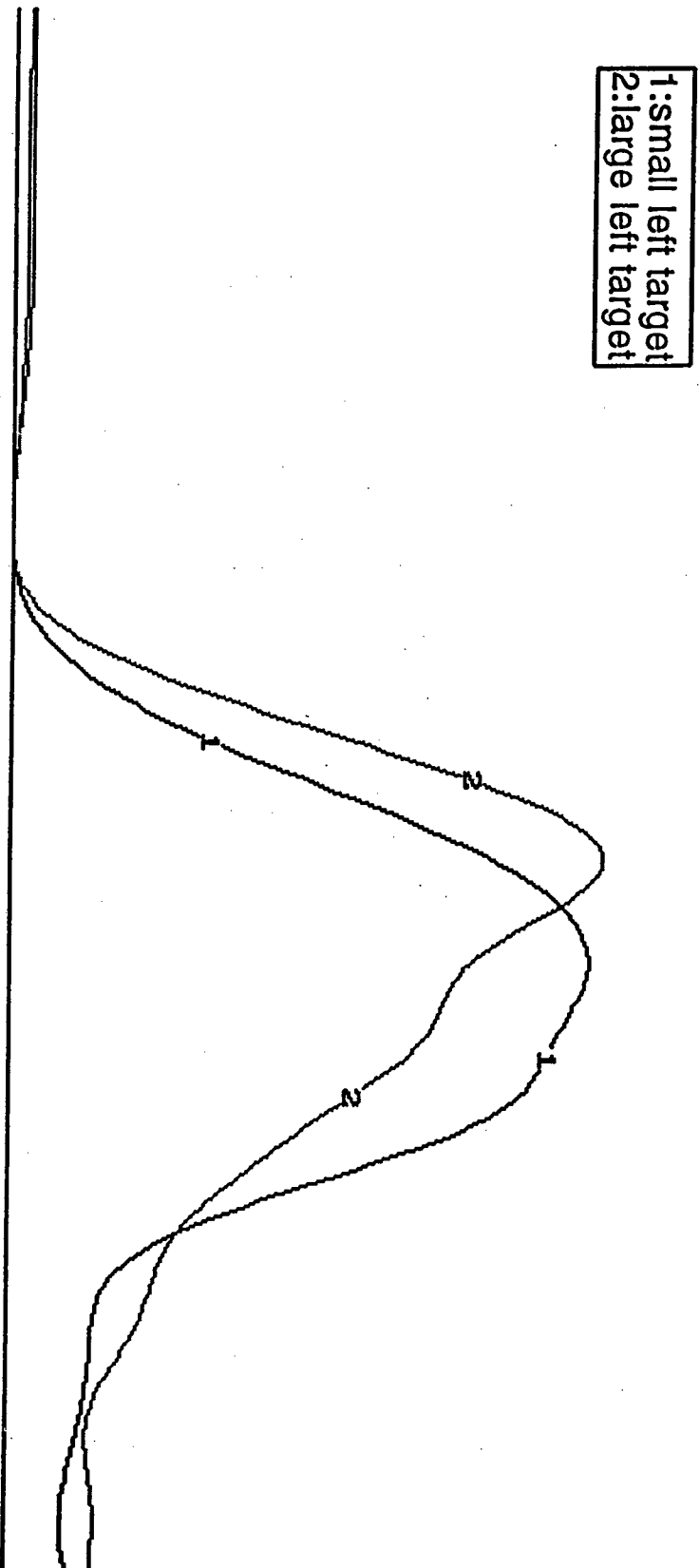
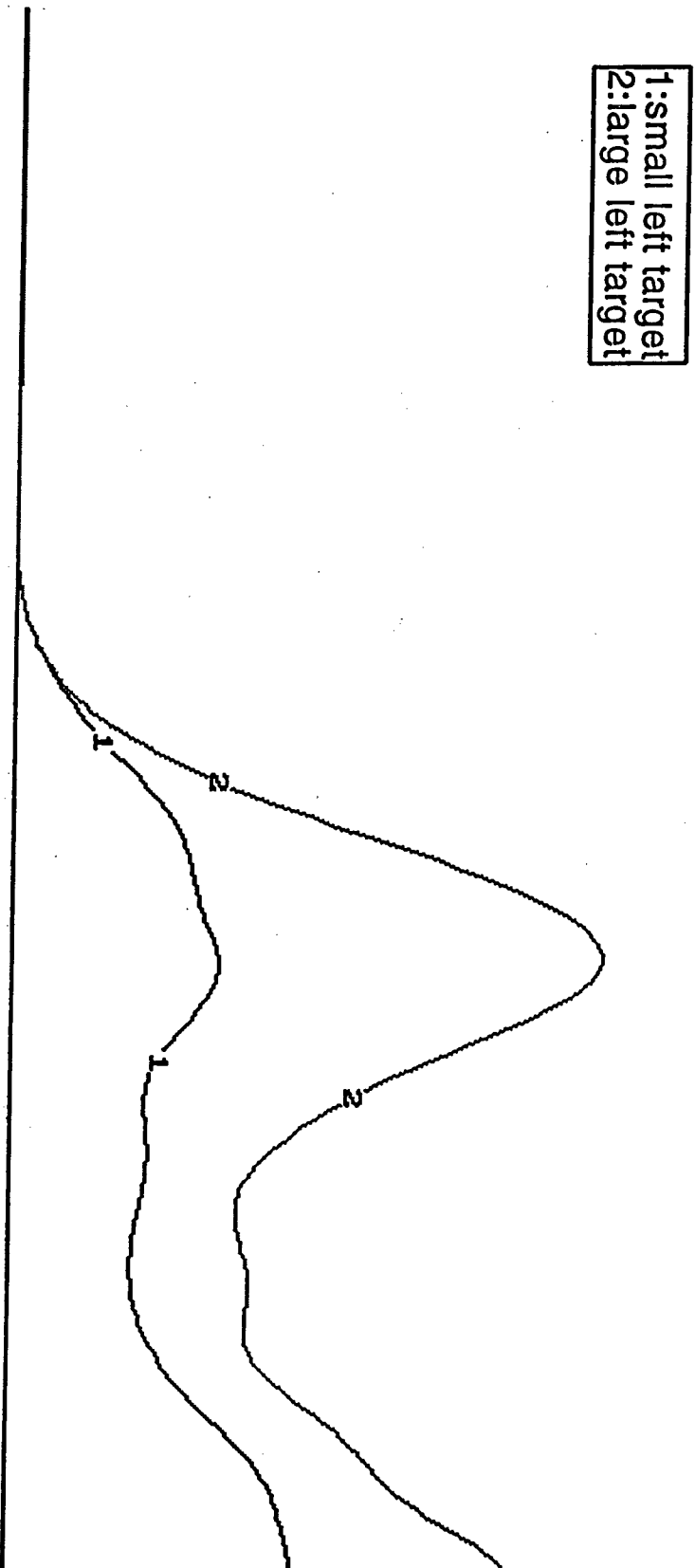


FIGURE 39: Small vs. Large Left Target  
(60 deg amplitude, 12 deg right target, co-contraction)





when the right target was 12° (figure 40). However, no consistent height increase occurred when the right target was 6° (figure 41). The triceps EMG profile of the 30° movement also had a steeper slope than did the 60° movement, when the right target was small and when the subjects utilized a co-contraction strategy (figure 42). Finally, the height of the triceps EMG profile consistently increased as the right target size increased, for the 60° amplitude only (figure 43). All other EMG height and slope comparisons did not yield consistent results.

### *Control Trials*

The extension movement time (ET) of the control trials was compared to that of the testing trials. For the E condition, the control trials were 2 ms longer (on average) than were the testing trials. However, since the control trials were faster than the testing trials in five of the eight conditions and slower than the testing trials in three conditions, the standard deviation was large (22 ms). In addition, the standard deviation of the control trials was 25 ms longer (on average) than was the standard deviation of the testing trials. This was likely due to the smaller number of trials that subjects completed in the control condition (3 trials as compared to 7 trials in the testing condition). Taking the large standard deviations into account, it is unlikely that any of the small differences between the means of the two right targets, two left targets, or the two amplitudes, were consistently different.

In the EF condition, the ET of the control conditions was consistently longer than that of the testing conditions by an average of 30 ms (standard deviation, 7 ms). Thus, as expected, subjects took a longer time to make a movement when they were not required to react quickly to a stimulus.

### *Discarded Trials*

Trials were discarded if the reaction time was not between 100 ms and 500 ms, if the movement was not continuous, or if one or two targets were missed. The number of discarded trials based on each of these criteria appear in Appendix A. Very few trials were discarded due

FIGURE 40: Small vs. Large Amplitude  
(12 deg left target, 12 deg right target)

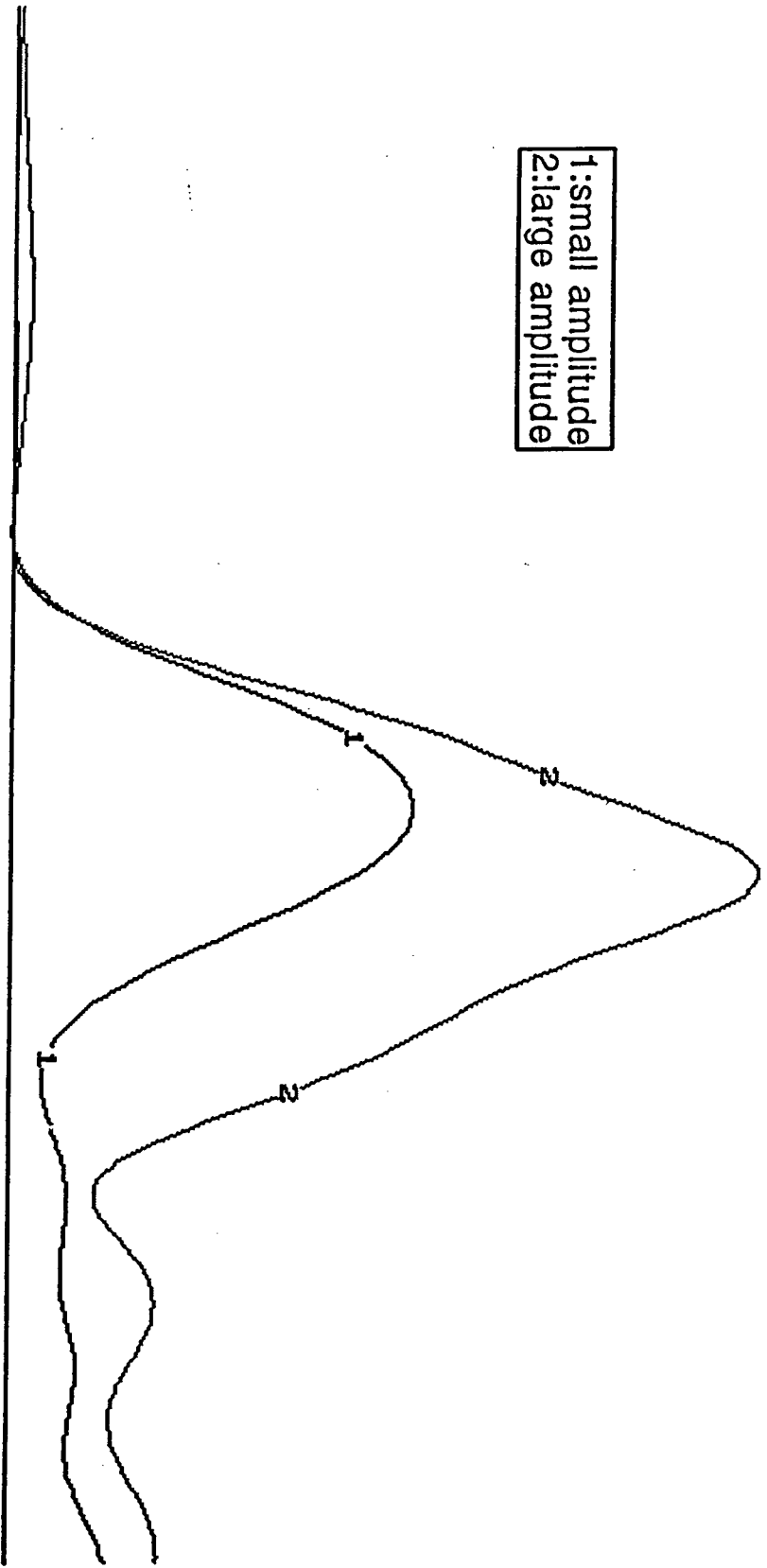


FIGURE 41: Small vs. Large Amplitude  
(12 deg left target, 6 deg right target)

