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Sequential Processes for Controlling Distance in Multijoint Movements

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Abstract

The purpose of this study was to examine the mechanisms underlying control of distance during multijoint movements in different directions. The findings revealed 2 sequential muscle torque impulses, which correlated with 2 events in the hand acceleration profile. These 2 events occurred prior to peak velocity, characterizing control in the initial acceleration phase of motion. The contribution of shoulder and elbow joint torque to each event varied with movement direction. However, regardless of direction, these 2 torque events appeared to be functionally distinguishable: a preplanned initiation event was responsible for the initial hand acceleration, whereas a 2nd modulation event adjusted acceleration in compensation for variations in acceleration. Thus, the findings support the idea that control of distance during multijoint movement occurs through sequential control mechanisms.

Keywords

distance; inverse dynamics; kinematics; reaching

Previous researchers on the control of goal-directed limb movements have differentiated between open- and closed-loop processing, starting as long ago as Woodworth's (1899) description of *initial-adjustment* and *current-control*. Many studies have elaborated on the nature of the two components of Woodworth's model by decomposing the movement into its acceleration and deceleration phases (Carlton, 1981; Carson, Chua, Elliott, & Goodman, 1990; Elliott et al., 1999; Mieschke, Elliott, Helsen, Carson, & Coull, 2001; Roy, Kalbfleisch, & Elliott, 1994; Soechting, 1984). The basic rationale for these studies was that the acceleration phase is associated with open-loop processing, which functions to initiate limb motion toward the target, whereas the deceleration phase is more dependent on sensory-based, closed-loop processing and acts to move in on the target. However, more recent research has shown that somatosensory feedback can influence movement trajectories prior to reaching peak velocity (Bagesteiro & Sainburg, 2003; Evarts & Tanji, 1974; Lacquaniti, Borghese, & Carrozzo, 1991; Marsden, Merton, & Morton, 1973; Matthews, 1991; Yamamoto & Ohtsuki, 1989). Thus, the acceleration phase itself may comprise complex processes that incorporate both feedforward and feedback elements of control.

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The mechanisms underlying the initial phase of single-joint movements have previously been characterized as sequential control processes and have been elaborated for both isometric and movement tasks (Brown & Cooke, 1981a, 1984; Ghez & Vicario, 1978; Gordon & Ghez, 1987a, 1987b; Mustard & Lee, 1987). Previous studies have shown that the amplitude and duration of the initial force pulse, agonist electromyographic (EMG) burst, or acceleration pulse can be independently varied to produce different motor responses. The amplitude of such measures has been shown to scale with task variables, such as target force or distance (Brown & Cooke, 1981a; Ghez, 1979; Gordon & Ghez, 1987a), and is resistant to peripheral sensory influences (Brown & Cooke, 1981b), reflecting the contribution of preplanning mechanisms. Moreover, numerous studies have shown that variations in the duration of acceleration, torque, or force are inversely related to the initial amplitude of these variables and thus appear to compensate for inaccuracies in planning (Bermejo & Zeigler, 1989; Brown & Cooke, 1981b; Gordon & Ghez, 1987a, 1987b). It should be stressed that scaling of both amplitude and duration occurs within the initial acceleration phase, prior to reaching peak tangential velocity.

However, similar processes have not been established for controlling the distance of multijoint movements. In fact, it is plausible that such mechanisms would not be apparent in multijoint movements, when the relationship between hand kinematics and joint kinetics is nonlinear and complex (Hollerbach & Flash, 1982; Sainburg, Ghez, & Kalakanis, 1999; Smith & Zernicke, 1987). Thus, control strategies observed during single-joint movements may not be relevant to multijoint coordination. The purpose of this study was to examine how movement distance is controlled during multijoint targeted reaching movements.

Method

Participants

Participants were 6 neurologically intact right-handed adults (1 man, 5 women) aged from 21 to 25 years who performed point-to-point reaching movements. Only right-handers were recruited. We determined handedness using a 12-item version of the Edinburgh inventory (Oldfield, 1971). The participants gave informed consent prior to participation.

