An Examination of Rapid Positioning Movements with Spatiotemporal Constraints

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ABSTRACT. Unidirectional positioning movements with spatiotemporal constraints were examined as a test of impulse-timing theory (Schmidt, 1976; 1980; Wallace, 1981). Movements were examined at the kinematic, kinetic, and neuromuscular levels in three experiments. In the first experiment, displacement was held constant while five different movement times were examined. Both amplitudes and durations of the EMG and the kinetic variables were related to movement time. The results generally support the impulse-timing model. In the second experiment, movements were performed to a target at each of four distances in a constant movement time. EMG and force amplitudes and, unexpectedly, active-force duration were modulated to achieve changes in displacement when movement time was constant. In the third experiment, movement time and displacement were simultaneously varied resulting in four conditions with equal average velocities. The results of this experiment were not as clear and exhibited individual differences. EMG duration did not always vary with changes in movement time. The results of all three experiments could not be adequately accounted for by the impulse-timing model.

ARM MOVEMENTS can have a variety of spatiotemporal goals. Common among these are obtaining a desired position, moving in a specified amount of time, or arriving at a position as fast as possible. Specific examples of these goal-directed movements are reaching for a stationary object, drawing a bow across a violin, or throwing a fastball, respectively.

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D. C. Shapiro & C. B. Walters

It has previously been suggested that slow movements may be controlled differently than fast or "ballistic" movements (e.g., Stetson & McDill, 1923; Kornhuber, 1971; Hallett, Shahani, & Young, 1975). The emphasis of our present paper is on the production of ballistic movements.

The control of rapid positioning movements has received a great deal of experimental attention in the last decade (e.g., Bouisset & Lestienne, 1974; Hallett & Marsden, 1979; Lestienne, 1979; Marsden, Obeso, & Rothwell, 1983). A problem of primary interest regarding the control of these movements has been the nature of the information specified in the central motor command. To address this problem, univariate positioning responses have been examined at various levels. These simple actions are studied because the relationship among the kinematic, kinetic, and neuromuscular variables are more direct than for multi-joint actions where interactive terms are involved (Hollerbach & Flash, 1982).

Our focus in the following experiments is on various characteristics of rapid movements in order to make inferences concerning their control.

One general approach employed to study the structure of the motor command has been to manipulate certain movement requirements (e.g., displacement, velocity) to determine any invariances (e.g., relative timing) at the levels examined (Shapiro, in press). The logic is that invariances reflect the command structure and suggest how the central nervous system simplifies the control problem. This is analogous to Newtonian mechanics simplifying the explanation of physical motion, with a few relatively simple rules governing a variety of actions.

A common experimental manipulation in motor control studies has been the variation of movement displacement. The control of displacement has been examined in human subjects for finger flexions and extensions (Freund & Büdingen, 1978), thumb flexions (Hallett & Marsden, 1979), elbow flexions and extensions (Brown & Cooke, 1981; 1984; Cooke, Brown, Forget, & Lamarre, 1985; Hallett & Koshbin, 1980; Lestienne, 1979; Wallace & Wright, 1982; Wadman, Denier van der Gon, Guezee, & Mol, 1979), and shoulder abductions (Angel, 1974). In cats, Ghez and colleagues (e.g., Ghez, 1978; and Ghez & Vicario, 1979) have varied distance utilizing a tracking task. In several of these studies, subjects were required to move as fast as possible over the different displacements. The general finding for these maximal tasks is that agonist burst duration remains constant while amplitude is modulated to achieve changes in movement displacement. It is also apparent that absolute movement time remains nearly constant regardless of the required displacement (e.g., Freund & Büdingen, 1978; Hallett & Koshbin, 1980; Hallett & Marsden, 1979).

The above findings suggest a strategy that subjects tend to adopt given this specific set of movement requirements and has led to the formulation of two simple models of control. Based on their evidence from both static and dynamic contractions, Freund and Büdingen (1978) proposed a "speed-control system" in which time to peak force is held constant while magnitude of force is varied to achieve different levels of isometric force or velocity. Ghez (1979) independently noted constancy of time to...
peak force and EMG duration in step-tracking movements of cats. A "pulse-step" model was formulated (Ghez, 1979), similar in concept to the speed-control system, with the addition of a "step" component to determine final force level or limb position. In studies where distance was manipulated but subjects were not required to move maximally, agonist burst durations tended to remain constant (Brown & Cooke, 1981; Ghez & Vicario, 1978), which is in agreement with both models. In a subsequent study, however, Brown and Cooke (1984) observed an increase in agonist burst duration with an increase in displacement. The gradation was discontinuous in nature, with burst durations reported to increase in approximate multiples of 70 ms. This result was also reported in a subsequent study on a deafferented patient (Cooke et al., 1985).