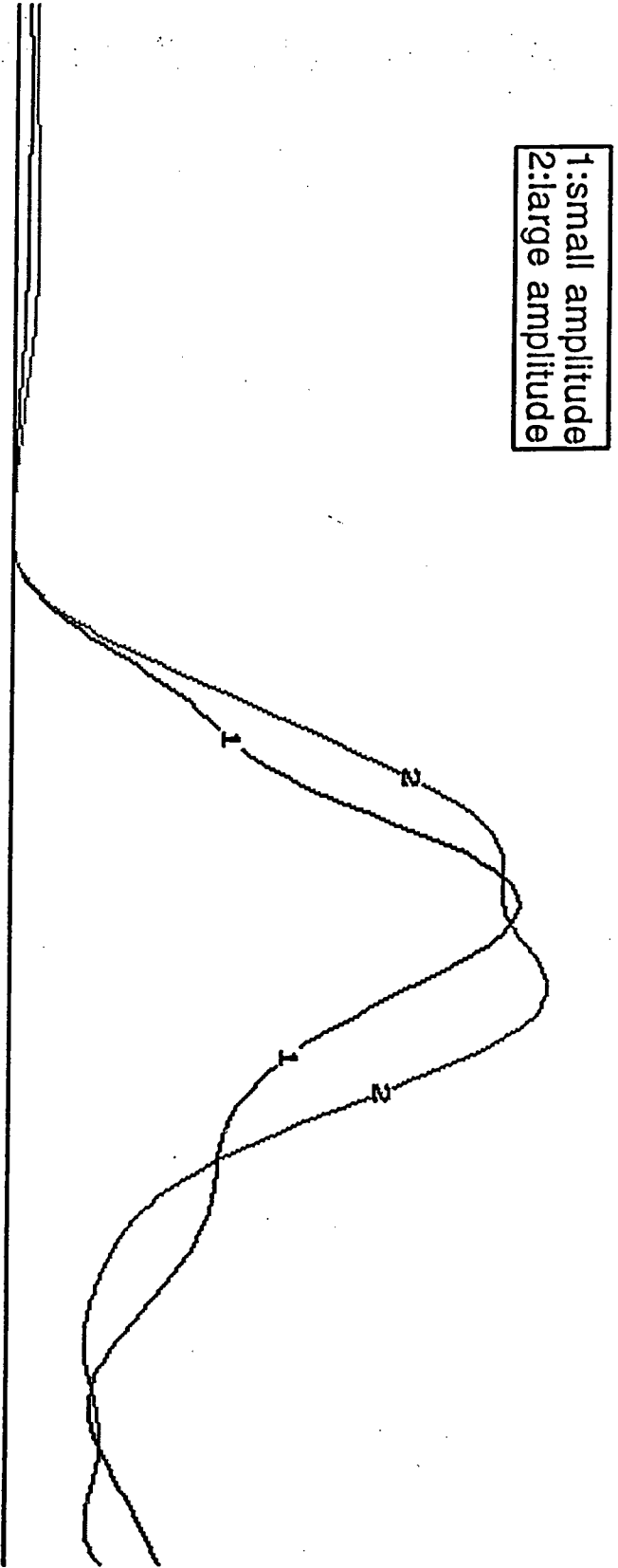


FIGURE 42: Small vs. Large Amplitude

(12 deg left target, 6 deg right target, co-contraction)

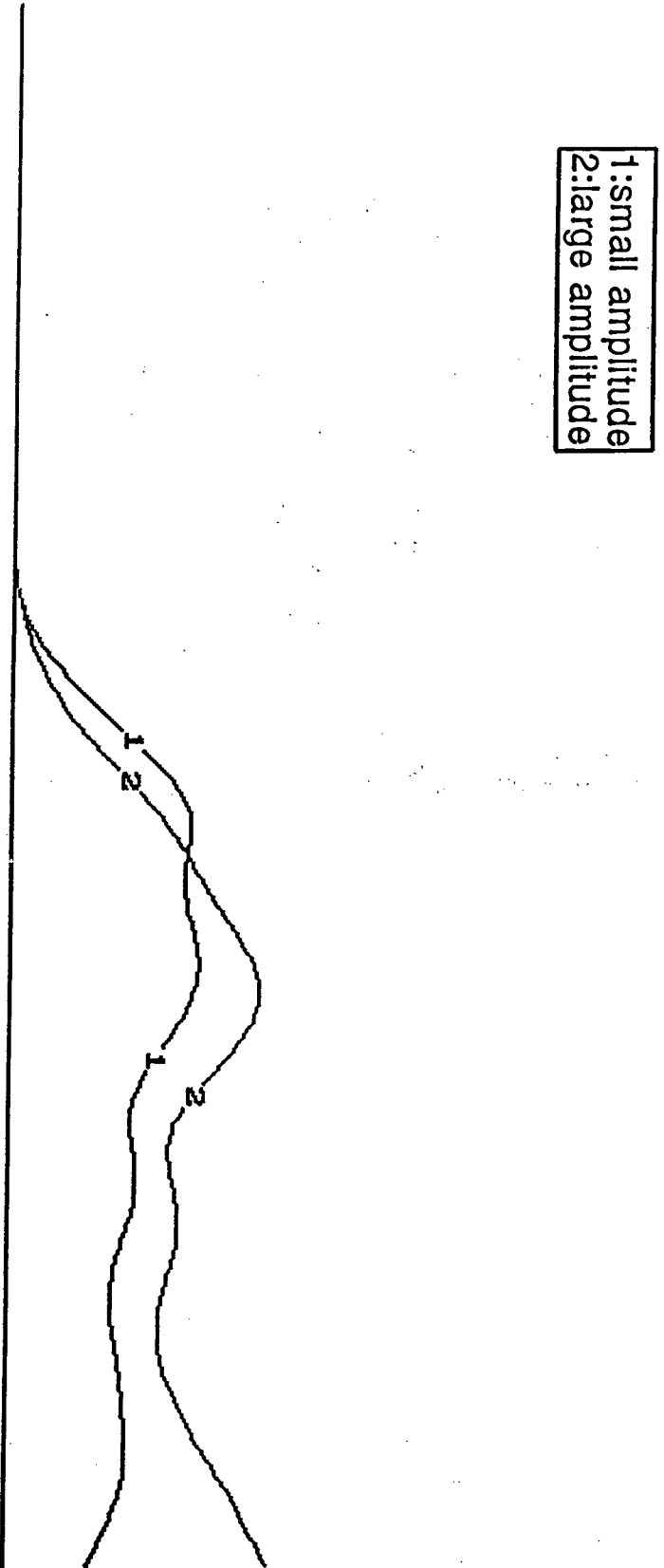
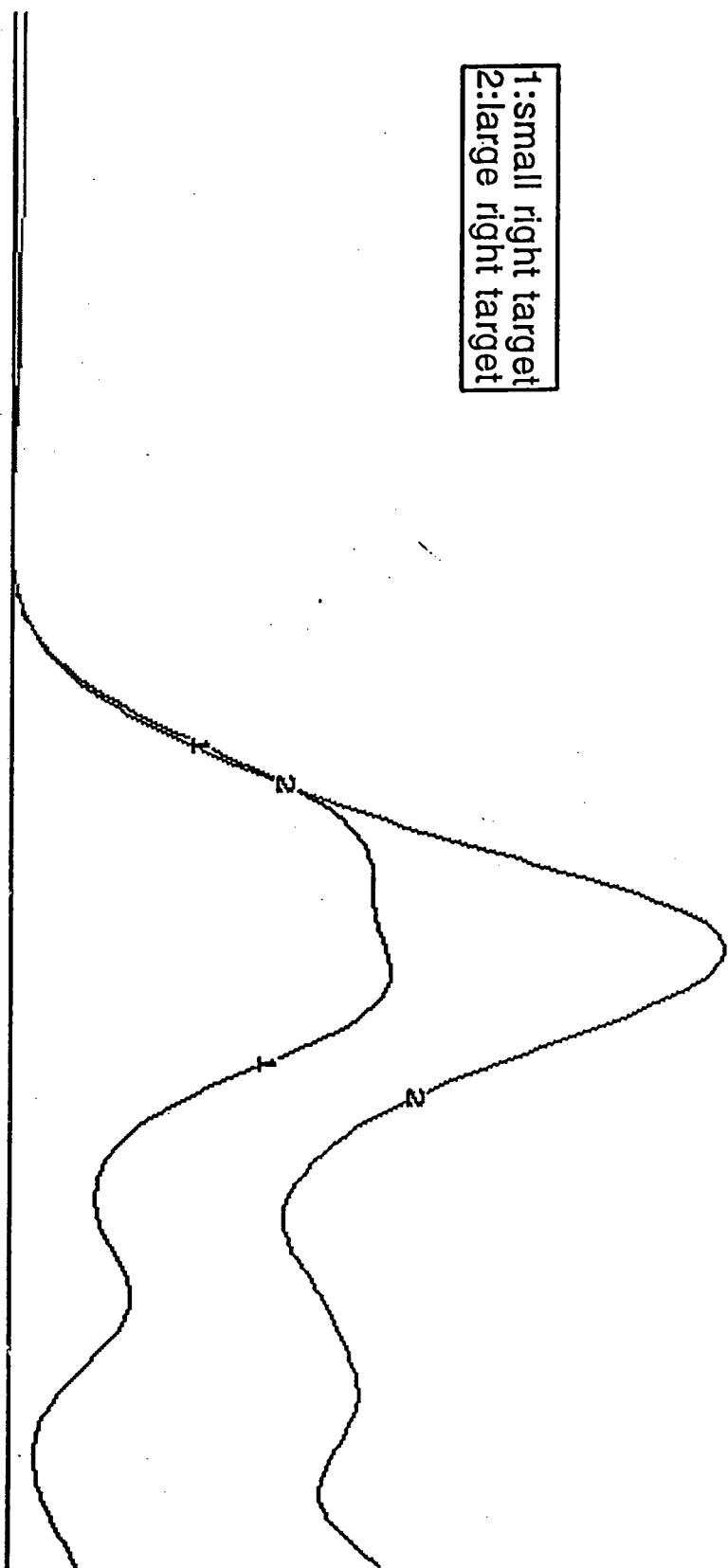


FIGURE 43: Small vs. Large Right Target  
(12 deg left target, 60 deg amplitude)



to the reaction time and the non-continuous movement criteria (usually less than 1 trial per condition). However, more trials were discarded due to the missed target criteria. The number of trials rejected in the EF condition ( $\underline{M}=2.8$ ) was greater than that in the E condition ( $\underline{M}=0.4$ ). In the E condition, subjects could make a corrective movement to successfully contact the target if their primary movement overshot or undershot the target. However, if a subject's point of reversal missed the target in the EF condition, the subject had already reversed direction and could not make a corrective movement to successfully contact the target. The average number of discarded trials was similar for the left target sizes of  $6^\circ$  and  $12^\circ$  ( $\underline{M}=1.6$ ) and was also similar for the  $30^\circ$  and  $60^\circ$  amplitudes ( $\underline{M}=1.7$ ). However, more trials were discarded in the  $60^\circ$  EF condition ( $\underline{M}=3.3$ ) than were discarded in the  $30^\circ$  EF condition ( $\underline{M}=2.3$ ). Finally, more trials were discarded for the  $6^\circ$  right target ( $\underline{M}=2.3$ ) than were discarded for the  $12^\circ$  right target ( $\underline{M}=1.0$ ). These results suggest that subjects found it more difficult to successfully contact the target when the amplitude of the movement was increased and when the size of the right target was decreased.

## DISCUSSION

### *Reaction Time*

The time required to prepare and initiate the extension-flexion movement was longer than that for the extension movement. By itself, this result appeared to support Henry and Rogers (1960) hypothesis that movements which are more complex (defined by an increase in the number of movement segments comprising the response) take a longer time to program. However, when the extension and extension-flexion reaction time results were combined with the more specific reaction time analysis for the effect of the reversal component, support for the response complexity hypothesis was weakened. Under conditions of constant target size and total movement amplitude, the reversal component did not affect the pre-motor or the simple reaction time. Specifically, the reaction times for a 60° extension movement and a 30° extension-flexion movement were similar. While the motor reaction time was found to be longer when the response included a reversal component, this time difference was not large enough to result in a variation of the simple reaction time. Thus, the time required to prepare and initiate a response was only affected by the addition of the flexion movement segment when the amplitude of the extension movement segment remained constant (i.e., when the amplitude of the entire movement was increased). Similarly, previous experiments which supported the response complexity hypothesis (Canic & Franks, 1989; Fischman, 1984; Garcia-Colera & Semjen, 1987; 1988; Hulstijn & van Galen, 1983; Lajoie & Franks, 1995; van Donkelaar & Franks, 1991a; 199b) have concurrently manipulated response complexity and movement amplitude by maintaining the amplitude of the initial movement segment constant. The increase in programming time required to prepare the more complex movements in both the present and these previous experiments was likely due to the increase in the overall amplitude and duration of the response rather than to the increase in response complexity per se.

Subjects also took a longer time to prepare and initiate their movements when the

amplitude of the movement was increased. Both simple and pre-motor reaction time were longer for the 60° movements than they were for the 30° movements, while motor reaction time was not affected. Further, both simple and pre-motor reaction time had a significant amplitude by right target size interaction effect. That is, the difference between the reaction times of the small and large amplitude movements was greater for the 12° target than it was for the 6° target. This interaction effect was mainly due to the consistent reaction time between the small and large amplitudes of the extension movement to the 6° target (see figures 6 and 7). In addition, it appeared that subjects utilized on-line control when they made the 60° extension movement to the 6° target (as evidenced by the long movement time, long velocity time two, and the high number of significant deviations and zero line crossings). Thus, a trade-off between pre-programming and on-line control may have occurred for this experimental condition. Introspective reports from subjects indicated that they found it extremely difficult to successfully contact the 6° target when the amplitude was 60°. The trade-off from pre-programming to on-line control in this difficult condition may explain the amplitude by right target size pre-motor reaction time interaction effect.

The motor reaction time was greater when the left target was small, as compared to when the left target was large. However, the pre-motor reaction time was not affected by the size of the left target. Thus, a small left target affected the electromechanical delay in the muscles, but not the time required to program a response.

#### *Extension Movement Kinematics*

Subjects took a longer time to make the extension movement than they did to make the extension segment of the extension-flexion movement, due to an increase in the time spent in the second velocity phase. Recall that subjects terminated their movement on the right target in the extension condition, but reversed on this target in the extension-flexion condition. Thus, it took subjects a longer time to stop a movement on a defined target than it did to reverse a movement on the same target. Previous experiments have also suggested that the control



mechanisms for movements which stop on a target and those for movements which reverse on a target are different (Adam et al., 1993). In general, the EMG profile of a movement which stops on a target usually consists of a triphasic pattern of activity (agonist-antagonist-agonist), while that of a movement which reverses on a target contains only agonist-antagonist bursts (with the antagonist becoming the agonist for the reversal movement; Enoka, 1994, pp.14, 251). In the present experiment, the quadruphasic and triphasic EMG patterns (extension-flexion movements) equated to the agonist-antagonist burst pattern described by Enoka (1994). Subjects utilized these patterns for the extension-flexion movement slightly less ( $\bar{M} = 2.3$  trials per condition) than they did the triphasic pattern for the extension movement ( $\bar{M} = 3.0$  trials per condition). Thus, some of the difference in these initial movement segments between the extension and extension-flexion conditions can be attributed to the time required to accommodate the clamping of the extension movement. In addition, this difference in extension movement time can also be attributed to the larger number of corrective submovements which occurred in the extension movement, as compared to the extension-flexion movement. In summary, the control processes involved in stopping a discrete movement (extension condition) required more time than did those involved in the reversal of a continuous movement (extension-flexion condition).