Experimental Setup

Figure 1A shows the general experimental setup. Participants sat facing a computer screen with their right arm supported over a horizontal tabletop, positioned just below shoulder height (adjusted to participants' comfort), by a frictionless air-jet system. A start circle, target, and cursor representing finger position were projected on a horizontal back-projection screen positioned above the arm. A mirror, positioned parallel and below this screen, reflected the visual display, giving the illusion that the display was in the same horizontal plane as the fingertip. The display was calibrated to ensure that this projection was veridical. This virtual reality environment prevented participants from having vision of their arm during the experiment. All joints distal to the elbow were immobilized using an adjustable brace. In addition, movements of the trunk and scapula were restricted using a butterfly-shaped chest restraint. Position and orientation of each limb segment were sampled using the Flock of Birds (Ascension Technology, Burlington, VT) magnetic 6-DOF movement-recording system. A 6-DOF sensor was attached to the upper arm segment by an adjustable plastic cuff, and another sensor was fixed to the air-jet sled where the forearm was fitted. The sensors were positioned approximately at the center of each arm segment. The three-dimensional (3D) positions of the following three bony landmarks were digitized using a stylus that was rigidly attached to a Flock of Birds sensor: (a) index fingertip; (b) lateral epicondyle of the humerus; and (c) the acromion, directly posterior to the acromioclavicular joint. This position was updated at 103 Hz, as data were received by the computer's serial port. Screen redrawing occurred quickly enough to maintain the cursor on the fingertip throughout the sampled arm movements. Digital

data were collected at 103 Hz using an Apple computer, which controlled the sensors through separate serial ports, and stored on disk for further analysis. The data were digitally resampled at 100 Hz for analysis. Custom computer algorithms for experimental control and data analysis were written in REAL BASIC (REAL Software, Inc., 2004), C, and Igor Pro (Wavemetrics, Inc., 2004).

Kinematic Data

The 3D positions of the index finger, elbow, and shoulder were calculated from sensor position and orientation data. Elbow and shoulder angles were then calculated from these data. All kinematic data were low-pass filtered at 12 Hz (3rd order, dual-pass Butterworth) and differentiated to yield angular velocity and acceleration values. Usually, each trial started with the hand at zero velocity, but small oscillations of the hand sometimes occurred within the start circle. Thus, the *onset of movement* was defined by the last minimum (below 6% maximum tangential velocity) prior to the maximum in the index finger's tangential velocity profile. *Movement termination* was defined as the first minimum (below 6% maximum tangential velocity) following the peak in tangential velocity.

Kinetic Data

The arm was modeled as a two-segment, inverted pendulum, with the proximal end (shoulder point) free to move in the horizontal plane. Using inverse dynamic analysis, we calculated values for muscle torque and interaction torque for each joint (elbow and shoulder). The sum of muscle and interaction torques (i.e., net torque) is directly proportional to joint acceleration and is inversely proportional to limb inertia (Sainburg et al., 1999). Computationally, the joint muscle torque represents the rotational effect of muscle forces acting on the segment, but it is important to note that this calculation cannot directly serve as a substitute for the neural activity within the muscles acting at that joint. However, even if neural input is constant, different force output may occur, depending on muscle length, rate of length change, and recent activation history (Zajac, 1989). Muscle joint torques may reflect, but cannot distinguish between, individual muscle forces that may counter each other during cocontraction. Muscle joint torques may include passive components of movement, such as the effect of soft tissue deformation. Nevertheless, we used joint muscle torque as a measure of net output of the neuromuscular system (Wadman, Denier van der Gon, & Derksen, 1980).

The following equations detail how we computed the three torque components and analyzed them for the elbow and shoulder joints. The inertia and mass of the forearm support are 0.0247 kgm² and 0.58 kg, respectively. Limb segment inertia, center of mass, and mass were computed from regression equations using participants' body mass and measured limb segment lengths (Winter, 1990).

For elbow joint torques,

$$\begin{aligned} T_{e_M} &= T_{e_N} - T_{e_I} \\ T_{e_N} &= (I_e + m_e r_e^2) \ddot{\theta}_e \\ T_{e_I} &= m_e r_e \sin(\theta_e + \theta_s) \ddot{x} - m_e r_e \cos(\theta_e + \theta_s) \ddot{y} - l_s m_e r_e \sin(\theta_e) \dot{\theta}_s^2 - (I_e + m_e r_e [r_e + l_s \cos(\theta_e)]) \ddot{\theta}_s \end{aligned}$$

For shoulder joint torques,

$$\begin{aligned}
T_{s_M} &= T_{s_N} - T_{s_I} + T_{e_M} \\
T_{s_N} &= (I_s + m_s r_s^2 + m_e l_s^2 + m_e l_s r_e \cos(\theta_e)) \ddot{\theta}_s \\
T_{s_I} &= (m_s r_s \sin(\theta_s) + m_e l_s \sin(\theta_s)) \ddot{x} - (m_s r_s \cos(\theta_s) + m_e l_s \cos(\theta_s)) \ddot{y} \\
&\quad - \left(m_e r_e \left[l_e \cos(\theta_e) \ddot{\theta}_e + l_s \sin(\theta_e) \dot{\theta}_e^2 + 2 l_s \sin(\theta_e) \dot{\theta}_s \dot{\theta}_e + l_s \sin(\theta_e) \dot{\theta}_s^2 \right] \right)
\end{aligned}$$

