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Effect of movement speed on limb segment motions for reaching from a standing position

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Abstract The performance of a standing reaching task that necessitates some forward bending requires: (1) the coordination of multiple joints (i.e., the trunk and limb segments) to reach the target, and (2) the preservation of postural stability. It has been proposed that the neural control of multijoint reaching tasks can be simplified by time scaling of joint motions while keeping joint excursions the same. To determine if time scaling of joint motions was used in this more complex reaching task, we had 20 healthy subjects (10 male and 10 female) reach for two targets located in a parasagittal plane while standing on a force platform. Subjects reached for the targets at a comfortable speed and a fast paced speed. Sagittal plane motions of the right shank, thigh, pelvis, trunk, humerus, and forearm were measured. At the fast paced movement speeds subjects had significantly larger excursions of the thigh, pelvis, humerus, and forearm compared to the comfortable speed. Thus, segment motions are not simply time scaled for standing multijoint reaches. We explored three possible reasons for not obeying time scaling: (1) to reduce scaling of peak kinetic energy, (2) to reduce scaling of peak horizontal ground reaction force, and (3) a convergence of movement strategies at faster speeds. While subjects modified their movement strategy in relationship to movement speed, these changes had no

significant effect on the expected scaling of peak kinetic energy, or peak horizontal ground reaction forces. Given the intersubject differences in movement strategies used to perform these reaching tasks at the fast speeds, a convergence of movement strategies was ruled out. We propose that the increase in segment motions with speed may be a consequence of rules underlying motor output, the increases being greater for segments in which viscoelastic resistance to movement is more significant compared to inertial resistance.

Keywords Speed · Kinematic redundancy · Reaching · Posture

Introduction

Reaching tasks such as ringing a doorbell, wiping a child's face or retrieving the morning paper are so common in our everyday experience that we rarely contemplate the complexity of such motor tasks or the variety of movement patterns that can be used to perform them. With respect to reaching tasks performed from a standing position, the central nervous system (CNS) must solve two problems. One, the excursions of the limbs and the trunk must be planned such that the hand reaches the intended target; and, two, the excursions must be such that the projection of the body center of mass (COM) lies within the base of support after target contact. However, even with these two constraints, there are still an infinite number of joint configurations that can be used to complete these tasks, due to the kinematic redundancy inherent in these multijoint movements. Studies of how the redundancy is resolved are important for shedding light on CNS control of multijoint movements, but such studies are only at the beginning stages (for a brief review, see Hasan and Thomas 1999). The general aim of these studies is to discover the rules whereby a particular set of segment motions is chosen from among the infinitely many possible ones, as task variables are altered. In the present report we focus on the choice of

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segment motions for target-reaching movements at different instructed speeds.

One general principle proposed for simplifying the neural control of multijoint movements performed at different speeds is *time scaling* of joint motions (Hollerbach and Flash 1982). That is, one could perform the same reaching movement at a variety of speeds without a change in segment motions – except for scaling in time – by similar time scaling of the non-gravity muscle torques, and amplitude scaling of the torques by the square of the ratio of movement times. This scheme simplifies the multijoint control problem considerably, in that an inverse-dynamics computation valid for one speed is made applicable to all speeds by time and amplitude scaling of the requisite torques. The question arises whether this simplifying scheme has experimental support.

Although speed effects on movement characteristics have been studied extensively (Atkeson and Hollerbach 1985; Buneo et al. 1994; Gottlieb et al. 1996), there have been relatively few investigations of the effect of speed on the segmental motions in kinematically redundant systems. Schillings et al. (1996), employing small pen-in-hand movements by seated subjects, found greater contribution of the more proximal joints for higher speed movements. Nishikawa et al. (1999), utilizing large pointing movements of the hand, also by seated subjects, found no effect of speed on the three-dimensional kinematics of the arm, except, of course, for the altered time scale. In another set of seated reaching tasks, Zhang and Chaffin (1999) found no effect of movement speed on joint excursions. Thus, the empirical evidence for the effect of movement speed on joint excursions during seated reaches is murky. On the other hand, it is clear that excursions of the thigh, shank, and foot segments increase during human locomotion at fast speeds (Bianchi et al. 1998). The data of Alexandrov et al. (1998) indicate that during voluntary trunk flexion performed from a standing position, the ankle and knee joint angular excursions increase with speed. Furthermore, Stapley et al. (1999) demonstrate that anteroposterior displacements decrease with speed for the head and the shoulder, and increase for the hip in subjects performing full body reaching tasks. These studies suggest that movement speed does affect segment excursions of the shank, thigh and pelvis in movement tasks performed in standing.