Conflicting evidence has also been reported for maximal velocity actions. Wadman et al. (1979) found that when displacement increased, burst duration increased. These authors noted, however, that subjects increased movement time with increased displacement. Interestingly, in the aforementioned studies where movement time appears to be constant with changes in displacement (e.g., Hallet & Marsden, 1979), EMG burst duration also remains invariant. In the case where movement time appears to vary with distance (Wadman et al., 1979), burst duration varies as well.

In several cases, velocity and movement-time manipulations have been achieved by a qualitative instruction. For example, Bouisset and Lestienne (1974) and Lestienne (1979) requested subjects to move at "low, normal, and high speeds." Brown and Cooke (1981; 1984) instructed subjects to move "fast, accurate, or fast and accurate." These studies are somewhat difficult to interpret because movement times for each condition are not clearly documented. It appears in the Lestienne experiment (Figure 1, p. 410) that subjects vary agonist duration with changes in movement time. These EMG duration were reported to change proportionally with movement time for velocities greater than 3 rad/s. The actual movement times in the Brown and Cooke (1981) study are less clear. The authors report that the duration of the agonist burst was "relatively constant"; however, the data displayed (Figure 1, p. 102) tends to indicate that burst duration varies (although not systematically) with changes in instruction. Moreover, data from Brown and Cooke (1984) indicate that agonist burst durations are longer for fast than for fast movements for displacements of relatively large magnitudes.

Based on these previous studies, it is difficult to determine the relationship between the movement characteristics (i.e., movement time and displacement) and the possible invariances in kinetic and neuromuscular patterns, since not all the information is available regarding the actual movement conditions utilized to perform the task. Newell and colleagues (e.g., Newell, 1980; Newell, Hoshizaki, Carlton, & Halbert, 1979) have independently manipulated movement time, displacement, and velocity in a different but related context, that is, speed-accuracy trade-off issues. In a recent study, Wallace and Wright (1982) systematically examined changes in EMG duration as a function of two
movement times and displacements. In this experiment, either movement time or displacement was held constant. When movement time was constant burst duration remained constant and when movement time varied burst duration varied. Displacement had no effect upon EMG duration. This study represents the clearest control of movement time and displacement relative to the present concerns.

The results of the Wallace and Wright (1982) study partially support an impulse-timing model (Schmidt, 1976; 1980), formalized at the EMG level by Wallace (1981). The model proposes that both durations and amplitudes of the impulses representing accelerative and decelerative forces are modulated by the nervous system. The fundamental predictions of this model are that increases or decreases in overall movement time are accompanied by proportional changes in the temporal sequence of kinetic and neural events, while changes in force requirements are accomplished by an overall scaling of the amplitude of these events (Schmidt, 1982; Wallace, 1981). Support for temporal predictions of the model has come primarily from sequential rather than discrete movements (Armstrong, 1970; Carter & Shapiro, 1984; Hollerbach, 1978; Shapiro, 1976, 1979; Shapiro, Zernicke, Gregor, & Diestel, 1981; Terzuolo & Viviani, 1980). Although Wallace and Wright (1982) found support for the impulse-timing model in terms of burst durations, they did not find proportionality of burst duration with movement time. The limitations of their study are that EMG amplitudes were not measured and only two movement times and displacements were examined, precluding an examination of the linearity of the relationships.

The following experiments were performed to further examine the impulse-timing model (Wallace, 1981). Movement time, displacement, and average velocity were systematically manipulated and the timing and magnitude of the underlying kinetic and neural signals were measured. In the first experiment, movement time was manipulated while displacement was constant and in the second experiment the opposite conditions occurred. In the final experiment, movement time and displacement were simultaneously varied, keeping average velocity constant.

**Experiment 1**

Experiment one required subjects to vary movement time while maintaining a constant displacement. The impulse-timing model would predict temporal scaling of the dependent variables (EMG and force) with movement time.

**Method**

**Subjects**

Four right-handed male subjects participated in this experiment. None was paid for his services.
Apparatus and Task

The movement examined was horizontal elbow flexion, with the shoulder abducted 90°. The response apparatus consisted of a lightweight aluminum lever affixed to a virtually frictionless vertical axle. The subject’s elbow rested on a pad at the proximal end of the lever directly above the axle. Attached to the distal end of the lever was a vertical handgrip. A strain gauge was located between the lever and the handgrip and reflected the force overcoming the inertia of the lever. The height of the subject’s seat was adjustable so that the lever could be positioned exactly at shoulder level, thus isolating the muscles responsible for the action.