where m is segment mass, r is distance from proximal joint to center of mass, l is segment length, I is segment inertia, θ_s is shoulder angle, θ_e is elbow angle (see Figure 1B), x is shoulder position along x direction, y is shoulder position along y direction, T_{e_I} is elbow interaction torque, T_{e_M} is elbow muscle torque, T_{e_N} is elbow net torque, T_{s_I} is shoulder interaction torque, T_{s_M} is shoulder muscle torque, and T_{s_N} is shoulder net torque. Subscript e denotes lower arm segment, and s denotes upper arm segment. Derivations of joint torques have been described previously (Bagesteiro & Sainburg, 2002).

Experimental Task

All participants participated in two blocked experimental sessions of different movement directions: anterior and lateral. We selected these directions to systematically vary interjoint coordination requirements. In the anterior direction, shoulder and elbow joint torques act in opposite directions, requiring shoulder flexion and elbow extension. However, in the lateral direction, both shoulder and elbow extension was required. Hollerbach and Flash (1982) previously characterized such direction-dependent torque patterns.

Prior to all trials, we displayed the index finger position in real time as a screen cursor. The start location was 25 cm in front of the participants, directly along their midline. Participants were instructed to reach from the constant start position to one of four randomized targets along their mid-line. In the anterior direction, the target locations were 10 cm, 15 cm, 20 cm, and 25 cm away from the start location (see Figure 1B). In the lateral direction, the target locations were 10 cm, 15 cm, 20 cm, and 30 cm away from the start location. To best match the range of joint angles for torque comparison between sessions, the furthest target (Target 4) in the lateral direction was 30 cm from the start location, rather than 25 cm. The start circle, which remained constant throughout both sessions, was displayed as 2 cm in diameter, while all targets were displayed as 2.5 cm in diameter. Participants were to hold the cursor within the start circle for 200 milliseconds to trigger the audiovisual Go signal, which initiated each trial. They were instructed to “quickly yet accurately” move their finger (cursor) to “the center of the target and stop, using a single, uncorrected motion.” Feedback regarding the fingertip position (cursor display) was given to allow participants to position the hand in the start circle and then was removed at the Go signal. Although there were no explicit speed requirements, the maximum duration for each trial (1 s) was sufficient for recording the initiation and termination of each movement. Participants did not receive specific feedback about final position; instead, they were awarded points based on the distance between their final finger position and the center of the target. Final position errors of less than 1.25 cm were awarded 10 points, errors between 1.25 cm and 2.5 cm were awarded 3 points, and errors between 2.5 cm and 3.75 cm were awarded 1 point. The purpose of awarding points to each trial was merely to motivate our participants; we did not analyze points as dependent variables. Targets were presented in a pseudorandom order so that no single target was presented consecutively. The first 50 trials of each session were used for task familiarity, whereas analysis was conducted on the following 100 trials.

Data and Statistical Analyses

Measures of task performance were movement duration, constant final position error, peak tangential velocity and acceleration, peak elbow and shoulder muscle torque, and elbow and shoulder muscle torque impulse. We defined *peak joint torque* as the absolute maximum in the respective profiles from movement start to the time of peak tangential velocity, whereas we defined *torque impulse* as the signed area under the respective torque pulse. The profiles of tangential acceleration and joint muscle torque were typically bimodal; thus, we analyzed the first and second components separately, by calculating the signed area under the profile for each component. The *initial component* was defined as the signed area from movement start to the local minimum, and the *second component* was defined as the signed area from the local minimum to the time of peak velocity (see Figure 2). Trapezoidal integration over time was used to compute area.

We analyzed means of the individual dependent measures of task performance using a two-way mixed (split-plot) design, with direction (anterior or lateral) and target (1, 2, 3, or 4) as fixed effects within participant. Based on our design, we expected a main effect for target, $p < .05$. Post-hoc analyses were conducted using Tukey HSD and t tests within each direction, when warranted and relevant by a significant interaction effect. We also conducted simple linear regression analysis for select sets of data using JMP statistical software (SAS Institute, Inc., 2003). Comparison of correlation coefficients was accomplished by converting individual r values to z scores (normalized r) using Fisher transformation.