Movements with a greater amplitude took a longer time to complete and this increase in time was distributed symmetrically throughout the entire movement (in both the first and the second velocity phases). A similar trend was found in the EMG data. Taken as a percentage of the extension movement time, the durations of the agonist and antagonist bursts (from the triphasic and biphasic EMG patterns) remained constant regardless of movement amplitude. Thus, the increase in movement time was distributed symmetrically to each of the burst durations. Subjects also reached a greater peak velocity and peak acceleration when the amplitude of their movement was longer. This supports the findings of previous experiments (Corcos, Gottlieb, & Agarwal, 1988; Kasai & Seki, 1992) which found that movements with a longer amplitude reached a greater peak velocity.

Moving out of a smaller left target had limited effects on the kinematics of the extension movement. While there was no effect on the overall extension movement time, the time from movement initiation to peak acceleration was greater when the left target size was smaller. In addition, a smaller left target size resulted in a lower peak velocity and peak acceleration. Therefore, even though subjects started in the same position regardless of left target size (at the center of the left target), moving out of a smaller target affected the kinematics of the initial portion of the extension movement. The profile of the initial triceps EMG burst was also altered when subjects moved out of a smaller target; when the left target size decreased, both the slope (at the 60° amplitude) and the height (for co-contraction movements) of the triceps burst decreased. Since the force of a movement is related to the area under the EMG curve (Enoka, 1994, p.168), these EMG profile changes indicate that subjects used less force when they moved out of a smaller left target than they did when the left target was larger.

In the extension-flexion movement, the extension movement time remained constant regardless of the left target size. This result did not support the findings of previous experiments which varied the size of the second target in a reciprocal movement task (Adam et al., 1995; Lajoie & Franks, 1995) and in a two-target tapping task (Sidaway et al., 1995), while maintaining the size of the first target constant. Specifically, these experiments found that movement time to the first target was longer when the second target was small than it was when the second target was large. All of these experiments utilized circular targets, the diameter of which was varied by a factor of 4 (Sidaway et al., 1995), 5 (Lajoie & Franks, 1995), and 20 (Adam et al., 1995), while the width of the second target utilized in the present experiment was only varied by a factor of 2 (6° or 12°). Thus, a large variation in the size of the second target of a two segment movement response appears to be required in order to affect the kinematics of the initial movement segment.

Finally, when subjects moved into a smaller right target, their extension movement took a longer time to complete, had a slower peak velocity, and a lower peak acceleration. These

kinematic results were consistent with those generally expected of a movement with greater accuracy constraints (Corcos et al., 1988, Fitts, 1954; Fitts & Peterson, 1964; Milner & Ijaz, 1990; Sidaway, 1991; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Siegel, 1977). Specifically, subjects slow down their movement when they are required to successfully contact a small target. This phenomenon is commonly referred to as the speed-accuracy trade-off.

### *Flexion Movement Kinematics*

The kinematics of the flexion movement were very similar to those of the extension movement. When subjects moved a longer distance, their flexion movement took a longer time to complete (the time in both the first and second velocity phases was increased), had a larger peak velocity, and a larger peak acceleration. As subjects moved into a smaller left target, their flexion movement time was longer due to an increase in the amount of time spent in the second velocity phase. Thus, the control processes involved in stopping a movement on a small target took a longer time than those involved in stopping on a large target. Finally, as subjects moved out of a smaller right target, their flexion movement had a lower peak velocity, lower peak acceleration, and took a longer time. Further, this increase in time was due to an increase in the time spent in the first velocity phase. These kinematic differences which occurred in the flexion movement due to the variation in the right target size were related to the extension movement kinematics. When accuracy constraints were imposed by the small right target, the extension movement took a longer time and was slower. Subjects then maintained this slower movement speed as they reversed direction and made their flexion movement. It has been suggested by Adam et al. (1995) that elastic energy would be stored if the first movement in a reciprocal movement task was made to a large target. This stored elastic energy could then be utilized to execute a faster second movement with a higher peak velocity, as compared to if the first target had been smaller. Adam's hypothesis also explains the present findings; that the kinematics of the extension movement affected those of the flexion movement. In addition,

these results suggest that subjects controlled the extension-flexion response as one continuous movement, rather than as two separate movement segments.

### *Point of Reversal*

In the extension-flexion movements, subjects reversed their movement to the right of target center when the amplitude was  $30^\circ$  and to the left of target center when the amplitude was  $60^\circ$ . Since subjects completed the experimental conditions in a randomized order, they would be likely to overshoot the smaller amplitude movement and conversely undershoot the larger amplitude movement. This trend was readily apparent in the practice trials, particularly at the first instance in time when the amplitude of the movement was altered. This effect was explained in Helson's psychological relativity theory which suggested that the effect of a stimulus is related to a subject's adaptation level (Engen, 1971, p.59). Specifically, the adaptation level of a subject is determined by past and present experience and is therefore related to the mean of the variation in the stimuli. For example, if subjects are performing movements which have two different amplitudes, the adaptation level would be set to an amplitude which falls somewhere between these two distances. In the present experiment, subjects were required to contact the target in the testing trials. However, they still appeared to overshoot the center of the target in the short amplitude movement and undershoot the target center in the long amplitude movement.

The variability of the reversal point also increased when the movement amplitude was longer. When the amplitude of a movement increases, the variability inherent in the trajectory of that movement would also increase, resulting in a more variable reversal point. This finding is similar to that of Schmidt and colleagues (Schmidt et al., 1979) who found that the within-subject standard deviation of the endpoints of an aiming movement (referred to as effective target width) increased as the movement amplitude increased. In addition, the variability of the reversal point increased when the target size increased, verifying that subjects performed according to the task instructions; to use the entire width of the target as the endpoint for each

segment of the movement.

### *Effect of Index of Difficulty*

Movement amplitude had more of an effect on extension movement time than did index of difficulty. In addition, movement time was found to increase when the amplitude and target size doubled, but the index of difficulty remained constant. These results did not support Fitt's hypothesis that index of difficulty determines the movement time of a response (Fitts, 1954). Contrary to the paradigm used in the present experiment, Fitts' hypothesis was specifically formulated for reciprocal movements. It was the average movement time of the multiple segments of these responses which was found to increase with the increase in index of difficulty. In addition, the independent effects of amplitude and target size on movement kinematics have previously been investigated (Corcos et al., 1988). While movement time was affected equally by amplitude and target size, peak velocity was found to be only one-third as sensitive to target size as it was to distance. In contrast, movement time in the present experiment was more sensitive to movement amplitude than it was to target size. However, since index of difficulty is defined to increase with an increase in movement amplitude or with a decrease in target size (Fitts, 1954), movements in the present experiment were still affected by the index of difficulty of a response.

A trade-off may have also occurred between pre-programming and on-line control for the index of difficulty of 4.32. In the extension movement, the pre-motor reaction time was greater for the index of difficulty of 3.32 at 60° than it was for the index of difficulty of 4.32 at 60° (see figure 9). While the pre-motor reaction time also varied between these conditions for the extension-flexion movement, the difference was not as large. Conversely, movement time was greater for the index of difficulty of 4.32 at 60° than it was for the index of difficulty of 3.32 at 60° (see figure 12). Therefore, extension movements with the large amplitude, made to the small target size, may have been too difficult for subjects to entirely pre-program.

In terms of reaction time, Fitts and Peterson (1964) concluded that the effect of index of

difficulty on reaction time was consistent, but very small. Similar to the results of the present experiment, Fitts and Peterson found that reaction time increased with an increase in amplitude and a decrease in target width, while only the effect of amplitude was significant. In contrast to the results of the present experiment and those of Fitts and Peterson, Sidaway (1991) found that reaction time was more dependent upon the index of difficulty of a response than it was on movement amplitude. However, Sidaway defined index of difficulty in terms of the angle subtended by the diameter of a circular target. Index of difficulty remains constant if the variation in either the diameter of a circular target or the width of a non-circular target is the same (with constant amplitude). However, the area available within the target differs for these two cases. For example, if the target width is doubled in the present experiment, the area available for the subject to contact the target is doubled. In contrast, the area of a circular target increases by a factor of four when the target diameter is doubled (since the area of a circle is related to the radius squared). Therefore, a variation in the size of a circular target will result in a greater variation in the contact area than will the same variation of the targets used in the present experiment. This may explain why Sidaway found differences in reaction time to occur with a variation in index of difficulty (because the targets had a greater effect), while reaction time in the present experiment was more affected by movement amplitude than it was by index of difficulty.

### *Measures of On-Line Control*

Two measures of on-line control were used in the present experiment: significant deviations and zero line crossings of the acceleration profile. At the time of a significant deviation, the slope of the velocity profile was altered and the displacement curve often varied in curvature. On the other hand, zero line crossings of the acceleration profile were related to a change in the direction of the velocity profile and tended to be associated with the occurrence of a corrective movement in the displacement trace. Therefore, while both of these measures were used to indicate the occurrence of on-line control of a movement, zero line crossings

indicated a greater change in the movement trajectory than did significant deviations.

A greater number of zero line crossings were found to occur in the extension movement than in the extension segment of the extension-flexion movement. As suggested earlier, a movement which terminated on a target required a greater degree of control than one which reversed on a target. In addition, movements with a larger amplitude required more on-line control (as evidenced by an increase in significant deviations and zero line crossings) than did movements with a smaller amplitude. The pre-motor reaction time was also greater when the amplitude was larger. Thus, movements with a larger amplitude were generally more difficult to prepare and control than were movements with a smaller amplitude. Finally, the number of significant deviations and zero line crossings increased as the target size decreased. Again, this was specifically related to the termination of movement within a smaller target. The number of zero line crossings increased in the extension movement when the right target was small and increased in the flexion movement when the left target was small. Similar to the results of previous experiments (Carlton, 1981; Elliott et al., 1991; van Donkelaar & Franks, 1991a; 1991b) the significant deviations and zero line crossings which occurred in the acceleration profiles of the movements in the present experiment predominated in the second velocity phase. Therefore, subjects controlled their movements on-line when the amplitude of the movement was large and when the terminal target size was small.

### *Patterns of EMG Activity*

Similar to the kinematic results, the EMG data indicated that subjects used a combination of pre-programming and on-line control to control their movements. Since the reciprocal innervation and the co-contraction patterns differed from the onset of EMG activity (the onset of the antagonist activity was either before or after the peak EMG of the agonist activity), the initial portion of the EMG pattern was pre-programmed. However, subjects may have controlled further portions of their EMG activity on-line. In the present experiment, many subjects used co-contraction at the mid-point of the movement while they utilized

reciprocal innervation at movement onset. This mid-co-contraction strategy can be explained in two ways. First, subjects pre-programmed the switch from reciprocal innervation to co-contraction. Second, subjects pre-programmed reciprocal innervation and then switched to co-contraction on-line. Since the stiffness of the elbow joint is greater with co-contraction (Ghez, 1991), this pattern is generally more stable than is reciprocal innervation. If a subject predicted that their reciprocal innervation movement was going to be unsuccessful (in terms of contacting the target) the subject switched to the more stable EMG pattern in order to successfully contact the target. Further, no evidence was found of a switch in the opposite direction. That is, subjects did not decrease the stability of their movement by switching from the more stable co-contraction strategy to the less stable reciprocal innervation strategy.

Individual subjects were found to use both the reciprocal innervation and the co-contraction strategies in different trials under the same movement constraint conditions (e.g., movement complexity, amplitude, and target size). If these EMG patterns were pre-programmed, the same subject would be expected to consistently choose the same pattern of activity under the same movement constraint conditions. However, an analysis of the chronological order of these strategies can explain the variability of their occurrence, in terms of the success or failure of the previous trial. For example, if a subject missed the target on a particular trial, it is likely that they would utilize the more stable co-contraction strategy on their subsequent trial in order to increase their chances for success. While trials which immediately followed a discarded trial used co-contraction more than they did reciprocal innervation, the percentage of time for which this occurred (61.5%) was similar to the percentage of trials which used co-contraction averaged over the entire experiment (59.3%). The results of a second chronological order analysis provided more support for the hypothesis that subjects pre-programmed their pattern of EMG activity for their subsequent movement based on the success of their previous trials. If subjects experienced repeated success on at least two trials using the co-contraction strategy, they were more likely to continue to use this strategy rather than switching to the reciprocal innervation strategy. Specifically, once a streak



of successful trials using the co-contraction strategy had started, subjects switched to a reciprocal innervation strategy a much lower percentage of time (23%) than this strategy was used on average throughout the experiment (40.7%). In summary, it is likely that the pattern of EMG activity used in the extension-flexion movement of the present experiment was pre-programmed and also controlled on-line. In addition, it appears that the co-contraction strategy may have been used as the default strategy. Not only did subjects utilize this strategy more often than they did the reciprocal innervation strategy, subjects often switched to the co-contraction strategy during movement execution after utilizing an alternative strategy for movement initiation.

The question remains as to whether it is possible to identify particular strategies utilized by the central nervous system to control movement. In the present experiment, Gottlieb's speed-sensitive and speed-insensitive strategies were tested by comparing the slope and height of the initial triceps burst for the 6° and 12° right target sizes (speed-sensitive strategy) and for the 30° and 60° amplitudes (speed-insensitive strategy). Recall that there is some debate as to whether Gottlieb's strategies differ as saturation may play a role in the speed-insensitive strategy. Gottlieb tested the speed-insensitive strategy by comparing movements of different distances under conditions of a large target size. However, more support for the distinctness of this strategy could be found if different distances produced a variation in height at a consistent sub-maximal slope. In the present experiment, the amplitude comparison at the 12° targets produced results similar to those of Gottlieb's speed-insensitive strategy; the height increased as the amplitude of the movement increased and the slope did not vary. In addition, this variation in height occurred at a less than maximal slope. However, the comparison of movement amplitudes at the 6° targets indicated that the slope of the 30° movement was steeper than that of the 60° movement, while the height did not vary. These results indicate that the speed-insensitive strategy is limited to movements which are made to large targets.