A potentiometer was attached to the bottom of the axle supporting the lever. Its output was sent to an FM tape recorder (Vetter Model-D eight channel). The signal from the strain gauge was preamplified (Grass Model 7P1) and then amplified (Grass Model 7DA) before being recorded. Electromyographic signals were also amplified (Grass Model 7P3 preamplifier and Model 7DA driver amplifier) prior to recording.

A telegraph key was utilized to serve two functions. Once the experimenter pressed the key, a step change in DC voltage was recorded on the FM tape to trigger subsequent data digitization. The key also activated a Lafayette Instruments bank timer, which illuminated a start light after a delay of 200 ms. A microswitch was situated at the movement-start location and upon movement initiation triggered a sweep on a storage oscilloscope (Tektronix 5113). The starting position was located at the approximate resting equilibrium point for the muscles acting at the elbow, 75° from full extension (Lestienne & Pertuzon, 1974), so that baseline neuromuscular activity could be held to a minimum. A metal strip, 2 cm wide, served as a target. The goal of the task was an elbow flexion of 30° to the target in a variety of movement times.

Procedure

A brief description of the experiment was presented during EMG electrode preparation and placement. Ag-AgCl surface electrodes were placed approximately 2.5 cm apart over the belly of the biceps brachii (agonist) and triceps lateralis (antagonist). Subjects were informed that the goal of the task was to move accurately to the target in various movement times. Practice trials were performed prior to the experimental trials until each of five bandwidths contained ten responses. The bandwidths were defined by the following movement times ± 5 ms: 150, 180, 210, 240, and 270 ms. A brief rest period was allowed prior to the experimental trials. Data collection then continued until 25 trials were gathered within each of the movement time bandwidths. Temporal feedback was not given to the subject after each trial, although qualitative feedback (e.g., “speed up a little”) was given near the end of the session to facilitate the filling of each bandwidth. No knowledge of results (KR) regarding amplitude was required because the subjects had vision of any spatial error occurring. Rest periods were given after every
D. C. Shapiro & C. B. Walters

60 experimental trials. Filling all the movement-time bandwidths with 25 trials each required a total of between 180 and 230 responses.

Data Analyses

All data manipulations were performed by a D.E.C. 11/23 MNC computer. The data were digitized at a sampling rate of 500 Hz. The displacement channel was smoothed with a 10 ms moving-window average, and the EMG channels were digitally rectified and smoothed with an 18 ms window. All channels were synchronized at movement initiation, which was determined as a point exceeding 2 SD above the position baseline signal. Trials were then selected into the five movement-time bandwidths if they passed the spatial criterion of being within ±10% (3°) of the target displacement in addition to the movement time criteria discussed above.

The data in each of the five movement-time subsets were analyzed in the following manner. Movement times were determined by measuring the time elapsed between movement initiation and the first peak in the displacement trace. The oscillations characterizing the termination of rapid limb movements (Crossman & Gooden, 1963/1983; Kelso & Holt, 1980; Walter, 1985) make it somewhat difficult to select the endpoint of a movement; however, it was felt that the peak displacement criterion best expressed the “transport time” (Lestienne, 1979) of the limb from starting point to target. Values for other kinematic, kinetic, and electromyographic variables of interest (onset, cessation, peak, and time to peak values) were determined by using interactive graphics (Walter, 1984), with the experimenter placing a cursor at each point or “landmark” to be analyzed. All amplitude measures were in arbitrary units and were converted into magnitudes relative to each subject’s peak magnitude to simplify comparisons between subjects. Each variable was averaged across trials within each condition for display purposes, while individual trials were used for statistical analyses.

Three types of statistical analyses were performed on the means of the trial-by-trial analysis of the data. Within-subject Pearson product-moment correlations were calculated to examine the relationships between the variables. One-way analyses of variance (ANOVA) with repeated measures were also performed on several dependent measures to detect significant differences between the experimental conditions. Finally, polynomial regressions were computed to determine the order of equations best fitting the data.

Results

Kinematics

The experimental trials included for analyses attained the kinematic requirements specified in the methods section. The averaged displacement data for one subject is depicted in Figure 1a, and demonstrates that displacement was constant while movement time varied.
in Table 1 are the average movement times and amplitudes for all subjects. Average peak velocities ranged from 162°/s to 353°/s. The responses were thus quite rapid.

Kinetics

Force duration. Figure 1b includes the average force traces for a single subject. The accelerative and decelerative force durations appeared to increase as movement time increased. Included in Table 1 are means and standard deviations for all subjects. The increases were significant for both accelerative, \( F(4,12) = 133.69, p < .001 \), and decelerative, \( F(4,12) = 96.25, P < .001 \), force durations for all subjects. Time to peak force also increased with increased movement time, \( F(4,12) = 12.68, p < .001 \).