Results

Task Performance

Figure 3A shows typical hand paths for each target distance in each direction. Movements were generally well adapted to the amplitude of the target, with relatively straight trajectories and a tendency to overshoot the target. Regardless of target direction, movement distance and duration scaled with target— $F(3, 5) = 903.6, p < .0001$; $F(3, 5) = 16.9, p < .0001$; respectively—as shown in Figure 3B (top, middle). Although movement amplitude varied systematically with target amplitude, there was no significant interaction between direction and target for constant final position error, $F(3, 5) = 1.24, p = .31$, which remained approximately 2–3 cm for all movements (see Figure 3B, bottom). Thus, participants had similar spatial performances across target directions.

Tangential Kinematics

Figure 4 shows the average tangential kinematics for a representative participant. In both directions, peak velocity scaled with target distance (see Figure 4, top), which was achieved by varying both the amplitude and duration of acceleration (see Figure 4, bottom). The scaling of these variables with target distance was systematic across participants, as shown in Figure 5A. There was a significant interaction between direction and target for peak velocity, $F(3, 5) = 6.32; p < .01$, because of larger velocities in the lateral direction, $F(1, 5) = 29.17, p < .0001$. Nevertheless, peak velocity was a strong predictor of movement distance (see Figure 5B).

Peak accelerations were comparable in both directions, as indicated by no main direction effect, $F(1, 5) = 0.10, p = .76$, and no interaction effect, $F(3, 5) = 0.50, p = .68$. Acceleration durations, though, were significantly longer in the lateral direction, $F(1, 5) = 4.22, p < .05$, resulting in the larger peak velocities observed in this direction. Although we have previously shown that both the amplitude and duration of acceleration can predict distance in single-joint movements (Sainburg & Schaefer, 2004), neither of these measures correlated well with distance during multijoint movements (see Figure 5B, middle graphs). These weak correlations suggest that

the scaling of tangential velocity with distance is achieved through changes in both amplitude and duration of tangential acceleration.

We also quantified the amplitude of deceleration across targets for further kinematic analysis. Peak deceleration was significantly larger in the lateral direction, $F(1, 5) = 63.2, p < .0001$, showing a greater increase across targets than in the anterior direction, $F(3, 5) = 14.33, p < .0001$ (Figure 5A). Because the limb slows down after peak speed to approach final position, it is not surprising that peak deceleration was well correlated with peak velocity (see Figure 5B, bottom graph). In other words, the amplitude of deceleration was a function of peak velocity, which is determined by both the amplitude and the duration of acceleration.

Sequential Pulses of Tangential Acceleration

As depicted in Figure 4 (bottom), the acceleration profiles for all targets had two distinct pulses prior to the time of peak velocity (acceleration cross-zero). This phenomenon does not typically occur in single-joint movements, where the acceleration phase tends to be unimodal (Ghez, 1979). For the present study, we quantified the integral of the initial and second pulses of these two-pulse acceleration profiles.

Figure 6A shows the integrated pulses of acceleration for both directions, averaged across participants. The total area of the initial pulse (solid line) increased significantly by target in both directions, $F(3, 5) = 14.21, p < .0001$, as did the area of the second pulse (dotted line), $F(3, 5) = 125.75, p < .0001$. In the anterior direction, the area of the initial pulse was always significantly greater than that of the second pulse (all targets, $p < .01$), whereas in the lateral direction, the amplitude of initial and second pulses was dependent on target distance.

However, more interesting is the relationship between the initial and second pulses within each trial. As shown in Figure 6B, the area of the second pulse was negatively correlated with the area of the initial pulse. The strength of this negative correlation did not vary significantly by direction, $F(1, 5) = 2.19, p = .15$, or by target, $F(3, 5) = 0.45, p = .71$. This effect has previously been demonstrated in single-joint isometric force production and has been thought to reflect compensation for inaccuracies in initial planning mechanisms (Gordon & Ghez, 1987b). In the present study, the inverse relationship between the two pulses suggests that the second acceleration pulse might act to fine-tune the effects of the initial acceleration moment. Because the timing of the first peak in acceleration did not vary significantly by target in either direction, $F(3, 5) = 2.70, p = .07$, and occurred early in the movement (anterior $M \pm SD = 77 \pm 15$ ms; lateral $M \pm SD = 58 \pm 13$ ms), these findings suggest that the amplitude of the initial pulse was scaled to target distance by anticipatory mechanisms. Thus, the two acceleration pulses prior to peak velocity appear to be distinct in their functions: The first initiation pulse accelerates the hand, whereas a second modulation pulse might adjust such accelerations to scale tangential velocity with intended movement distance, regardless of direction.