The speed-sensitive strategy was not supported by the results of the present experiment. As the right target size increased, the height of the triceps EMG profile increased (for the 60°

amplitude), while the slope did not consistently vary. Gottlieb and colleagues (1989) accounted for exceptions to their two strategies by stating that subjects were not forced to conform to one of the two strategies but that the strategies were available to be used as a 'suggestion' of control by the central nervous system. More specifically, the two strategies described how subjects executed their movements, but not whether subjects chose to use them. Since such a large number of the comparisons made in the present experiment yielded results which were not consistent with either of these strategies, it is likely that these comparisons were not simply an exception to the rule. Rather, the nervous system did not appear to control the agonist EMG activity in terms of two distinct strategies. The central nervous system most likely controlled individual features of the EMG profile, such as slope and height, by controlling the force of the required muscle contraction.

## CONCLUSION

The main goal of the present experiment was to determine whether the time required to program a limb movement was affected by response complexity, by movement amplitude, by target size, or by some combination of these factors. In general, the forearm extension-flexion movements made in the present experiment were programmed prior to movement initiation. Increasing response complexity and movement amplitude resulted in an increase in the time required to prepare and initiate these movements. However, the increase in pre-motor reaction time which occurred with the increase in response complexity was attributed to the overall increase in movement amplitude and duration, rather than to the increase in response complexity *per se*. However, the increased pre-programming of movements with greater amplitudes did not occur to the exclusion of other forms of movement control; evidence of on-line control was also found in movements with large amplitudes. In addition, movement kinematics were affected by the movement amplitude as subjects took a longer time and reached a higher peak velocity and peak acceleration when the amplitude increased.

While the terminal target size had no effect on the time required to pre-program a movement, evidence of on-line control occurred for movements which were made to smaller target sizes. Thus, in the present experiment, subjects accounted for an increase in the accuracy constraints of a task by modifying their movement trajectory during movement execution. Moreover, movements to smaller targets took a longer time to complete and reached a lower peak velocity and peak acceleration. However, the variation in target size had no effect on the durations of the triceps and biceps EMG bursts (relative to movement time) or the pattern of EMG activity. Regardless of target size or movement amplitude, subjects utilized a co-contraction EMG pattern more often than they did a reciprocal innervation pattern. These EMG patterns appeared to be programmed prior to movement initiation and also controlled on-line. Further, subjects appeared to control the force of their movements by altering features of the EMG profile, such as the slope and the height of the initial triceps burst.

In summary, subjects pre-programmed their movements prior to movement initiation. However, when the accuracy constraints were increased (either by an increase in amplitude or a decrease in target size) subjects utilized on-line control in order to successfully complete their movements.

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# APPENDIX A

## Mean and Standard Deviation Values for all Dependent Variables

### *Simple Reaction Time (ms)*

Mean and standard deviation for each of the 16 conditions\*.

Mean and standard deviation for each of the 16 conditions									
	Amplitude 30°				Amplitdue 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	210 (29)	206 (34)	199 (33)	195 (33)	214 (39)	204 (31)	218 (33)	213 (30)	207 (8)
EF	228 (40)	225 (35)	233 (45)	220 (57)	233 (42)	233 (44)	244 (57)	229 (37)	231 (7)
	215 (14)				224 (13)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
219 (12)	219 (17)	222 (15)	216 (13)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, E refers to extension, and EF refers to extension-flexion.



*Pre-motor Reaction Time (ms)*

Mean and standard deviation for each of the 16 conditions\*.

Mean and standard deviation for each of the 16 conditions :									
Amplitude 30°					Amplitdue 60°				
R 6°		R 12°		R 6°		R 12°			
L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°		
E	153 (25)	152 (30)	144 (30)	144 (33)	157 (28)	151 (25)	164 (29)	160 (28)	153 (7)
EF	166 (39)	163 (28)	170 (44)	162 (51)	170 (33)	172 (35)	179 (51)	168 (33)	169 (5)
	157 (10)				165 (9)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
161 (8)	161 (12)	163 (11)	159 (9)

*Motor Reaction Time (ms)*

Mean and standard deviation for each of the 16 conditions\*.

	Amplitude 30°				Amplitdue 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	57 (11)	54 (12)	55 (12)	51 (10)	56 (14)	53 (15)	54 (12)	53 (12)	54 (2)
EF	62 (15)	62 (14)	64 (14)	58 (13)	64 (12)	62 (13)	65 (18)	60 (13)	62 (2)
	58 (5)				58 (5)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
59 (4)	58 (5)	60 (5)	57 (4)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, E refers to extension, and EF refers to extension-flexion.

*Extension Movement Distance (°)*

Mean and standard deviation for each of the 16 conditions\*.

	Amplitude 30°				Amplitdue 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	29.9 (0.7)	30.1 (0.7)	30.7 (1.7)	30.1 (1.8)	59.7 (1.1)	59.9 (1.7)	59.6 (1.2)	59.4 (1.7)	44.9 (15.7)
EF	30.4 (0.9)	29.6 (1.2)	30.1 (1.5)	30.1 (1.9)	60.1 (0.8)	59.6 (1.5)	59.4 (2.1)	59.4 (2.8)	44.8 (15.8)
	30.1 (0.3)				59.6 (0.3)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
44.9 (15.9)	44.9 (15.6)	45.0 (15.7)	44.8 (15.8)

*Extension Movement Time (ms)*

Mean and standard deviation for each of the 16 conditions\*.

	Amplitude 30°				Amplitdue 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	308 (52)	292 (77)	243 (77)	258 (67)	454 (98)	400 (66)	355 (85)	364 (82)	334 (72)
EF	262 (83)	253 (88)	217 (59)	209 (53)	339 (93)	340 (87)	282 (60)	285 (69)	273 (49)
	255 (34)				352 57				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
331 (69)	277 (58)	308 (75)	300 (64)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, E refers to extension, and EF refers to extension-flexion.

*Extension Movement: Velocity Time One (ms)*

Mean and standard deviation for each of the 16 conditions\*.

Mean and standard deviation for each of the 10 conditions :									
	Amplitude 30°				Amplitdue 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	127 (26)	119 (26)	115 (26)	119 (24)	143 (29)	143 (32)	135 (31)	131 (24)	129 (11)
EF	140 (35)	143 (47)	127 (25)	126 (25)	156 (39)	152 (33)	144 (26)	140 (34)	141 (11)
	127 (10)				143 (8)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
140 (12)	130 (10)	136 (13)	119 (45)

*Extension Movement: Velocity Time Two (ms)*

Mean and standard deviation for each of the 16 conditions\*.

Mean and standard deviation for each of the 16 conditions :									
Amplitude 30°					Amplitdue 60°				
R 6°		R 12°			R 6°		R 12°		
L 6°	L 12°	L 6°	L 12°		L 6°	L 12°	L 6°	L 12°	
E	195 (46)	185 (68)	141 (57)	155 (51)	322 (89)	267 (58)	232 (72)	244 (72)	218 (60)
EF	136 (63)	124 (57)	105 (43)	96 (31)	193 (77)	199 (74)	148 (41)	153 (48)	144 (37)
	203 (65)				220 (59)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
203 (65)	159 (53)	184 (69)	178 (58)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, E refers to extension, and EF refers to extension-flexion.

*Extension Movement: Acceleration Time One (ms)*

Mean and standard deviation for each of the 16 conditions\*.

	Amplitude 30°				Amplitdue 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	87 (19)	80 (14)	80 (15)	80 (12)	88 (18)	90 (18)	85 (19)	83 (20)	84 (4)
EF	93 (20)	90 (19)	84 (19)	80 (14)	97 (23)	94 (17)	89 (19)	85 (16)	89 (6)
	84 (5)				89 (5)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
90 (5)	73 (30)	88 (5)	85 (5)

*Extension Movement: Peak Velocity (°/s)*

Mean and standard deviation for each of the 16 conditions\*.

	Amplitude 30°				Amplitdue 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	252 (65)	284 (83)	293 (81)	278 (79)	362 (92)	384 (89)	403 (112)	416 (98)	334 (64)
EF	241 (77)	249 (79)	268 (86)	275 (79)	362 (115)	353 (90)	393 (104)	404 (102)	318 (68)
	268 (18)				385 (23)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
311 (60)	341 (68)	322 (65)	330 (66)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, E refers to extension, and EF refers to extension-flexion.

*Extension Movement: Peak Acceleration (%/s/s)*

Mean and standard deviation for each of the 16 conditions\*.

Mean and standard deviation for each of the 16 conditions :									
Amplitude 30°					Amplitdue 60°				
R 6°		R 12°		R 6°		R 12°			
L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°		
E	3656 (1659)	4370 (2306)	4751 (2306)	4324 (2000)	4575 (2056)	4801 (1677)	5450 (2380)	5765 (2275)	4712 (662)
EF	3101 (1516)	3342 (1549)	3692 (1515)	4051 (1978)	4198 (2017)	4091 (1531)	4821 (2145)	5245 (2323)	4068 (715)
	3910 (561)				4868 (589)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
4017 (599)	4762 (713)	4281 (766)	4499 (756)

*Flexion Movement Distance (°)*

Mean and standard deviation for each of the 8 conditions\*.

Mean and standard deviation for each of the 6 conditions :									
Amplitude 30°					Amplitdue 60°				
R 6°		R 12°			R 6°		R 12°		
L 6°	L 12°	L 6°	L 12°		L 6°	L 12°	L 6°	L 12°	
EF	30.6 (1.5)	30.5 (1.4)	30.6 (2.2)	31.4 (2.6)	60.2 (1.4)	59.9 (1.9)	59.6 (2.2)	59.6 (3.0)	45.3 (15.5)
	30.7 (0.4)				59.8 (0.3)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
45.3 (17.0)	45.3 (16.5)	45.3 (16.9)	45.4 (16.6)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, E refers to extension, and EF refers to extension-flexion.

*Flexion Movement Time (ms)*

Mean and standard deviation for each of the 8 conditions\*.

	Amplitude 30°				Amplitdue 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
EF	302 (74)	285 (73)	287 (53)	242 (56)	398 (96)	384 (62)	375 (70)	345 (65)	327 (56)
	279 (26)				376 (22)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
342 (57)	312 (59)	341 (54)	314 (63)

*Flexion Movement: Velocity Time One (ms)*

Mean and standard deviation for each of the 8 conditions\*.

	Amplitude 30°				Amplitude 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
EF	120 (39)	118 (51)	100 (34)	96 (30)	176 (57)	179 (49)	151 (34)	140 (35)	135 (32)
	109 (12)				162 (19)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
148 (34)	122 (28)	137 (34)	133 (35)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, and EF refers to extension-flexion.

*Flexion Movement: Velocity Time Two (ms)*

Mean and standard deviation for each of the 8 conditions\*.

Mean and standard deviation for each of the 6 conditions :									
Amplitude 30°					Amplitdue 60°				
R 6°		R 12°			R 6°		R 12°		
L 6°	L 12°	L 6°	L 12°		L 6°	L 12°	L 6°	L 12°	
EF	187 (52)	171 (37)	192 (35)	152 (33)	237 (52)	212 (39)	232 (50)	207 (49)	199 (29)
	176 (18)				222 (15)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
202 (29)	196 (34)	212 (26)	186 (29)

*Flexion Movement: Acceleration Time One (ms)*

Mean and standard deviation for each of the 8 conditions\*.

Mean and standard deviation for each of the 8 conditions :									
Amplitude 30°					Amplitdue 60°				
R 6°		R 12°			R 6°		R 12°		
L 6°	L 12°	L 6°	L 12°		L 6°	L 12°	L 6°	L 12°	
EF	79 (16)	75 (13)	71 (16)	76 (22)	96 (25)	95 (22)	87 (16)	89 (23)	84 (10)
	75 (3)				92 (4)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
86 (11)	81 (9)	83 (11)	84 (10)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, and EF refers to extension-flexion.

*Flexion Movement: Peak Velocity (°/s)*

Mean and standard deviation for each of the 8 conditions\*.

Mean and standard deviation for each of the 6 conditions :									
Amplitude 30°					Amplitdue 60°				
R 6°		R 12°			R 6°		R 12°		
L 6°	L 12°	L 6°	L 12°		L 6°	L 12°	L 6°	L 12°	
EF	215 (64)	218 (69)	234 (73)	242 (78)	320 (85)	307 (72)	337 (78)	345 (74)	277 (55)
	227 (13)				327 (17)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
265 (56)	290 (60)	277 (61)	278 (58)

*Flexion Movement: Peak Acceleration (°/s/s)*

Mean and standard deviation for each of the 8 conditions\*.

Mean and standard deviation for each of the 6 conditions :									
Amplitude 30°					Amplitdue 60°				
R 6°			R 12°		R 6°			R 12°	
L 6°		L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
EF	2450 (1250)	2516 (1359)	2837 (1478)	3037 (1862)	3093 (1725)	2888 (1413)	3373 (1863)	3396 (1480)	2949 (351)
	2710 (276)				3188 (243)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
2858 (449)	3161 (271)	2938 (392)	2959 (364)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, and EF refers to extension-flexion.



*Extension Movement: Number of Significant Deviations*

Mean and standard deviation for each of the 16 conditions\*.

Mean and standard deviation for each of the 16 conditions									
Amplitude 30°					Amplitdue 60°				
R 6°		R 12°		R 6°		R 12°			
L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°		
E	0.07 (0.14)	0.04 (0.07)	0.02 (0.08)	0.03 (0.06)	0.36 (0.28)	0.22 (0.19)	0.15 (0.23)	0.14 (0.19)	0.13 (0.12)
EF	0.12 (0.2)	0.08 (0.16)	0.08 (0.2)	0.04 (0.09)	0.26 (0.31)	0.3 (0.32)	0.11 (0.2)	0.23 (0.27)	0.15 (0.1)
	0.06 (0.03)				0.22 (0.09)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
0.18 (0.12)	0.1 (0.07)	0.15 (0.11)	0.14 (0.1)

*Extension Movement: Number of Zero Line Crossings*

Mean and standard deviation for each of the 16 conditions\*.

Mean and standard deviation for each of the 16 conditions:									
Amplitude 30°					Amplitdue 60°				
R 6°		R 12°		R 6°		R 12°			
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	1.48 (0.48)	1.47 (0.31)	1.13 (0.19)	1.18 (0.16)	1.67 (0.47)	1.49 (0.55)	1.29 (0.33)	1.31 (0.3)	1.38 (.18)
EF	1.12 (0.21)	1.15 (0.27)	1.01 (0.04)	1.0 (0.0)	1.15 (0.24)	1.0 (0.0)	1.21 (0.29)	1.04 (0.11)	1.09 (0.08)
	1.19 (0.19)				1.27 (0.22)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
1.32 (0.24)	1.15 (0.12)	1.26 (0.22)	1.21 (0.2)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, E refers to extension, and EF refers to extension-flexion.