The impulse-timing model would predict that the ratio of the accelerative and decelerative force durations to the sum of these force durations would be constant. The proportions are entered in Table 1 and both the accelerative, \( F(4,12) = 1.45, p > .05 \), and the decelerative, \( F(4,12) = .55, p > .05 \), force duration proportions were indeed not significantly different across movement-time conditions. A polynomial regression analysis revealed a significant linear component for accelerative force, \( t(18) = 13.03, p < .001 \), and decelerative force, \( t(18) = 4.78, p < .05 \), durations.

Force amplitude. There was a strong inverse relationship between peak force and movement time. As indicated in Table 1, as movement time
<table>
<thead>
<tr>
<th></th>
<th>150 ms</th>
<th>180 ms</th>
<th>210 ms</th>
<th>270 ms</th>
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<td>151.3(1)</td>
<td>180.0(1.5)</td>
<td>209.5(7)</td>
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<td>30.6(6)</td>
<td>30.8(3)</td>
<td>30.8(3)</td>
<td>30.4(7)</td>
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<td>115(6)</td>
<td>129(5)</td>
<td>158(10)</td>
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<tr>
<td>Decelerative force duration (ms)</td>
<td>128(11)</td>
<td>132(7)</td>
<td>170(9)</td>
<td>195(11)</td>
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<tr>
<td>Time to peak force (ms)</td>
<td>51(8)</td>
<td>62(11)</td>
<td>71(11)</td>
<td>96(40)</td>
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<td>.44(.02)</td>
<td>.43(.02)</td>
<td>.43(.02)</td>
<td>.45(.03)</td>
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<td>.57(.03)</td>
<td>.57(.03)</td>
<td>.55(.03)</td>
</tr>
<tr>
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<td>.73(.08)</td>
<td>.56(.09)</td>
<td>.33(.05)</td>
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<tr>
<td>Decelerative force amplitude (proportions)</td>
<td>1.00(0)</td>
<td>.78(.06)</td>
<td>.59(.06)</td>
<td>.40(.05)</td>
</tr>
</tbody>
</table>

Note: Values are means (±SD).
increased, peak accelerative, $F(4,12) = 146.7, p < .001$, and decelerative, $F(4,12) = 117.31, p < .001$, forces significantly decreased. This can be observed in the averaged data for one subject displayed in Figure 1b. In addition, there was a high positive relationship between the peak amplitudes of the accelerative and decelerative force curves (.99, .99, .99, and .98) for each subject.

**EMG**

**Agonist EMG.** Figure 1c demonstrates the average biceps activity for one subject. The EMG activity with the greatest peak and shortest duration represents the 150-ms condition, and the shortest peak with the longest duration represents the 270-ms condition. A progressive increase is evident in the duration of the biceps activity as the movement time is lengthened. These duration changes were significant, $F(4,12) = 6.36, p < .05$, across subjects. A polynomial regression analysis revealed a significant linear component, $t (18) = 2.11, p < .05$ (Figure 2). An in-

![Figure 2. Average biceps EMG duration for all subjects plotted against movement time in Experiment 1.](image)
crease in burst duration with increased movement time supports the impulse-timing model. A strict interpretation of this view (Wallace, 1981), however, would predict that the ratio of EMG duration to movement time should remain constant across changes in movement time. This was not the case for the biceps proportions, $F(4,12) = 47.43, p < .001$. Relative biceps peak amplitudes were .99 (.02), .87 (.11), .61 (.16), .52 (.20), and .37 (.14). Examination of biceps amplitude revealed a significant decrease in this parameter as movement time increased, $F(4,12) = 26.51, p < .001$.

Antagonist EMG. Triceps burst durations displayed characteristics similar to those of the biceps. The durations tended to increase with increased movement time, as demonstrated by the average data for the subject displayed in Figure 1d. The EMG activity with the greatest peak and shortest duration represents the 150-ms condition and the shortest peak with the longest duration represents the 270-ms condition. It was very difficult, however, to determine the cessation of activity of these bursts and therefore the durations could not be accurately quantified. A decrease in relative triceps amplitude was found to be 1.0 (0), .78 (.08), .54 (.15), .44 (.16), and .36 (.19) as movement time increased. This decrease was significant, $F(4,12) = 26.28, p < .001$. In addition, there was a positive relationship between the peak amplitudes of the biceps and triceps EMG (.95, .90, .99, and .98) for all subjects.

Kinetics and EMG

Strong relationships were obtained between the peak amplitudes of the biceps burst and the peak accelerative force for each subject (.98, .92, .98, and .95). A similar relationship was evident between the decelerative force and the amplitude of the triceps burst. The correlations for each subject were .98, .99, .99, and .99.