Sequential Pulses of Elbow and Shoulder Muscle Torque

The presence of initiation and modulation pulses in the tangential acceleration profile suggests that two distinct neural events occur during the acceleration phase of the movement. However, the relationship between tangential kinematics and joint kinetics is nonlinear and complex during multijoint movements (Hollerbach & Flash, 1982; Sainburg et al., 1999; Smith & Zernicke, 1987). Therefore, we next analyzed the elbow and shoulder joint torques during the initial acceleration phase of motion to determine the relationship between the acceleration pulses and joint torque. Much as in our analysis of the hand acceleration profile, we quantified initial and second impulses of muscle torque for the elbow and shoulder by integrating joint muscle torque with respect to the timing of the acceleration pulses (see Figure 2).

The tangential velocity and acceleration profiles for the acceleration phase of a typical movement in each direction are shown in the insets of Figure 7. Below the kinematic profiles are the corresponding elbow muscle torque and shoulder muscle torque profiles during the acceleration phase, with negative values indicating extension. Both elbow and shoulder muscle torque profiles tended to show two peaks, regardless of direction. The presence of two distinct pulses of muscle torque prior to peak velocity was consistent across participants (see Figure 8). Regardless of direction, the amplitude of both initial elbow, $F(3, 5) = 9.99, p < .0001$, and shoulder, $F(3, 5) = 13.62; p < .0001$, muscle torque impulses scaled with target distance. It is not surprising that the direction of the torque pulses depended on the direction of the movement, such that anterior movements were initiated with extensor muscle torque at the elbow and flexor torque at the elbow, whereas lateral movements were initiated with extensor muscle torque at both joints. The second impulse of elbow muscle torque approximated zero in the later portion of the acceleration phase during anterior movements (see Figure 8), indicating that subsequent hand acceleration in this direction was produced by shoulder torque. However, in the lateral direction, both joints show substantial muscle torque later in the acceleration phase.

Although we observed two distinct peaks, or pulses, in both elbow and shoulder muscle torque profiles, the timing of maximum elbow and shoulder muscle torque was also dependent on movement direction. In the anterior direction, larger elbow muscle torque was produced early during the first pulse, whereas shoulder muscle torque was largest later in the acceleration phase, during the second pulse. However, in the lateral direction, larger shoulder muscle torque was produced early, whereas elbow muscle torque was largest later in the acceleration phase. Although Figure 7 shows muscle torque profiles for one target, the timing of maximum torque production did not vary significantly across targets in either direction: elbow $F(3, 5) = 1.04, p = .39$; shoulder $F(3, 5) = 0.73, p = .54$. Thus, we collapsed across targets in Figure 9 to show that maximum elbow muscle torque (108 ± 47 ms) occurred significantly earlier than did shoulder muscle torque (169 ± 48 ms) in the anterior direction ($p < .0001$), and maximum shoulder muscle torque (73 ± 11 ms) occurred earlier than did elbow muscle torque (119 ± 34 ms) in the lateral direction ($p < .0001$) consistently across all participants. Thus, in the present study, distinct torque events were distributed differently across the joints, depending on movement direction.

Correlations Between Hand Acceleration and Joint Torque

Despite the nonlinear relationship between tangential kinematics and muscle activation during multi-joint movement, Figure 10 shows significant linear correlations between pulses of tangential acceleration and joint muscle torque. The initial acceleration pulse was strongly correlated with the initial muscle torque impulses of both elbow and shoulder in both directions (see Figure 10A). In contrast, for anterior movements, the second acceleration pulse correlated only with a second pulse of shoulder muscle torque, because elbow muscle torque was minimal later in the acceleration phase. However, for lateral movements, the second acceleration pulse was correlated with muscle torque impulses at both joints (see Figure 10B). The relative contributions of elbow and shoulder muscle torque to the initiation and modulation of acceleration varied substantially across movement directions. However, the tendency toward two distinct hand acceleration peaks was consistent across our task conditions.

Discussion

Previous studies of single-joint movements have shown that the amplitude and duration of agonist EMG, joint torque, and hand acceleration appear to be independently modulated during the initial acceleration phase of motion. Scaling of amplitude has been shown to be largely determined through preplanned mechanisms (Bouisset & Lestienne, 1974; Brown & Cooke,

1981a; Ghez, 1979; Ghez & Vicario, 1978; Gordon & Ghez, 1987a). In contrast, researchers have demonstrated that variations in torque duration may compensate for inaccurate specification of torque amplitude (Bermejo & Zeigler, 1989; Gordon & Ghez, 1987b). The purpose of the present study was to examine whether similar sequential control processes may contribute to the acceleration of multijoint movements. The temporal and amplitude-based characteristics of two distinct muscle torque events suggest that they serve as an initiation pulse and a subsequent modulation pulse, which together assure effective scaling of peak tangential velocity with intended movement distance. Although the distribution of these two events across the joints differs depending on the direction of the movement, the sequential nature of this control appears to be preserved across directions.