*Flexion Movement: Number of Significant Deviations*

Mean and standard deviation for each of the 8 conditions\*.

Amplitude 30°					Amplitude 60°				
R 6°		R 12°			R 6°		R 12°		
L 6°	L 12°	L 6°	L 12°		L 6°	L 12°	L 6°	L 12°	
EF	0.23 (0.24)	0.17 (0.26)	0.14 (0.15)	0.12 (0.2)	0.38 (0.35)	0.48 (0.37)	0.29 (0.34)	0.35 (0.45)	0.27 (0.13)
	0.17 (0.05)				0.38 (0.08)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
0.32 (0.14)	0.23 (0.11)	0.26 (0.1)	0.28 (0.17)

*Flexion Movement: Number of Zero Line Crossings*

Mean and standard deviation for each of the 8 conditions\*.

Mean and standard deviation for each of the 6 conditions									
Amplitude 30°					Amplitdue 60°				
R 6°				R 12°	R 6°			R 12°	
L 6°		L 12°		L 6°	L 12°	L 6°		L 12°	
EF	1.94 (0.4)	1.79 (0.61)	2.07 (0.61)	1.67 (0.36)	1.89 (0.82)	1.76 (0.56)	1.84 (0.46)	1.76 (0.54)	1.84 (0.13)
	1.87 (0.17)				1.81 (0.06)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
1.85 (0.08)	1.84 (0.17)	1.94 (0.1)	1.75 (0.05)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, and EF refers to extension-flexion.

*Reversal Point Distance (°)*

Mean and standard deviation for each of the 8 conditions\*.

Mean and standard deviation for each of the 6 conditions									
Amplitude 30°					Amplitude 60°				
R 6°		R 12°			R 6°		R 12°		
L 6°	L 12°	L 6°	L 12°		L 6°	L 12°	L 6°	L 12°	
EF	0.31 (0.96)	0.11 (0.47)	0.11 (1.6)	0.39 (1.44)	-0.06 (0.83)	-0.31 (0.87)	-0.45 (1.72)	-0.38 (1.88)	-0.04 (0.32)
	0.23 (0.14)				-0.3 (0.17)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
0.01 (0.26)	-0.08 (0.4)	-0.02 (0.32)	-0.05 (0.36)

*Reversal Point Variability (°)*

Mean and standard deviation for each of the 8 conditions\*.

Mean and standard deviation for each of the 6 conditions :									
	Amplitude 30°				Amplitude 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
EF	1.43 (0.32)	1.68 (0.31)	2.53 (0.78)	2.4 (0.49)	1.75 (0.47)	1.74 (0.37)	2.87 (0.63)	2.63 (0.69)	2.13 (0.54)
	2.01 (0.54)				2.25 (0.59)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
1.65 (0.15)	2.61 (0.2)	2.14 (0.67)	2.11 (0.47)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, and EF refers to extension-flexion.

*Number of Discarded Trials: Unacceptable Reaction Time*

Mean and standard deviation for each of the 16 conditions\*.

	Amplitude 30°				Amplitude 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	0.2 (0.4)	0.1 (0.3)	0.1 (0.5)	.1 (0.4)	0.1 (0.4)	0.1 (0.3)	0 (0)	0.1 (0.3)	0.1 (0.1)
EF	0 (0)	0.1 (0.3)	0.1 (0.4)	0.6 (1.6)	0.4 (0.5)	0.1 (0.3)	0.5 (1.1)	0.1 (0.3)	0.2 (0.2)
	0.2 (0.2)				0.2 (0.2)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
0.1 (0.1)	0.2 (0.2)	0.2 (0.2)	0.2 (0.2)

*Number of Discarded Trials: Non-Continuous Movement*

Mean and standard deviation for each of the 16 conditions\*.

	Amplitude 30°				Amplitude 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	0.4 (0.9)	0.5 (0.7)	0.1 (0.4)	0.1 (0.3)	1.9 (3.0)	0.8 (1.2)	0.2 (0.4)	0.3 (0.5)	0.5 (0.6)
EF	0.4 (1.1)	0.1 (0.4)	0.4 (0.6)	0.1 (0.4)	0.1 (0.4)	0.3 (0.6)	0.8 (0.6)	0.3 (0.8)	0.3 (0.2)
	0.7 (1.3)				0.6 (0.6)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
0.6 (0.6)	0.3 (0.2)	0.5 (0.6)	0.3 (0.2)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, E refers to extension, and EF refers to extension-flexion.

*Number of Discarded Trials: Missed Target*

Mean and standard deviation for each of the 16 conditions\*.

	Amplitude 30°				Amplitdue 60°				
	R 6°		R 12°		R 6°		R 12°		
	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	L 6°	L 12°	
E	0.1 (0.4)	1.3 (1.7)	0.4 (0.6)	0.1 (0.4)	0.8 (1.7)	0.5 (0.7)	0.3 (0.6)	0.2 (0.8)	0.5 (0.4)
EF	3.4 (2.9)	3.0 (2.2)	2.1 (1.9)	0.6 (0.9)	4.5 (3.3)	4.4 (3.2)	2.7 (2.1)	1.4 (1.5)	2.8 (1.4)
	1.4 (1.3)				1.9 (1.8)				

Mean and standard deviation for each target width, collapsed across all other conditions.

R 6°	R 12°	L 6°	L 12°
2.3 (1.8)	1.0 (1.0)	1.8 (1.6)	1.4 (1.5)

\*Standard deviations appear in parentheses. R refers to right target width, L refers to left target width, E refers to extension, and EF refers to extension-flexion.

## **APPENDIX B : PILOT EXPERIMENT**

### **Response Programming as a Function of Accuracy and Complexity: Evidence from Latency and Kinematic Measures.**

#### **Abstract**

This experiment investigated the programming of movements which varied in complexity and accuracy. Response complexity was manipulated by varying the number of movements in the task; subjects made single and reversal arm movements while holding a stylus in their right hand. Each complexity condition was performed with three levels of accuracy: no accuracy, low accuracy, and high accuracy. Accuracy was defined as the angle subtended by the target at the start position. The time required to program a movement was found to increase with an increase in response complexity as well as with an increase in the accuracy constraints of the task. However, movements with no accuracy constraints had similar programming requirements and movement kinematics as those movements which had low accuracy constraints. The single movement was slower than the first movement of the reversal movement and it took longer to complete the first movement of the high accuracy condition than that of the low and no accuracy conditions. In addition, when the size of the first target was held constant, the kinematics of the movements made to that target varied depending upon the size of the second target. These results support an interpretation of response programming in which movement constraints are programmed prior to the initiation of movement.

#### **Introduction**

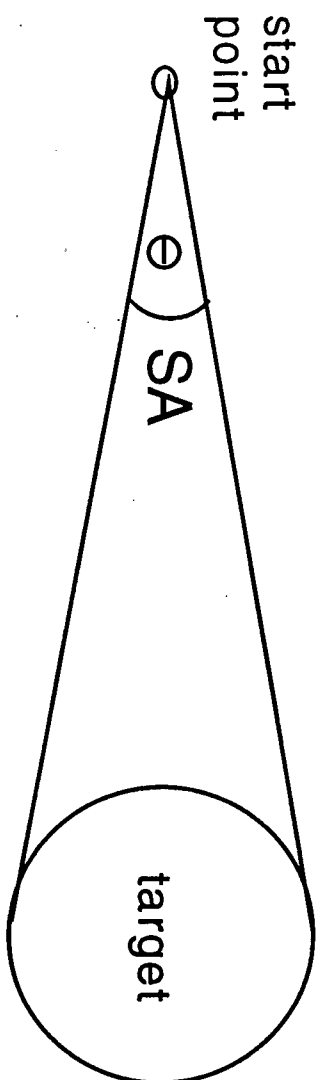
The time required to program a response was originally thought to be dependent upon

response complexity, as defined by the number of movement segments comprising the response (Henry & Rogers, 1960). However, recent evidence suggested that it was the accuracy demand of a response which primarily determined programming time. Sidaway, Christina, and Shea (1988) quantified accuracy in terms of the index of difficulty (ID) of a movement, based on Fitts' (1954) equation for ID. Relating the ID of a movement to the amplitude and target width of that movement ( $ID = \log_2[2A/W]$ ), Fitts found that average movement time increased with ID for reciprocal tapping responses. Further, Fitts and Peterson (1964) also found that ID also had a small but consistent effect on reaction time. To accommodate for single aiming movements, Sidaway and colleagues modified Fitts' equation such that ID was based on the angle subtended (SA) by the target at the start position (figure 1);  $ID = \log_2(\cot[SA]/2)$ . Since the targets were circular, SA provided the same index for the horizontal and vertical width. Using this equation, the ID of a movement increases as the SA decreases, thus leading Sidaway to hypothesize that reaction time would also increase with a decrease in SA.

Two explanations were proposed to account for Sidaway's SA hypothesis (Sidaway et al., 1988). First, it was suggested that a subject's movement trajectory must become more precise with a decrease in SA. This would require a change in the motor unit spatial and temporal recruitment pattern when accuracy constraints were increased. The second explanation addressed the variability of movement which is caused by inherent neural noise. When a subject moves to a target subtending a large angle, a high level of noise can be tolerated since the movement can be variable yet still contact the target. However, when the subtended angle is smaller, the motor system must inhibit the excess neural noise. Both of these explanations relate to an increase in the complexity of the programming required for a specific movement, which increases the time required to program the response.

In a further investigation of this SA hypothesis, Sidaway et al. (1988) re-evaluated the results of a previous study (Fischman, 1984) which found that programming time increased

FIGURE 1



$\Theta$  = Subtended Angle as defined by  
Sidaway et al. (1988)



with an increase response complexity. Fischman investigated straight line movements and movements which involved perpendicular directional changes under different complexity conditions. While gripping a stylus, subjects were required to contact a series of circular targets. Regardless of whether a change in direction occurred, the premotor reaction time increased as the number of movements in the response increased. However, all targets were of equal size and the distance to the final target always increased as the number of targets increased. Therefore, the angle subtended by the final target (at the start point) decreased as the number of targets increased. Sidaway and colleagues (Sidaway, Schoenfelder-Zohdi, & Moore, 1990) identified these factors as potential confounds in Fischman's experiment and applied a more stringent test of the SA hypothesis by manipulating both the SA and the position of the highest ID target, within a series of three targets. While reaction time was not affected by the position of the target which subtended the smallest angle, it did increase with a decrease in SA. A further test of this hypothesis manipulated SA under conditions of constant complexity (Fischman & Mucci, 1990) and also found that reaction time increased as the accuracy constraints of the task increased.

In order to specifically compare the hypothesis that programming time is dependent upon response complexity to the hypothesis that predicts programming time is determined by the ID of a movement, Sidaway performed an experiment in which the number of movements was varied separately from SA (Sidaway, 1991, experiment 3). In this experiment, subjects were required to contact a series of one, two, or three targets, all of which subtended the same angle. This procedure was repeated with three different subtended angles for a total of nine movement tasks. While the premotor reaction time was found to increase with a decrease in SA, it did not increase when the number of movements increased. While these results supported Sidaway's SA hypothesis, the response complexity hypothesis was not supported despite the fact that other experiments have found a complexity effect to exist for tasks in which accuracy was held constant (Canic & Franks, 1989; Garcia-Colera & Semjen, 1987;

1988; Hulstijn & van Galen, 1983).

Previous research which has investigated the SA hypothesis has consistently utilized a straight-line target tapping task, such as that used by Fischman (1984). One limitation of such a task is that the first target is always closest to the start position while subsequent targets are farther away (Fischman & Mucci, 1990; Gordon & Christina, 1991; Sidaway, 1991; Sidaway et al., 1988; Sidaway et al., 1990). To test the generalizability of the SA hypothesis, Fischman and Yao (1994) placed the first target farther away from the start position than the subsequent targets. To contact these subsequent targets, subjects reversed the direction of their movement after contacting the first target. Reaction time for a single movement was found to be faster than that for a reversal movement and Fischman and Yao concluded that SA was likely not the sole crucial element that determined programming time in this particular task. However, SA is defined by the total distance from the start position to the target (Sidaway et al., 1988). Since all of the targets in Fischman and Yao's study were of equal size, the accuracy constraints of the task increased as the number of movements increased. Therefore, it is not possible to determine whether response complexity or SA was responsible for the increase in reaction time. The present experiment was designed to resolve this issue by manipulating the number of movements (one straight line movement or a two movement reversal) while maintaining a constant subtended angle.

In addition, the present experiment was designed to investigate the programming requirements for movements with no accuracy constraints. If programming time is directly related to the accuracy constraints of a task (Sidaway, 1991), a movement which has no accuracy constraints should have a shorter reaction time than one which has accuracy constraints. Limb movements which were made without accuracy have been investigated in two previous experiments. In the first experiment, subjects made finger movements either to a target or without an experimentally defined endpoint (Laszlo & Bairstow, 1974). When the finger movements were directed to a target, the reaction time was longer than that for the

movements performed with no accuracy requirements. The second experiment required subjects to cross a piece of moving paper, using a pen, on which a random double dot pattern was printed (Laszlo & Livesey, 1977). Subjects were instructed to avoid all dots (no accuracy), contact one dot (low accuracy), or contact two dots (high accuracy). While the reaction time for the low and high accuracy conditions was similar, the time to initiate a movement with no accuracy constraints was less than that for movements with accuracy constraints. It should be noted that the no accuracy condition in this experiment involved some degree of accuracy as subjects were required to avoid the moving dots. A true no accuracy condition would have required subjects to cross the paper with no concern of either contacting or avoiding dots. The results of these two experiments were explained in terms of the differences involved in the planning requirements for movements with and without accuracy demands, where planning was described as being dependent on the goal of the movement and previous experience (Laszlo, 1992). Further, it was suggested that no two movements are identical in terms of programming (see Laszlo, 1992, for a further discussion of planning and programming processes). Therefore, the increased reaction time which occurred for movements with accuracy demands was explained as an increase in the time required to plan these movements; the complexity of the programming for movements with and without accuracy constraints was thought to be similar. Since there was no quantified metric for accuracy in Laszlo's experiments, the present experiment investigated the effect of the presence and absence of accuracy constraints on reaction time, as defined by Sidaway's metric of index of difficulty.