Experiment 2

Experiment two required subjects to vary angular displacement while holding movement time constant. Temporal invariance of the control variables would be predicted by the impulse-timing model.

Method

Subjects

Four right-handed male subjects, three of whom were in the previous study, participated in this experiment. None was paid for his services.

Apparatus and Task

The apparatus and task were described in detail in the previous section. The goal of the task was an elbow flexion of each of four different amplitudes; 20, 30, 40, and 50°. The criterion movement time was set so that each subject was moving at approximately 70% of maximum
average velocity for the 50° condition. This velocity was chosen because it is submaximal yet still fairly rapid, and resulted in a movement time of 200 ms for each of the 4 subjects.

Procedures

Each of the 4 subjects performed all four conditions. Subjects initially performed 60 practice trials, 15 at each of the four target distances. A 5-min rest was then administered, followed by 50 experimental trials blocked within each condition. Subjects performed the four conditions in random order. Movement-time KR to the nearest 10 ms was provided after each practice and experimental trial to facilitate data collection. Rest periods were provided between conditions so that muscular fatigue would be minimized.

Data Analyses

Initial data manipulations were similar to those described for Experiment 1. The data were subsequently placed into groups containing only those trials passing the spatiotemporal criteria imposed for each condition. The spatial criterion was again ±10% of the target displacement. The temporal bandwidth was ±10 ms of the goal movement time. The statistical analyses utilized in the previous experiment were incorporated in this study.

Results

Kinematics

Figure 3a displays the average displacement curves for a single subject when movement time was constant and displacement varied. Entered in Table 2 are the average movement times and amplitudes for all subjects. Peak velocity magnitudes ranged from 180°/s to 490°/s for all subjects.

Kinetics

Force durations. Figure 3b demonstrates the average force curves for a single subject. The changes in both accelerative- and decelerative-force durations appear to be slight. Table 2 includes the average force durations for all subjects. Accelerative force durations decreased with an increase in displacement, $F(3,9) = 9.95, p < .01$. A concomitant increase in decelerative force durations appeared to be evident; however, there were no significant differences, $F(3,9) = .60, p > .05$, across displacement conditions. Time to peak force (Table 2) decreased for responses of greater displacement, $F(3,9) = 4.35, p < .05$. The significant changes in durations are not predicted by the impulse-timing model.

Force Amplitudes. The kinetic variable most highly related to changes in movement displacement was force amplitude, as indicated by the average data for the subject displayed in Figure 3b. As displacement increased (Table 2), peak accelerative, $F(3,9) = 113.8, p < .001$, and peak
D. C. Shapiro & C. B. Walters

![Graphs illustrating displacement and force-time curves](image)

**Figure 3.** (a) Average displacement curves, (b) force-time curves, (c) biceps EMG activity, and (d) triceps EMG activity for a single subject in Experiment 2.

Decelerative, $F(3, 9) = 141.66$, $p < .001$, force amplitudes increased. Peak amplitudes of the accelerative- and decelerative-force curves were again found to be highly related, as indicated by the magnitude of the correlation coefficients for all subjects: .99, .99, .98, and .92.5

**EMG**

**Agonist EMG.** Figure 3c displays the average biceps activity of one subject. The greatest peak represents the 50° displacement condition and the shortest peak the 20° condition. The relative constancy of agonist duration was characteristic of all subjects, with means and between-subject standard deviations of 141(53), 139(41), 147(47), and 141(42) ms. There was no significant change in biceps duration, $F(3, 9) = .57$, $p > .05$. Since movement time and biceps duration both remained constant, the ratio between these variables did not differ across displacement conditions, as predicted by the impulse-timing model. The peak biceps magnitudes relative to the maximum amplitudes were .44(.14), .62(.10), .82(.17) and .99(.03) as displacement increased. Peak biceps EMG activity increased with an increase in displacement, $F(3, 9) = 28.59$, $p < .001$.

**Antagonist EMG.** Figure 3d contains the average triceps EMG activity for the same subject presented in the previous figures. The greatest peak represents the 50° condition and the shortest peak the 20° displacement condition. The pattern of findings for the triceps activity essentially paralleled that for the biceps activity. It was again difficult to quantify
Table 2
Kinematic and Kinetic Measures of Experiment 2

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<th>Angular displacement condition</th>
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<tbody>
<tr>
<td></td>
<td>20°</td>
</tr>
<tr>
<td>Movement time (ms)</td>
<td>199.4(9)</td>
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<tr>
<td>Displacement (deg)</td>
<td>20.8(4)</td>
</tr>
<tr>
<td>Accelerative force duration (ms)</td>
<td>141(20)</td>
</tr>
<tr>
<td>Decelerative force duration (ms)</td>
<td>149(29)</td>
</tr>
<tr>
<td>Time to peak force (ms)</td>
<td>78(16)</td>
</tr>
<tr>
<td>Accelerative force amplitude (proportions)</td>
<td>.39(.07)</td>
</tr>
<tr>
<td>Decelerative force amplitude (proportions)</td>
<td>.43(.04)</td>
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</table>