Evidence for Initial and Corrective Responses in Single-Joint Tasks

Our findings are consistent with previous single-joint studies that have concerned a two-component control process within the acceleration phase of motion. Gordon and Ghez (1987a) found that during targeted isometric force pulses, participants varied height of their force pulses with target force. They did so by varying the slope of the produced force pulses. Thus, even at the onset of force production, the participants scaled their responses through preprogrammed mechanisms. However, when participants incorrectly scaled the initial phase of their response, they did not abruptly change the amplitude of their response (Gordon & Ghez, 1987b). Rather, participants modified the duration of their response, such that initial overshoot was followed by a decrease in time to peak force, whereas initial undershoot was followed by an increase in time to peak force, to maintain the appropriate time-integrated response for the given target. In our study, we found a similar relationship between the integrated initial and second pulses of acceleration. Within a given target, the area of the second pulse was negatively correlated with that of the initial pulse, suggesting that the neural activity that produced the second pulse was, in part, fine-tuning the initial neural output that produced the first pulse. Although such adjustments have previously been attributed to corrective, feedback-mediated mechanisms, we cannot determine whether such compensations in the present study were generated on the basis of (a) sensory information about peripheral events or (b) efference copy information generated internally (Brown & Cooke, 1981b; Desmurget & Grafton, 2000).

Numerous single-joint studies have also shown that there is a relationship between the amplitude and timing of force, or acceleration, and EMG activity, namely in initial agonist (AG1) and antagonist (ANT) activity. During isometric force production (Gordon & Ghez, 1987a, 1987b), the amplitude of AG1 corresponds to the amplitude of the initial force pulse. Likewise, during rapid elbow movements (Brown & Cooke, 1981a, 1984; Mustard & Lee, 1987), the amplitude of AG1 corresponds to the height, or the amplitude, of the acceleration pulse. In both types of tasks, the duration of the force or acceleration pulse corresponds to the duration of AG1 and the onset of ANT (Brown & Cooke, 1981b; Vicario & Ghez, 1984). Such findings have supported the idea that AG1 amplitude is determined through feedforward mechanisms, whereas the timing of AG1 and ANT likely depend on closed-loop processes. These neural components have been shown to be functionally distinct, such that initial amplitude of AG1 determines the rate of acceleration increase, whereas the duration of AG1 and onset of ANT determine the rate of acceleration decrease as it approaches peak velocity (Cooke & Brown, 1990). The present findings extend these sequential processes to multijoint movements. We identified two phases of the tangential (hand) acceleration profile that correlate with discrete joint torque events. An initial torque impulse appears to specify initial movement parameters, whereas a second impulse appears to compensate for variations in acceleration in response to the first event.

Almeida, Hong, Corcos, and Gottlieb (1995) suggested that the organization of control processes is similar during unconstrained, multijoint movements and constrained, single-joint movements, although it is likely that the neural strategies themselves are adapted to the dynamic environment (Graham et al., 2003; Scheidt & Rymer, 2000). Scheidt and Rymer compared the kinematic and dynamic performances of single- and multijoint movements in the same target configuration. They found that the shoulder EMG activity that previously acted to fix the shoulder in place was progressively reduced through practice as participants learned to rely on the external stabilization. Thus, participants adjusted their strategy as they adapted to the mechanical conditions of the experimental environment. In other words, what was encoded in the neural strategy differed between the multijoint and single-joint conditions. It is not surprising that strategic adjustments in muscle activity occur when task conditions change between multi- and single-joint movements. However, the present findings emphasize that the organization of sequential mechanisms controlling movement distance may be similar between multijoint and single-joint movements, although the expression of control might vary across the various joints that are involved in the movement.