The purpose of the present experiment therefore was to determine whether the time required to program a limb movement is affected by the presence of subsequent movements, by the accuracy constraints imposed on those movements, or by some combination of these factors. It was expected that an increase in both the number of movements in the response and the accuracy constraints of the task would result in an increase in the time required to program

that specific movement. This hypothesis incorporates both the increased involvement of the neuromotor coordination centers suggested by Henry and Rogers (1960) as well as the inhibition of neural noise and the required changes in the motor unit recruitment pattern suggested by Sidaway et al. (1988). In addition, the kinematic properties of the movements involved in this experiment were investigated in order to more fully understand the programming requirements for movements that vary in complexity and accuracy.

## **Method**

### *Subjects*

Twelve right hand dominant subjects (students at the University of British Columbia or members of the university community) volunteered to participate in this experiment. All subjects were naive to the hypothesis being tested and were inexperienced at the task. The experiment was carried out according to the ethical guidelines of the University of British Columbia Behavioral Sciences Screening Committee for research and other studies involving human subjects. The data from one subject were excluded from the analysis, since the mean of that subject's data was consistently 2.5 standard deviations higher than the mean of the group.

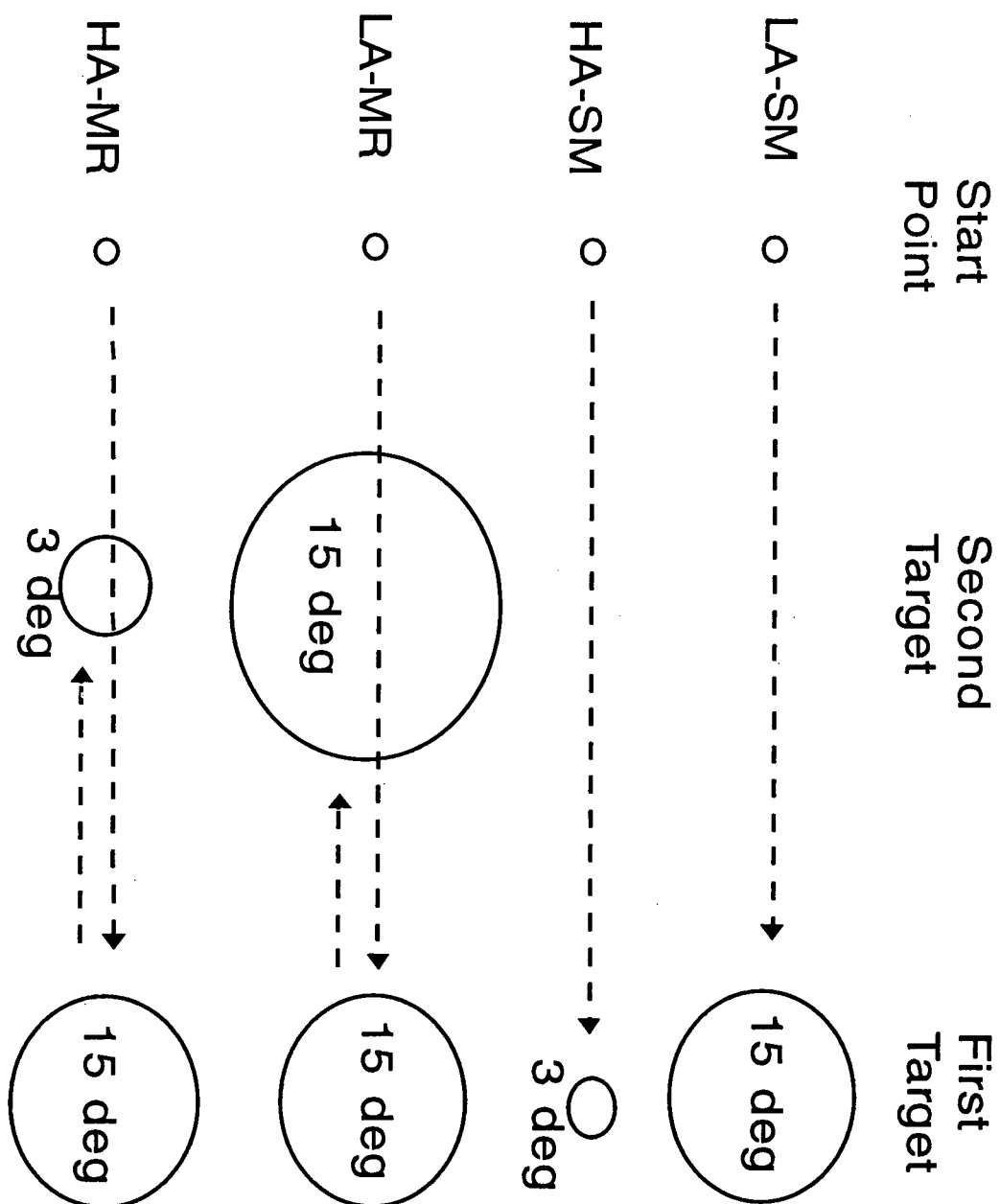
### *Apparatus and Task*

The experiment was performed on and controlled by a NCR 3125 pen computer, consisting of a horizontal screen (19.8 cm x 14.8 cm), an auxiliary keyboard, and a stylus that was not attached to the computer. Data were input by pressing the tip of the stylus on the screen. The computer sampled the input from the stylus at a rate of 200 Hz and was programmed in Borland Turbo PASCAL 6.0 to control the experiment. Data collection commenced 100 ms prior to the imperative stimulus and was collected for 2 seconds.

Subjects were required to make either a single arm movement (SM) or a movement reversal (MR) with their right arm. In the SM condition, subjects made a rightward movement from the start position to the first target and, in the MR condition, followed this movement by a leftward movement of half the amplitude of the initial movement to the second target. Each complexity condition consisted of three levels of accuracy: no accuracy (NA), low accuracy (LA), and high accuracy (HA). In the NA condition, there were no targets and subjects were not given accuracy instructions. In the LA and HA conditions, the targets subtended angles of  $15^\circ$  and  $3^\circ$ , respectively. The first target of the MR conditions subtended an angle of  $15^\circ$  while the second target differed in SA (figure 2). The subtended angle of the second target was defined by the total distance from the starting point to the target (i.e. the additive distance of the two movements).

All conditions were randomized with the exception of the two NA conditions, which were completed first (in a randomized order). Since there was no experimentally determined movement amplitude in the NA condition, it was necessary to control for this through the remainder of the experiment. The amplitude of the movements made in the four accuracy conditions was calculated separately for each subject and was equal to the mean of the amplitude of the initial rightward movements made by that subject in the NA-MR condition. However, due to limitations of screen size, the largest movement which could be made in the accuracy conditions was 17.3 cm. The smallest rightward movement in the accuracy conditions was 3.0 cm, to maintain separation of the two targets and the start position. Therefore, while the movement amplitude differed for each subject, the subtended angles were equal for all subjects and the amplitude was constant for each subject across the NA-MR condition and the four accuracy conditions. The trials in each condition were blocked and each subject completed ten practice trials and ten test trials per condition. Twenty percent of all trials were catch trials in which the imperative stimulus did not occur (subjects committed anticipation errors in less than 1% of all trials).

FIGURE 2: Targets on screen of pen computer



The circular targets were displayed on the screen of the pen computer. While only the start position was visible in the NA condition, both the start position and a trace of the movement path of the stylus were visible in the four accuracy conditions. The targets were also visible throughout each trial in the accuracy conditions, with the exception of the second target in the MR conditions. To keep the initial rightward movement unobstructed from the second target, this target disappeared when the imperative stimulus occurred and reappeared when the movement reached  $\frac{3}{4}$  of the total distance to the first target. Subjects were informed of this target manipulation before the trials began.

### *Procedure*

The experiment was tested under quiet conditions in one testing session which lasted approximately one hour. Subjects were seated at a desk upon which the pen computer was placed, such that the start position was centered in front of each subject. In addition, subjects were permitted to rotate the screen in a counter-clockwise direction to ensure that their hand did not block their vision of the targets during movement execution. When subjects indicated they were ready to begin, a warning tone of 1000 Hz sounded. After a variable foreperiod of 1000-2500 ms, a 2000 Hz tone occurred. Subjects were instructed to react to the 2000 Hz tone as quickly as possible and to make one smooth movement to each target. These instructions were based on the findings of an experiment by Sidaway (1994) in which an interaction effect was found between accuracy and instructional set. In Sidaway's experiment, the subtended angle was manipulated and the instructions contained either form-emphasis or initiation-emphasis information. Subjects were instructed to react as quickly as possible in both sets of instructions and in the form-emphasis instructions were also told to contact the target using one smooth continuous movement. While the reaction times to the two subtended angles did not differ in the initiation-emphasis instructions, subjects reacted faster to the larger SA in the form-emphasis instructions. Thus, in order to eliminate a possible confound of instructional

set, the LA and HA conditions in the present experiment used instructions which were similar to the form-emphasis instructions used by Sidaway. In the NA condition, subjects were instructed to make one smooth movement to a location of their choice. Specifically, subjects were instructed to make a single movement in the rightward direction in the NA-SM condition and, in the NA-MR condition, to follow that movement by a leftward movement of approximately one-half the amplitude of their initial rightward movement. After the completion of each trial, subjects were given the following feedback: (1) a movement trace of their horizontal displacement, (2) their reaction time, and (3) information as to whether the targets had been contacted, overshoot, or undershot. A trial was considered to be unacceptable if a subject missed a target or had a reaction time which was not between 110 ms and 350 ms. This bandwidth of time was used following several pilot studies which had revealed consistent means and standard deviations for similar reaction time tasks. In the testing conditions, the unacceptable trials were repeated until ten acceptable trials were collected.

### *Dependent Variables*

Reaction time was the dependent variable which indicated the time required to program a response, measured as the time difference between the occurrence of the imperative stimulus and movement initiation. Movement initiation was defined as the first indication of movement on the displacement trace. In the MR condition, the initiation of the second movement was defined as the point of reversal, the greatest positive value on the displacement trace. The distance and time of the first movement (FMD and FMT, respectively) and the second movement (SMD and SMT, respectively) were calculated as the time from movement initiation to the point at which the velocity trace crossed the zero line. The velocity data were derived from the unfiltered distance data and the peak velocities of the first and second movements (PV and SPV, respectively) were defined as the greatest positive (first movement) and negative (second movement) values on the velocity trace. Peak velocity was then used as the



demarcation point between the two phases of the velocity curve. Specifically, the first velocity phase was defined as the time from movement initiation to peak velocity for the first and second movements (VT1 and SVT1, respectively), while the second velocity phase was defined as the time from peak velocity to zero velocity for each movement (VT2 and SVT2, respectively). In addition, the point at which there was a reversal of movement (on the first target of the MR conditions) was analyzed in terms of the location and variability of these reversal points, in both the horizontal and vertical direction. In addition, the number of catch trial errors and the number of unacceptable trials were also recorded.

### *Analysis*

The means and standard deviations of the acceptable test trials were calculated on both individual subjects and the group of 11 subjects. A two (complexity) by three (accuracy) repeated measures ANOVA was performed on the reaction time data and the kinematic data of the first movements. The kinematic data of the second movements were analyzed with a one-way RM ANOVA and a t-test was used to analyze the point of reversal data (LA-MR vs HA-MR). The alpha level for each analysis was set at 0.05 and the Huynh-Feldt correction factor was used. One-way Tukey post-hoc tests (Howell, 1992, p.363), two-way Tukey post-hoc tests (Toothaker, 1993, p.67) and Scheffé tests for interactions (Ferguson, 1971, p.270) were performed where necessary.

## **Results**

### *Reaction Time*

The two (complexity) x three (accuracy) RM ANOVA performed on the reaction time data indicated a significant main effect of both complexity,  $F(1, 10)=17.333$ ,  $p<.01$ , and

accuracy,  $F(2, 20)=4.118$ ,  $p<.05$ . The MR condition had a longer RT ( $M = 223$  ms) than did the SM condition ( $M = 213$  ms, table 1). In addition, the HA condition had a longer reaction time ( $M = 229$  ms) than did the NA and LA conditions<sup>1</sup> ( $M = 213$  ms). The interaction effect was not significant,  $F(2, 20)=0.925$ ,  $p>.05$ .