Note. Values are means (±SD).
the durations of the triceps bursts; however, perusal of the averaged triceps bursts suggests that the durations were relatively constant across displacement conditions. As displacement increased, triceps peak amplitude increased: .61(.09), .69(.03), .89(.07), and .97(.06). The amplitude increase was significant, $F(3,9) = 22.59, p < .001$. Thus, in order to move a greater distance in the same amount of time, amplitude modulation is a major modification in the neuromuscular patterning.

**Kinetics and EMG**

As EMG amplitude of the biceps increased, there was a concomitant increase in peak force. The within-subject correlations between average biceps amplitude and peak accelerative force for the four subjects were .98, .90, .99, and .90. A similar relationship was found between triceps amplitude and peak decelerative force (.98, .99, .99, and .81) for the 4 subjects.

**Experiment 3**

Each of the previous experiments included an independent manipulation of either movement time or displacement, resulting also in variations of average velocity. The present experiment covaries movement time and displacement while keeping average velocity constant. Based on our previous findings and the predictions of the impulse-timing model, we should expect linear relationships between EMG burst duration and movement time and between force duration and movement time. This would suggest that movement time and movement displacement may be independently controlled. If these relationships are not present, then this would imply a more complex interaction for the control of movement time and displacement.

**Method**

**Subjects**

Four right-handed male subjects, two of whom participated in the preceding two experiments, were utilized. None was paid for his services.

**Apparatus and Task**

The apparatus was the same as in the previous experiment. The task was again a horizontal elbow flexion from a starting position of $75^\circ$ of flexion. The experimental conditions included four displacement/movement time combinations, each deriving an average velocity of $130^\circ$/s: $20^\circ$/154 ms, $30^\circ$/231 ms, $40^\circ$/308 ms, and $50^\circ$/385 ms.

**Procedure**

All four conditions were performed by each subject in random order, with trials blocked within each condition. Each condition consisted of 50 experimental trials that were preceded by 10 practice trials. Subjects
received movement-time feedback following each trial and were able to observe their final position. Only agonist (biceps) EMG was recorded in this experiment due to the difficulty encountered in quantifying the antagonist in the previous experiments, a problem compounded by the longer movement times and lower average velocities utilized in the present experiment.

Data Analyses

Following the initial data manipulations described earlier, the trials were again selected into subsets determined by specific spatiotemporal criteria. As in Experiment 2, the spatial criterion was within ± 10% of the target displacement, and the movement-time criterion was defined by the goal movement time ± 10 ms. Following initial perusal of the data, it was determined that a qualitative rather than quantitative examination was warranted for some of the data, as the findings of greatest interest focused upon individual differences. Similar trends appearing across subjects, however, were again tested for significance via ANOVAs.

Results

Kinematics

Figure 4a displays the average displacement curves for a single subject when both movement time and displacement varied. Average movement times and amplitudes for all subjects are entered in Table 3. Peak velocities for all subjects ranged from 214 to 318°/s.

Kinetics

Force durations. The average force-time curves for the subject, displayed in Experiments 1 and 2, are located in Figure 4b and the temporal kinetic data for all subjects are entered in Table 3. Significant in-

![Figure 4. (a) Average displacement curves and (b) force-time curves for a single subject in Experiment 3.](image-url)
Table 3
Kinematic and Kinetic Measures of Experiment 3

<table>
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<tr>
<th></th>
<th>Angular displacement/Movement time</th>
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<tr>
<td></td>
<td>20°/154 ms</td>
<td>30°/231 ms</td>
<td>40°/308 ms</td>
<td>50°/385 ms</td>
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<tr>
<td>Movement time (ms)</td>
<td>154.4(6)</td>
<td>230.7(2.8)</td>
<td>304.1(5.2)</td>
<td>382.2(1.5)</td>
</tr>
<tr>
<td>Displacement (deg)</td>
<td>20.8(4)</td>
<td>31.0(6)</td>
<td>40.8(4)</td>
<td>50.3(1)</td>
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<td>Accelerative force duration (ms)</td>
<td>102(8)</td>
<td>144(12)</td>
<td>161(15)</td>
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<tr>
<td>Decelerative force duration (ms)</td>
<td>117(9)</td>
<td>144(12)</td>
<td>180(21)</td>
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<td>Accelerative force amplitude (proportions)</td>
<td>.61(20)</td>
<td>.66(18)</td>
<td>.71(18)</td>
<td>1.0(0)</td>
</tr>
<tr>
<td>Decelerative force amplitude (proportions)</td>
<td>.58(12)</td>
<td>.66(15)</td>
<td>.73(10)</td>
<td>1.0(0)</td>
</tr>
</tbody>
</table>