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REFERENCES

- Almeida GL, Hong DA, Corcos D, Gottlieb GL. Organizing principles for voluntary movement: Extending single-joint rules. *Journal of Neurophysiology* 1995;74:1374–1381. [PubMed: 8989378]
- Bagesteiro LB, Sainburg RL. Handedness: Dominant arm advantages in control of limb dynamics. *Journal of Neurophysiology* 2002;88:2408–2421. [PubMed: 12424282]
- Bagesteiro LB, Sainburg RL. Nondominant arm advantages in load compensation during rapid elbow joint movements. *Journal of Neurophysiology* 2003;90:1503–1513. [PubMed: 12736237]
- Bermejo R, Zeigler HP. Prehension in the pigeon: II. Kinematic analysis. *Experimental Brain Research* 1989;75:577–585.
- Bouisset S, Lestienne F. The organisation of a simple voluntary movement as analysed from its kinematic properties. *Brain Research* 1974;71:451–457. [PubMed: 4468071]
- Brown SH, Cooke JD. Amplitude- and instruction-dependent modulation of movement-related electromyogram activity in humans. *Journal of Physiology* 1981a;316:97–107. [PubMed: 7320884]
- Brown SH, Cooke JD. Responses to force perturbations preceding voluntary human arm movements. *Brain Research* 1981b;220:350–355. [PubMed: 7284760]
- Brown SH, Cooke JD. Initial agonist burst duration depends on movement amplitude. *Experimental Brain Research* 1984;55:523–527.
- Carlton LG. Processing visual feedback information for movement control. *Journal of Experimental Psychology: Human Perception and Performance* 1981;7:1019–1030. [PubMed: 6457106]
- Carson RG, Chua R, Elliott D, Goodman D. The contribution of vision to asymmetries in manual aiming. *Neuropsychologia* 1990;28:1215–1220. [PubMed: 2290495]

- Cooke JD, Brown SH. Movement-related phasic muscle activation: II. Generation and functional role of the triphasic pattern. *Journal of Neurophysiology* 1990;63:465–472. [PubMed: 2329356]
- Desmurget M, Grafton S. Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences* 2000;4:423–431. [PubMed: 11058820]
- Elliott D, Heath M, Binsted G, Ricker KL, Roy EA, Chua R. Goal-directed aiming: Correcting a force-specification error with the right and left hands. *Journal of Motor Behavior* 1999;31:309–324. [PubMed: 11177640]
- Evarts EV, Tanji J. Gating of motor cortex reflexes by prior instruction. *Brain Research* 1974;71:479–494. [PubMed: 4219749]
- Ghez C. Contributions of central programs to rapid limb movement in the cat. In: Asanuma, H.; Wilson, VJ., editors. *Integration in the nervous system*. Igaku-Shoin; Tokyo: 1979. p. 305–319.
- Ghez C, Vicario D. The control of rapid limb movement in the cat: II. Scaling of isometric force adjustments. *Experimental Brain Research* 1978;33:191–202.
- Gordon J, Ghez C. Trajectory control in targeted force impulses: II. Pulse height control. *Experimental Brain Research* 1987a;67:241–252.
- Gordon J, Ghez C. Trajectory control in targeted force impulses: III. Compensatory adjustments for initial errors. *Experimental Brain Research* 1987b;67:253–269.
- Graham KM, Moore KD, Cabel DW, Gribble PL, Cisek P, Scott SH. Kinematics and kinetics of multijoint reaching in nonhuman primates. *Journal of Neurophysiology* 2003;89:2667–2677. [PubMed: 12612006]
- Hollerbach MJ, Flash T. Dynamic interactions between limb segments during planar arm movement. *Biological Cybernetics* 1982;44(1):67–77. [PubMed: 7093370]
- Lacquaniti F, Borghese NA, Carrozzo M. Transient reversal of the stretch reflex in human arm muscles. *Journal of Neurophysiology* 1991;66:939–954. [PubMed: 1753296]
- Marsden CD, Merton PA, Morton HB. Latency measurements compatible with a cortical pathway for the stretch reflex in man. *Journal of Physiology* 1973;230(1):58P–59P.
- Matthews PB. The human stretch reflex and the motor cortex. *Trends in Neuroscience* 1991;14(3):87–91.
- Mieschke PE, Elliott D, Helsen WF, Carson RG, Coull JA. Manual asymmetries in the preparation and control of goal-directed movements. *Brain and Cognition* 2001;45(1):129–140. [PubMed: 11161367]
- Mustard BE, Lee RG. Relationship between EMG patterns and kinematic properties for flexion movements at the human wrist. *Experimental Brain Research* 1987;66:247–256.
- Oldfield RC. The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia* 1971;9(1):97–113. [PubMed: 5146491]
- REAL Software, Inc.. REAL Basic. Vol. (Version 5) [Computer software]. REAL Software, Inc.; Austin, TX: 2004.
- Roy EA, Kalbfleisch L, Elliott D. Kinematic analyses of manual asymmetries in visual aiming movements. *Brain and Cognition* 1994;24:289–295. [PubMed: 8185899]
- Sainburg RL, Ghez C, Kalakanis D. Intersegmental dynamics are controlled by sequential anticipatory, error correction, and postural mechanisms. *Journal of Neurophysiology* 1999;81:1045–1056. [PubMed: 10085332]
- Sainburg RL, Schaefer SY. Interlimb differences in control of movement extent. *Journal of Neurophysiology* 2004;92:1374–1383. [PubMed: 15115793]
- SAS Institute, Inc.. JMP. Vol. (Version 5.1) [Computer software]. SAS Institute, Inc.; Cary, NC: 2003.
- Scheidt R, Rymer WZ. Control strategies for the transition from multijoint to single-joint arm movements studied using a simple mechanical constraint. *Journal of Neurophysiology* 2000;83:1–12. [PubMed: 10634848]
- Smith JL, Zernicke RF. Predictions for neural control based on limb dynamics. *Trends in Neuroscience* 1987;10:123–128.
- Soechting JF. Effect of target size on spatial and temporal characteristics of a pointing movement in man. *Experimental Brain Research* 1984;54(1):121–132.
- Vicario DS, Ghez C. The control of rapid limb movement in the cat: IV. Updating of ongoing isometric responses. *Experimental Brain Research* 1984;55(1):134–144.