### *First Movement Kinematics*

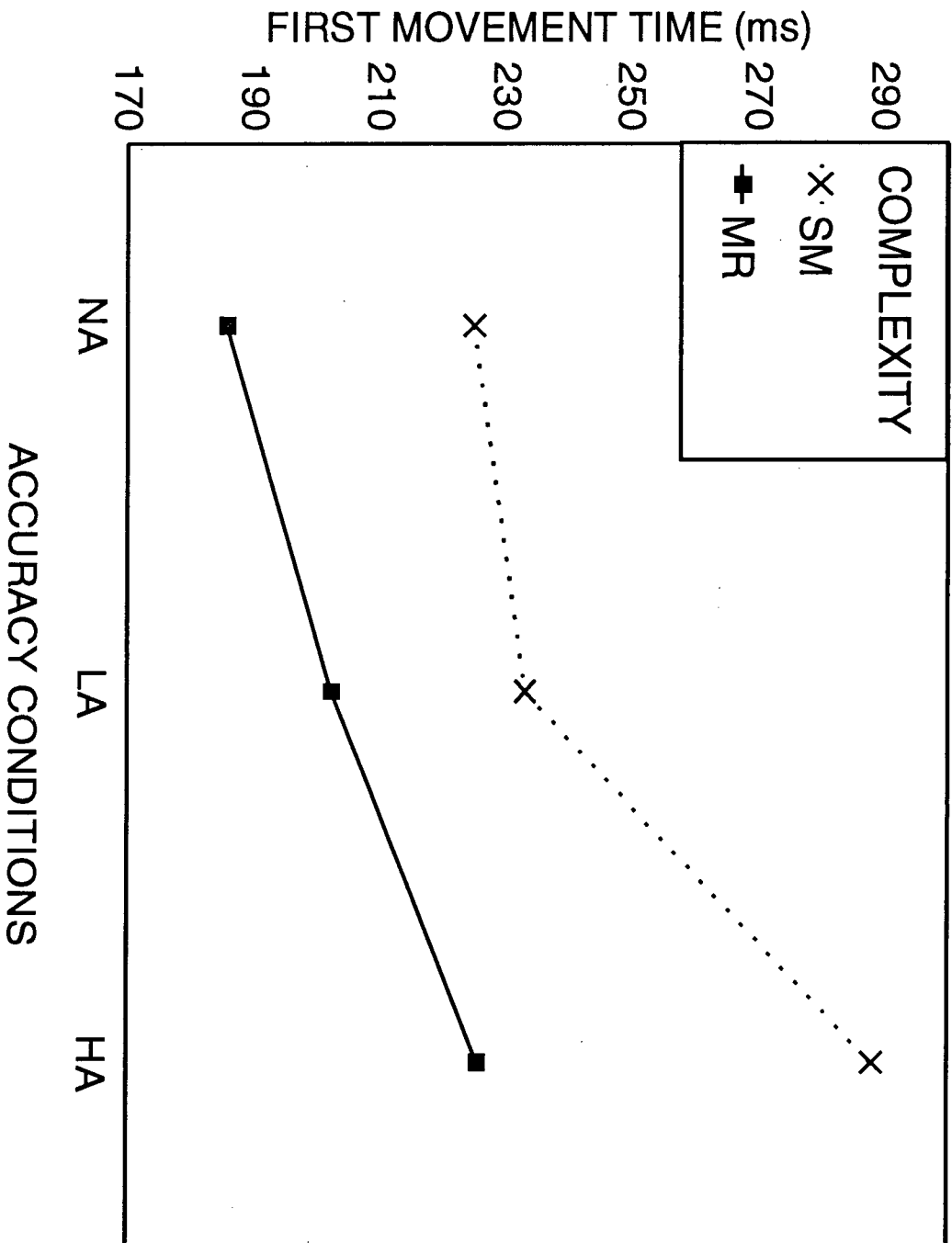
A two (complexity) x three (accuracy) RM ANOVA was performed on the kinematic variables FMT, FMD, PV, VT1, and VT2. Since none of the interaction effects for these variables were significant ( $p>.05$ ), the complexity and accuracy main effects of these variables are presented separately.

#### *Complexity*

A significant main effect occurred in the first movement time data,  $F(1, 10)=47.096$ ,  $p<.01$ , as the SM condition had a longer FMT than did the MR condition (figure 3). This significant main effect was not due to the distance subjects moved, since the main effect of complexity for FMD was not significant,  $F(1, 10)=0.117$ ,  $p>.05$ , (table 1). However, the main effect of complexity for peak velocity was significant,  $F(1, 10)=8.457$ ,  $p<.05$ , and the PV was greater in the MR condition ( $M = 73$  cm/s) than it was in the SM condition ( $M = 65$  cm/s, table 1).

The first movement kinematics were further analyzed by separating the velocity profile into two phases: the time from movement initiation to peak velocity and the time from peak velocity to movement termination. While the main effect of complexity for the VT1 data was not significant,  $F(1, 10)=4.372$ ,  $p>.05$ , it was for the VT2 data,  $F(1, 10)=50.478$ ,  $p<.01$ . The single movement condition had a significantly longer VT2 ( $M = 125$  ms) than did the movement reversal condition ( $M = 85$  ms, table 1). In summary, compared to the first movement of the movement reversal, the single movement had a longer movement time, a

FIGURE 3: First Movement Time



**Table 1.** Condition means for the dependent variables. Standard deviations are in parentheses.

	NA-SM	NA-MR	LA-SM	LA-MR	HA-SM	HA-MR
RT (ms)	205 (34)	221 (41)	207 (34)	219 (33)	227 (40)	230 (38)
FMT (ms)	225 (56)	186 (41)	233 (50)	202 (41)	288 (79)	225 (52)
FMD (cm)	8.6 (5.6)	8.1 (5.6)	8.7 (5.1)	8.3 (4.5)	8.6 (5.0)	8.7 (5.1)
PV (cm/s)	69 (42)	76 (44)	69 (34)	74 (38)	57 (25)	70 (36)
VT1 (ms)	112 (31)	110 (32)	121 (27)	120 (26)	139 (36)	130 (29)
VT2 (ms)	113 (27)	76 (10)	112 (24)	82 (17)	150 (48)	96 (27)
#UT (due to missed target)	0 (0)	0 (0)	0.3 (0.9)	2.8 (3.7)	11.4 (12.6)	7.0 (5.8)
#UT (due to reaction time)	0.3 (0.6)	0.5 (1.0)	0.3 (0.4)	0.4 (1.2)	0.4 (0.8)	0.8 (1.8)
SMT (ms)		151 (38)		171 (40)		200 (61)
SMD (cm)		5.1 (3.7)		4.7 (2.5)		4.6 (2.5)
SPV (cm/s)		51 (34)		48 (24)		42 (20)
SVT1 (ms)		55 (10)		64 (21)		77 (36)
SVT2 (ms)		96 (28)		107 (27)		122 (32)

lower peak velocity, and a longer deceleration phase.

### *Accuracy*

The RM ANOVA for the FMT data indicated that the main effect of accuracy was significant,  $F(2, 20)=15.586$ ,  $p<.01$ , and a Tukey post-hoc test showed that the HA condition had a significantly longer FMT than both the LA and NA conditions (figure 3). Similar to complexity, these differences in FMT occurred despite a constant FMD, since the main effect of accuracy was not significant,  $F(2, 20)=0.457$ ,  $p>.05$ . With a constant distance, it is generally expected that an increase in FMT would be accompanied by a decrease in peak velocity. However, the RM ANOVA for peak velocity indicated that the main effect of accuracy was not significant,  $F(2, 20)=2.426$ ,  $p>.05$ , even though the mean PV for the HA condition ( $M = 64$  cm/s) was lower than that of the NA and LA conditions ( $M = 72$  cm/s, table 1). For the VT1 data, the main effect of accuracy was significant,  $F(2, 20)=16.978$ ,  $p<.01$ , and a Tukey post-hoc test indicated that VT1 was longer in the HA condition ( $M = 135$  ms) than it was in the other two conditions ( $M = 116$  ms). Similarly, the main effect of accuracy was significant for VT2,  $F(2, 20)=12.183$ ,  $p<.01$  and VT2 of the HA condition ( $M = 123$  ms) was longer than that of the NA and LA conditions ( $M = 96$  ms). In summary, the longer FMT of the HA condition, as compared to the NA and LA conditions, was due to an increase in the time spent in both the acceleration and deceleration phases of the first movement.

### *Second Movement Kinematics*

A significant difference in second movement time occurred between the three accuracy conditions,  $F(2, 20)=7.148$ ,  $p<.01$ , and a Tukey post-hoc test showed that the mean SMT of the HA condition ( $M = 200$  ms) was greater than that of the NA condition ( $M = 151$  ms, table 1). These differences in SMT occurred despite the similarity of the second movement distance between conditions,  $F(2, 20)=0.905$ ,  $p>.05$ . While the peak velocity for the second movements

decreased as the accuracy constraints increased (table 1), these differences were not significant,  $F(2, 20) = 3.209$ ,  $p > .05$ .

Similar to the first movements, the second movements in the MR conditions were also separated into two velocity phases (VT1 and VT2) using peak velocity as the demarcation point. A significant difference occurred in the VT1 data,  $F(2, 20) = 4.540$ ,  $p < .05$ , and a Tukey post-hoc test indicated that VT1 was significantly greater in the HA condition ( $M = 77$  ms) than it was in the NA condition ( $M = 55$  ms, table 1). Similarly, VT2 was significantly greater in the HA condition ( $M = 122$  ms) than it was in the NA condition ( $M = 96$  ms, table 1),  $F(2, 20) = 5.637$ ,  $p < .05$ .

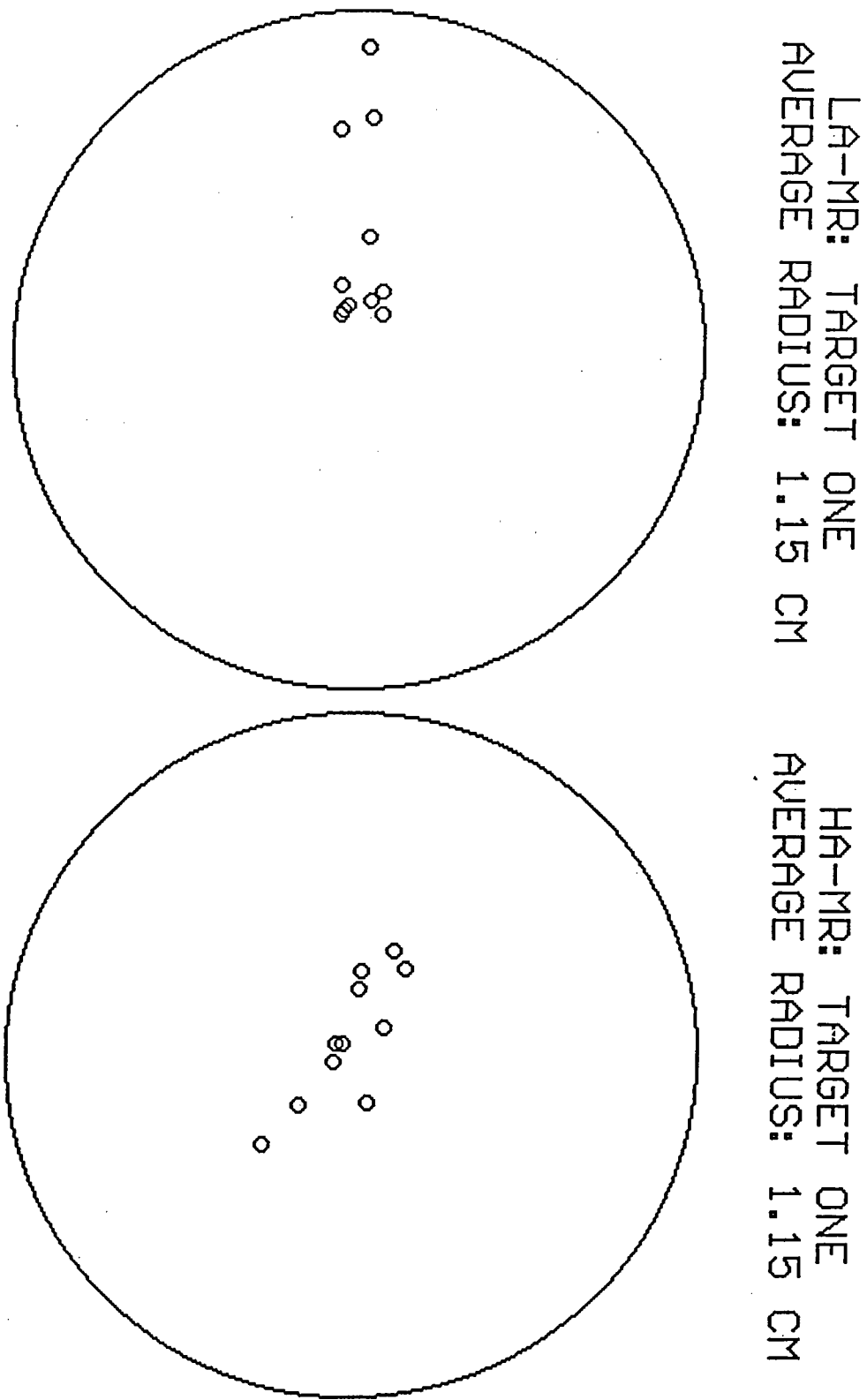
#### *Point of Reversal*

The points of reversal on the first target of the LA and HA MR conditions were analyzed in terms of location and variability. The mean location was expressed as the distance from the center of the target; points of reversal which were to the left or below the center were negative while those which were to the right or above the center were positive. A t-test showed that the point of reversal in the horizontal direction was significantly closer to the second target in the LA condition ( $M = -0.43$  cm),  $t(10) = 3.381$ ,  $p < .01$ , than it was in the HA condition ( $M = -0.07$  cm). However, the standard deviation of the reversal points from the two groups did not significantly differ ( $M = 0.4$  cm; figure 4). In the vertical direction, the point of reversal was similar in the LA and HA conditions as there were no significant differences for either location ( $M = 0.01$  cm) or standard deviation ( $M = 0.15$  cm).

#### *Unacceptable Trials*

The unacceptable trials were grouped according to the criteria for which they were dismissed. The number of trials which had a reaction time shorter than 110 ms or longer than 350 ms was similar throughout the different experimental conditions ( $M = 0.5$ , table 1).

FIGURE 4: Point of Reversal on First Target



However, due to the missed target criteria, there were more unacceptable trials in the HA condition ( $\bar{M} = 9.2$ ) than there were in the LA condition ( $\bar{M} = 1.5$ , table 1). No trials were excluded due to the missed target criteria in the NA condition (in which there were no targets). Thus, subjects repeated 48% of the trials in the HA condition and 0.1% of trials in the LA condition. The reaction time of the unacceptable trials in the HA condition were compared to that of the acceptable trials, to ensure that there were no fundamental differences between these two groups of responses. A 2 (complexity) by 2 (trial acceptability) RM ANOVA indicated that the reaction time for the unacceptable trials ( $\bar{M} = 232$  ms) was not significantly different from that of the acceptable trials ( $\bar{M} = 229$  ms),  $F(1, 10) = 0.861$ ,  $p > .05$ . In summary, these results reflect the fact that subjects had more difficulty attaining the target in the HA condition (especially when making a single movement) than they did in the NA and LA conditions.