Note. Values are means (±SD).
Increases in accelerative, $F(3,9) = 10.65, p < .01$, and decelerative, $F(3,9) = 89.26, p < .001$ force durations again accompanied increases in movement time. The proportion of each of these variables to total force duration (accelerative plus decelerative) remained constant across experimental conditions, $F(3,9) = 1.60, p > .05$, for both accelerative and decelerative proportions.

*Force Amplitudes.* Both accelerative and decelerative force amplitudes significantly increased, $F(3,9) = 11.8, p < .01$ and $F(3,9) = 19.46, p < .001$, respectively, as movement time and displacement increased (Table 3). Significant positive correlations between these variables were derived for 3 of the 4 subjects (.69, .95, .97, and .98).

**EMG**

The agonist EMG of the subject displayed previously is located in Figure 5. The highest peak corresponds to the 20°/154-ms condition. Fairly constant agonist durations are evident. Interestingly, this subject dem-
D. C. Shapiro & C. B. Walters

onstrated clear increases in EMG duration in Experiment 1 (Figure 1c), where the range of movement times was about half that used in the present experiment. The relationship between agonist EMG duration and movement time for all subjects is displayed in Figure 6. Proportionality between these variables was again not maintained for any subject across conditions, although burst duration generally increased with movement time.

Figure 6. Relationship between movement time and biceps EMG duration in Experiment 3. (Note: agonist durations for the subject denoted by the triangles could not be reliably determined for the movements with the greatest durations.)
Kinetics and EMG

Linear relationships between agonist EMG amplitude and accelerative-force amplitude were again derived. The correlations were significant for 3 of the 4 subjects: .84, .95, .98, and .99.

DISCUSSION

The present experiments were designed to examine the control of rapid limb movements with various spatiotemporal characteristics. Although such actions have been examined previously, prior experiments have not typically imposed specific movement criteria; rather, subjects have often been allowed to select their own timing, displacement, and/or velocity, or asked to move as fast as possible. Additionally, frequent lack of reporting of both spatial- and temporal-movement outcomes has made the interpretation of many of these studies difficult.

The experiments performed here attempted to systematically examine limb movements under a variety of task constraints, accepting for analysis only those trials achieving specific movement criteria. The impulse-timing model (Schmidt, 1976; 1980; Wallace, 1981) was examined and the overall data trends of the first two experiments appeared to be consistent with its predictions. The results, however, did not support a strict interpretation of this model. A broader range of movement criteria may have violated the predictions of the model to an even greater extent. In addition, the final experiment was not compatible with the impulse-timing predictions.

In the first experiment, subjects were instructed to vary the duration of movements of a constant displacement. Accelerative and decelerative impulse durations were directly related to movement time, with proportionality of each of these variables maintained across conditions. This is consistent with the impulse-timing view proposed by Schmidt, (1976; 1980). A high correlation was also found between accelerative and decelerative amplitudes, suggesting that these force parameters may be controlled concomitantly. Interestingly, a strong relationship was also evident between biceps and triceps amplitudes, further indicating a possibility of unitary scaling. A positive and linear relationship between agonist EMG burst duration and movement time was found. Burst durations were not graded in 70 ms increments as previously reported (Brown & Cooke, 1984).

Agonist EMG was not proportional to movement time, however, which is contrary to the predictions of Wallace (1981) and consistent with previous findings of Wallace and Wright (1982). Although pulse-step (Ghez, 1979) and speed-control (Freund & Büdingen, 1979) models do not specifically address the control of movements performed in varying movement times, these models cannot account for the systematic variation in EMG and kinetic durations found in these studies.

In the second experiment, movement time remained constant while the distances the subjects traversed varied. The impulse-timing model
predicts that temporal variables (e.g., EMG burst duration, time to peak force, etc.) should remain constant when overall movement duration is unchanged, regardless of changes in displacement. This was indeed the case for the duration of the agonist EMG burst and the duration of the decelerative force. Accelerative force duration in the 20° condition was 14% longer than in the 50° condition, however, and time to peak force was 26% longer for the former than the latter. Carlton, Robertson, Carlton, and Newell, (1985) also noted an increase in time to peak acceleration with a decrease in displacement; however, acceleration durations remained relatively constant. High correlations were again noted between peak accelerative and decelerative force and between biceps and triceps amplitude in the second experiment.