- Wadman WJ, Denier van der Gon JJ, Derksen RJA. Muscle activation patterns for fast goal-directed arm movements. *Journal of Human Movement Studies* 1980;6:19–37.
- WaveMetrics, Inc.. Igor Pro. Vol. (Version 5) [Computer software]. WaveMetrics, Inc.; Lake Oswego, OR: 2004.
- Winter, DA. Biomechanics and motor control of human movement. Wiley; New York: 1990.
- Woodworth RS. The accuracy of voluntary movement. *Psychological Review* 1899;3(Suppl 2):1–119.
- Yamamoto C, Ohtsuki T. Modulation of stretch reflex by anticipation of the stimulus through visual information. *Experimental Brain Research* 1989;77(1):12–22.
- Zajac FE. Muscle and tendon: Properties, models, scaling, and application to biomechanics and motor control. *Critical Reviews in Biomedical Engineering* 1989;17:359–411. [PubMed: 2676342]

FIGURE 1.

Schematic representations of (A) the experimental setup and (B) the task. θ_e denotes elbow angle; θ_s denotes shoulder angle.

FIGURE 2.

Example of a two-peaked tangential acceleration profile, where t_1 is the time of movement start, t_2 is the time of the local minimum, and t_3 is the time of peak velocity. Black shaded region indicates computed initial area; lined region indicates computed second area.

FIGURE 3.

(A) Average hand paths for each target in the anterior and lateral directions for a representative subject. The gray circle indicates target location, although target size is not drawn to scale.

(B) Mean and standard error of movement distance, duration, and constant final position error for each target in the anterior and lateral directions across participants.

FIGURE 4.

Average tangential velocity and acceleration profiles for each target in the anterior and lateral directions for a representative participant.

FIGURE 5.

(A) Mean and standard error of peak velocity, peak acceleration, acceleration duration, and peak deceleration for each target in the anterior and lateral directions across participants. (B) Movement distance and peak deceleration as a function of peak velocity, peak acceleration, and acceleration duration for representative participants using linear regression analysis. Each point represents a single trial, and points are grouped by direction: anterior (solid circle) and lateral (open circle). Corresponding r^2 values are within each scatter plot.

FIGURE 6.

(A) Mean and standard error of area of the initial (solid line) and second (dotted line) acceleration pulse for each target in the anterior and lateral directions. Schematic representation of each pulse is displayed on the y-axis. (B) Second acceleration pulse as a function of initial acceleration pulse within each target in the anterior and lateral directions for a representative participant. Target symbols and corresponding within-target r values are in the top right corner of the scatter plot.

FIGURE 7.

Elbow and shoulder muscle during the acceleration phase of a single movement to an intermediate target distance (target 2) in the anterior and lateral directions. Positive values indicate flexion direction; negative values indicate extension direction. Inset: Corresponding tangential velocity and acceleration profiles for the acceleration phase of these trials.

FIGURE 8.

Mean and standard errors of area of the initial and second muscle torque impulses at the elbow (solid line) and shoulder (dotted line) for each target in the anterior and lateral directions across participants. Positive torque is flexor; negative torque is extensor.

FIGURE 9.

Means and standard errors for time to maximum muscle torque at the elbow (black) and shoulder (white), collapsed across the four targets, in the anterior and lateral directions.

FIGURE 10.

(A) Initiation pulse: initial acceleration pulse as a function of initial elbow (solid circle) and shoulder (open circle) muscle torque impulses in the anterior and lateral directions for representative participants. (B) Modulation pulse: second acceleration pulse as a function of second elbow and shoulder muscle torque impulses in the anterior and lateral directions for representative subjects. In the anterior direction, only shoulder torque values are plotted, because elbow torque values were attenuated. Corresponding r^2 values are displayed in each scatter plot. Positive torque is flexor; negative torque is extensor.