## **Discussion**

### *Reaction Time*

Movements comprised of two segments took longer to prepare and initiate than did single movements. This result contradicts Sidaway's (1991) finding that the programming time of a response was not affected by complexity under conditions of constant accuracy. It is necessary to question whether the fundamental difference between the tasks of these two studies (imposed by the reversal component) could be responsible for this equivocal finding. First, response complexity effects have previously been found in tasks which included a reversal component (van Donkelaar & Franks, 1991a, 1991b) as well as in tasks which did not (Canic & Franks, 1989; Hulstijn & van Galen, 1983; Garcia-Colera & Semjen, 1987; 1988). Further, an experiment which specifically compared the reaction time for a straight line tapping task to that of a tapping task which included a reversal (Glencross, 1980, experiment 3) found

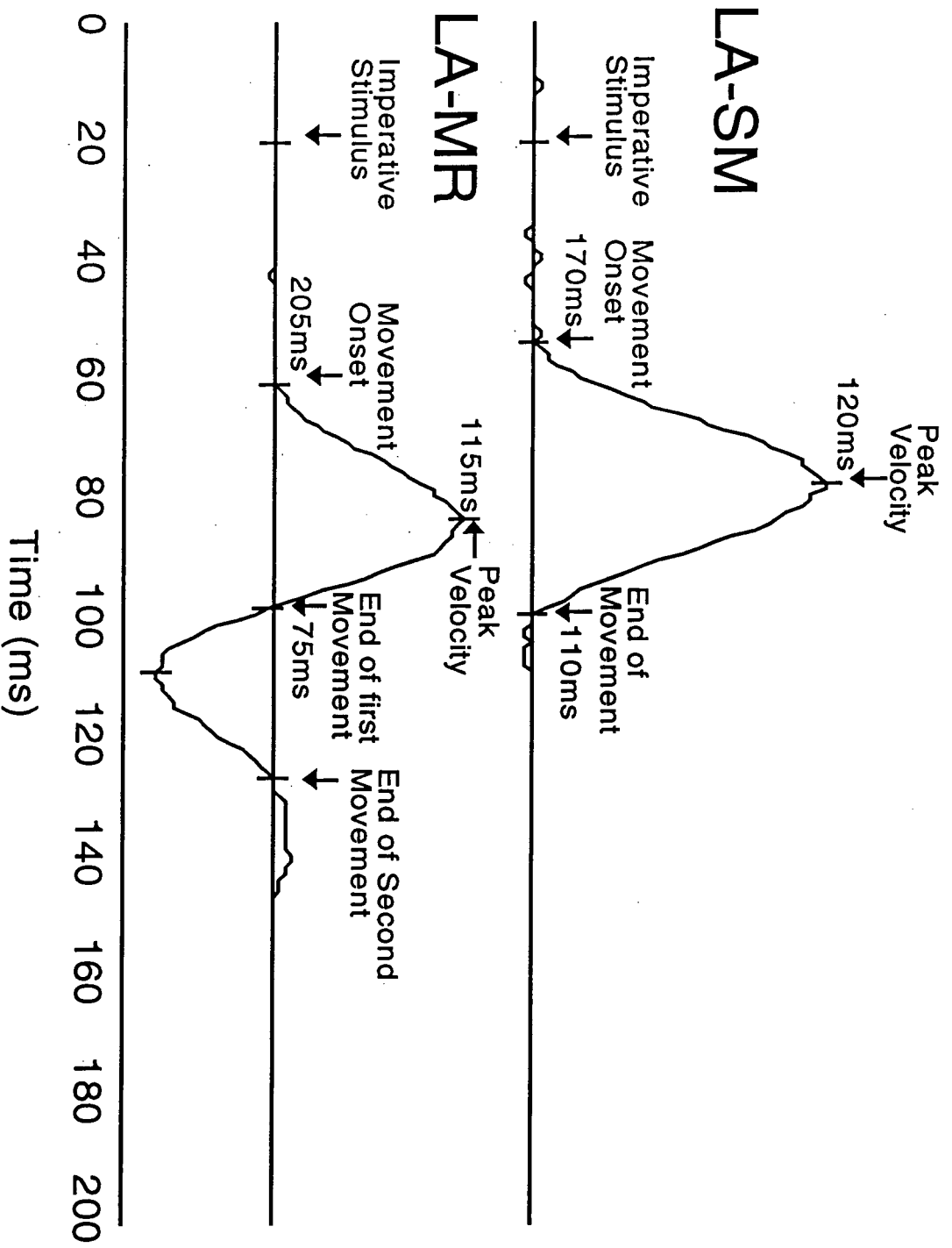


that the reaction times for these two tasks were similar. It therefore appears that the effect of response complexity is not task specific.

Limited support for Sidaway's subtended angle hypothesis was provided by the present finding that a movement with high accuracy constraints had a longer reaction time than did movements with low and no accuracy constraints. While the SA hypothesis predicted that reaction time would increase with an increase in the accuracy requirements of a task, no predictions were made as to what would occur if a task had no accuracy requirements. In the present experiment, it was hypothesized that the LA condition would have a longer reaction time than the NA condition. However, the reaction times of these two conditions were similar, suggesting that the 15 degree target may have constituted a similar accuracy constraint to that involved when there was no target. In contrast, previous experiments have found that the reaction time to a 15.1 degree target was significantly shorter than that to a larger 24.5 degree target (Gordon & Christina, 1991; Sidaway, 1991). The question which then arises is whether the SA hypothesis should be expected to hold for extremely large angles. When a subject is required to move in a rightward direction, a no target condition essentially equates to a target which subtends an angle of 180 degrees. Since any angle greater than 90 degrees corresponds to a negative ID, it is questionable whether Sidaway's equation should be applied to a no target condition.

In order to determine whether it was reasonable to compare movements which had accuracy constraints to those which did not, these two types of movements were assessed for differences in their kinematic properties. This was accomplished by analyzing the symmetry of the first and second velocity phases (i.e. the acceleration and deceleration phases) of the movements in the NA and LA conditions. For the single movements, the time from movement initiation to peak velocity was similar to the time from peak velocity to the termination of the movement, yielding a symmetrical velocity curve (figure 5). Although the first velocity phase was longer than the second velocity phase for the reversal movements (figure 5), this

FIGURE 5: Sample Velocity Traces



relationship remained constant across the NA and LA conditions. Since the kinematic properties of the NA and LA conditions were similar, it was concluded that it was valid to make comparisons between movements which did and did not have accuracy constraints. Perhaps subjects simply perceived the no accuracy and low accuracy conditions as being equally difficult. In the present experiment, the fifteen degree target appeared to be large in comparison with the size of the pen computer screen. In fact, if a subject was moving in a rightward direction, it would have been difficult to miss the target. Introspective reports from subjects indicated that, in general, subjects felt the high accuracy condition was difficult while the low accuracy condition was not.

### *Movement Kinematics*

The single movement was longer and slower than the first movement of the movement reversal. Recall that subjects terminated their movement on the first target in the single movement condition, but reversed on this target in the movement reversal condition. It is likely that the kinematic differences between the single and reversal movements occurred due to the control processes involved in stopping. Previous experiments have also identified the fact that the control mechanisms for movements which stop on a target and reverse on a target are different (Adam, van der Bruggen, & Bekkering, 1993). Specifically, the EMG profile of a movement which stops on a target consists of a triphasic pattern of activity (agonist-antagonist-agonist; Enoka, 1994, p.251) while that of a movement which reverses on a target contains only agonist-antagonist bursts (with the antagonist becoming the agonist for the reversal movement; Enoka, 1994, p.14). Although EMG data was not collected in the present experiment, the kinematic results support this particular hypothesis. The VT2 of the single movement was longer than that of the movement reversal, a time increase which could accommodate the extra agonist burst found to occur in discrete movements (Enoka, 1994, p. 251). However, EMG analysis would be necessary to verify a relationship between VT2 and

the final agonist burst.

In the HA condition, subjects took a longer time to complete the first movement than they did in the NA and LA conditions. Previous experiments have also found that the time to complete the first movement in a series of movements increased with the accuracy demands of the task (Sidaway, 1991; Sidaway, Sekiya, & Fairweather, 1995). While Chamberlin and Magill (1989) have interpreted an increase in movement time to be an indication of on-line programming (programming which occurs during the first movement), the results of another experiment (Fischman & Reeve, 1992) dispute this claim. Fischman and Reeve found that the movement time of a one movement response was less than that of the initial segment of a two movement response, regardless of whether or not subjects were required to contact the second target in the two movement response. These results led Fischman and Reeve to conclude that the increase in movement time occurred because subjects adopted a strategy of restraining their limb as it approached the initial target. Further, it was suggested that this strategy could be planned prior to movement initiation.

In order to determine whether the increased FMT of the HA condition in the present experiment was due to on-line programming, three measures were investigated. First, on-line programming has been found to predominantly occur between the peak velocity and the end of a movement (van Donkelaar & Franks, 1991b). If this were the case, the velocity profile would be asymmetric and VT2 would be longer than VT1. However, the HA velocity data from the present experiment indicated that the velocity profile was symmetrical for the single movement and asymmetrical for the first movement of the movement reversal, with VT1 longer than VT2. Second, significant deviations in the acceleration profile (a decrease in the data between successive maximum points of acceleration) have been used as an indication of corrective adjustments (Carlton, 1981; van Donkelaar & Franks, 1991b). In the present experiment, only two subjects showed an increase in significant deviations in the HA conditions, compared to the LA and NA conditions. A third measure used as an indicant of on-

line programming in the present experiment was the time at the end of the velocity trace (EVT) between the first zero line crossing and when the velocity trace stabilized at zero. In the present experiment, movement termination was defined as the time when the velocity trace crossed the zero line. In some cases, the velocity profile continued to deviate from zero after this point. This EVT likely represented movement corrections which occurred in the opposite direction to the primary direction of motion (e.g. a leftward correction for the single movement). If the EVT was longer in the HA condition than it was in the LA and NA conditions, an on-line programming explanation would be supported. That is, the time required to complete movement corrections after the velocity trace crossed the zero line would be greater in the high accuracy condition than in the NA and LA conditions. However, analysis of EVT for single movements indicated that EVT for the HA condition was less than that for the NA and LA conditions. In the HA condition, only three subjects made corrective movements after the velocity trace first crossed the zero line while approximately twice as many subjects made these corrections in the LA and NA conditions. Recall that subjects moved slower in the HA condition than in the LA and NA conditions, therefore the slower movement of the HA condition may have allowed for an increased precision of stopping with few corrective movements. Taken together, these three measures (VT2, significant deviations, and EVT) do not support the occurrence of on-line programming during the HA condition. Rather, these measures support the hypothesis that movements with high accuracy constraints were programmed during the reaction time, before movement initiation (referred to as pre-programming). In the HA condition, it is likely that subjects pre-programmed a more precise movement trajectory (Sidaway, 1991; Sidaway et al., 1988; Fischman & Reeve, 1992) than they did in the LA and NA conditions. Specifically, subjects pre-programmed a slower movement in order to accurately attain a target which subtended a smaller angle.

The accuracy constraints imposed by the second target of the movement reversal condition also affected the kinematics of the movement to the first target. In the LA-MR and

the HA-MR conditions, the first target subtended the same ( $15^\circ$ ) angle and it was the second target which imposed the accuracy constraint. The high accuracy condition had a longer first movement time (both VT1 and VT2 were increased) and a slower peak velocity than did the low accuracy condition. In a target tapping task, Sidaway, Sekiya, and Fairweather (1995) also found that when the size of the first target was held constant, the size of the second target affected movement time to the first target; movement time was greater when the second target was smaller. Sidaway et al. also found that, when the second target was smaller, the mean location of contact points on the first target was less variable and was closer to the second target. These findings led Sidaway et al. to conclude that the accuracy demands of both targets were pre-programmed. In contrast, the results of the present experiment indicated that the mean location of reversal points was closer to the second target in the LA condition than it was in the HA condition, with a similar standard deviation for both conditions. Thus, subjects attained the center of the first target more accurately in the HA-MR condition than they did in the LA-MR condition. Assuming that subjects were aiming for the center of the first target, a slower movement (such as that made in the HA condition) would be expected to attain the intended endpoint more accurately than would a faster movement (such as that made in the LA condition).

The majority of the variability in end point location was accounted for in the horizontal direction (see figure 4). However, when circular targets are used, the subtended angle provides the same index for target height as it does for target width. The small standard deviation in the vertical direction suggests that the movements in this experiment did not contain a large amount of inherent variability in the vertical direction. Thus, if the target was changed to an ellipse such that the width remained constant and the height was decreased (as compared to the present circle), it is likely that the overall accuracy constraints of the task would not be greatly affected. In contrast, if the target was changed to an ellipse such that the height remained constant and the width was decreased, the overall accuracy constraints of the task would

increase. That is, since the majority of the inherent variability existed in the horizontal direction, a limitation to this variability would affect the accuracy constraints of the task. However, the subtended angle would not change in the case of the latter ellipse, since SA is dependent only on the height of the target and on the target's distance from the start point. It appears that the index of difficulty of a movement may be affected more by the width of a target than the height, a construct which is not accounted for in the present definition of ID.

In conclusion, the present experiment demonstrated that the time required to program a limb movement was affected both by the number of movements in the task and by the accuracy constraints imposed on those movements. These results provide support for the original response complexity hypothesis proposed by Henry and Rogers (1960) as well as for Sidaway's (1988) SA hypothesis. However, further research which measures the electrical activity of the agonist and antagonist muscles is necessary in order to fully investigate Sidaway's hypothesis that the increase in programming time required for accurate movements is related to changes in the motor unit recruitment pattern. In addition, the kinematics of the first movement were found to vary dependent on the presence of a subsequent movement and on the accuracy constraints of the task, regardless of whether those accuracy constraints were imposed by the first or second target. This investigation of movement kinematics also revealed that the precision required for movements with high accuracy constraints was likely programmed prior to movement initiation, rather than on-line.

## Notes

1. The Tukey post-hoc analysis on the main effect of accuracy showed that the difference between the HA condition and the NA and LA conditions just barely failed to reach significance (the critical value was greater than the difference between the HA and NA

conditions by 0.27 and greater than that of the HA and LA conditions by 0.315). However, since the means of the NA and the LA conditions were similar and were much less than that of the HA condition (table 1), it is reasonable to conclude that the significant difference indicated by the main effect of accuracy occurred because the RT was longer in the HA condition than it was in the NA and LA conditions.

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