These findings support the impulse-timing model based upon the neuromuscular level of analysis (Wallace, 1981). The invariant agonist EMG duration across different displacements is inconsistent with the findings of Brown and Cooke (1984). This discrepancy is perhaps due to a change in movement time along with displacement in their study. The findings of constancy also support predictions of the speed-control and pulse-step models. As noted earlier, previous evidence in support of these views has primarily been derived from studies using movements of fairly constant durations (e.g., Freund & Büdingen, 1978; Ghez & Vicario, 1978; Hallett, Shahani, & Young, 1975). These models may, therefore, account for the control of movements whose duration is selected by the subjects, in which movement time often remains constant. The changing temporal variables associated with the accelerative-force curves are contradictory to the impulse-timing model proposed by Schmidt (1976; 1980). The findings from this experiment generally indicate that EMG amplitude is directly related to displacement when movement duration is held constant.

Experiment 3 included the manipulation of covarying movement time and displacement while maintaining constant average velocity. If the duration and magnitude of impulses are controlled independently (Schmidt et al., 1979), then the findings for temporal variables of force and EMG should parallel those for Experiment 1; that is, scaling of temporal kinetic and EMG measures with movement time should be independent of displacement. The kinetic results were in fact similar to those in Experiment 1, with increases in movement time again accompanied by proportional increases in accelerative and decelerative force durations. The EMG data was much more equivocal, however, as individual differences were apparent among subjects. The most interesting finding was the constancy of burst duration displayed by the subject who had exhibited the clearest scaling of EMG with movement time in Experiment 1 (compare Figures 1c and 5). This was evident despite the fact that the range of movement times in Experiment 3 was nearly double that in Experiment 1 (231 ms vs. 120 ms). The agonist durations of the other subjects generally increased with movement time; however, this increase was again not proportional to movement duration.

The inconsistencies between findings for EMG and force durations in
Rapid Positioning Movements

Experiments 2 and 3 are perhaps due to a large amount of overlap between agonist and antagonist muscles. A previous investigation using the same task (Shapiro, in press) and a cursory observation of antagonist activity in the present study both indicate a high degree of cocontraction for this task. Were contractions of the muscles sequential, the forces generated would be expected to be approximately equal in duration to the burst durations, with an appropriate temporal lag due to the electromechanical delay. The presence of cocontraction, however, dictates that the resultant force exerted be a function of the difference in magnitude of the opposing muscle forces. This implies that cocontraction of agonist and antagonist muscles must be incorporated in future motor control models applied to the production of rapid actions.

Interestingly, in all experiments there was a strong relationship between peak force and amplitude of EMG activity. Biceps amplitude varied with accelerative force amplitude and triceps amplitude varied with decelerative force amplitude. These positioning movements display this relationship despite the high degree of cocontraction between agonist and antagonist muscles.

In summary, when either time or space is manipulated separately (Experiments 1 and 2), the impulse-timing model is partially supported. However, this model in itself is not sufficient to account for the data. When concomitant variations of both dimensions occur (Experiment 3), an interaction is observed and individual differences emerge. This appears to be particularly damaging to recent motor-control models that suggest temporal and magnitude dimensions of the impulses propelling limb movements are modulated independently by the nervous system (Freund & Büdingen, 1978; Ghez, 1979; Schmidt, 1976; Wallace, 1981).

The inconsistent findings for temporal measures of force and EMG activity indicate potential difficulties in the search for invariant relationships between these levels of analysis, a problem noted long ago by Bernstein (1935/1967). Moreover, individual muscles may not be the appropriate level of analysis for determining programmed variables (Duyssens, 1982). Muscle collectives, or “coordinative structures” (Kugler, Kelso, & Turvey, 1980), may prove to be a more useful level for examining this issue. Individual differences observed at both kinematic and neuromuscular levels further complicate the development of parsimonious models of motor control. An increased emphasis upon within-subject designs might therefore be effective in studying these issues.

NOTES

1. The purpose of this study was to examine variations in force and EMG occurring with systematic changes in movement time. Therefore, specific spatiotemporal criteria were utilized. We selected a strict temporal criteria of ±5 ms to insure the examination of similar movements within each bandwidth with no movement time overlaps between adjacent bandwidths.

2. The same subject's data were presented in all of the figures in Experiments 1, 2, and 3 for comparison purposes. The data from this subject were selected because it most clearly demonstrated the findings. The figures are tracings of the computerized data plots and averaged for display purposes only.
D. C. Shapiro & C. B. Walters

3. The sum of accelerative and decelerative force durations do not equal movement time since oscillations were present at the termination of the movement. Therefore, total force duration was greater than movement time.

4. A $r > .81$ is required for significance at the .05 level.

5. A $r > .95$ is required for significance at the .05 level.

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