The primary purpose of the present study is therefore to determine the effects of instructed speed on the rotational excursions of the body segments that contribute to target-reaching movements performed from a standing position. Hypothesis 1 is that the rotational excursions of the shank, thigh, pelvis, trunk, upper arm, and forearm segments are affected by instructed speed when reaching for the same target. We will show that the hypothesis is supported for most segments and thus contradicts the simplifying idea of time scaling.

Our second purpose is to explore possible reasons for lack of time scaling of all the segmental motions. The first possible reason for abandoning time scaling of segment

motions is to reduce peak kinetic energy at fast movement speeds. Because the kinetic energy contribution of each segment is proportional to the square of its speed, the total kinetic energy should scale as $(1/MT)^2$ if movements were time scaled, where MT is movement time. However, if time scaling is not obeyed then the scaling of kinetic energy could be different. Thus Hypothesis 2.1 is that peak kinetic energy (normalized by $(1/MT)^2$) will be less for fast movements to the same target.

A second reason for abandoning time scaling is to reduce the likelihood of slipping at fast movement speeds by reducing the peak horizontal ground reaction force (GRF) for these reaches. Peak horizontal GRF should scale at $(1/MT)^2$ if segment motions are time scaled. Thus Hypothesis 2.2 is that peak horizontal GRF (normalized $(1/MT)^2$) will be less for fast movements to the same target.

A third possible reason for abandoning time scaling is that high-speed movements may necessitate a convergence in movement strategies across subjects. For the purposes of this paper, a movement strategy is defined as “a set of rules for apportioning segment excursions to perform a particular movement task.” Thomas et al. (1998) showed, for comfortable-speed pointing movements from a standing position to a target positioned at approximately knee height, that all subjects bend the trunk forward and counterbalance it by a backward translation of the pelvis. However, some individuals keep the knees extended and plantarflex at the ankles, whereas others let the pelvis descend by flexing the knees and dorsiflexing the ankles. That is, different individuals use different movement strategies to perform identical reaching tasks. Hypothesis 2.3 is that the two strategies, exemplified by plantarflexion or dorsiflexion at the ankles seen at the slower speed, will converge at the higher speed to the same strategy for all subjects. Finally, because Thomas et al. (1998) showed in a similar task that the choice of plantarflexion vs. dorsiflexion strategies is correlated with the subject’s gender, we will revisit this issue on the basis of the data obtained in the present study.

Some of the results of this study have been reported earlier in abstract form (Thomas 2000; Thomas et al. 2000).

Materials and methods

Twenty healthy normal individuals, ten men (mean age = 25.5 years, range = 21–38 years) and ten women (mean age = 25.9 years, range = 20–37 years) participated in this experiment. All participants signed informed consent, and the institutional review board of the University of Illinois at Chicago approved this study.

Procedure

The following anthropometric measures were obtained from the subjects: height, weight, trunk length (umbilicus to acromion process), pelvic length (greater trochanter to umbilicus), hip height (greater trochanter to floor), thigh length (greater trochanter to

lateral joint line of knee), shank length (lateral joint line of knee to lateral malleolus), foot length (medial malleolus to great toe), humerus length (acromion process to lateral epicondyle), forearm length (lateral epicondyle to radial styloid), and hand length (radial styloid to tip of index finger).

Reaching tasks

Subjects were positioned barefoot on a force platform (AMTI OR6-5, 51×46 cm) located 16 cm above floor height such that their lateral malleoli were aligned with a line through the center of the plate. Prior to the start of a reaching task, subjects were instructed to stand up straight and maintain their right hand on a flexible, carbon electrode strapped to their anterior proximal thigh, which was connected to a contact-detector circuit. The subjects were instructed to “wait for the go signal and then reach for the target, touch the target with the right index finger and maintain contact with the target until instructed to return to an upright posture.” A light-emitting diode (LED) located in front of the subject adjacent to the target was used for the “go” signal. The target consisted of a metal plate, 3×2 cm, which was also connected to a contact-detector circuit. When subjects began the reaching task, contact with the thigh electrode was broken and a timer started. When the subject’s contact with the target was detected, the timer stopped. Movement times, determined from the timer, were used for training the subject for the fast paced trials, as described later. The subjects were instructed to keep their left arm at their side during the reaching task.

Target location

Two target positions were employed, “low” and “high,” whose locations were based on the subject’s trunk and pelvic length, arm length (humerus + forearm), and hip height (Fig. 1). The “low” target was placed in a position calculated so that the subject (with the elbow fully extended and the shoulder flexed 90°) could, in theory, reach the target by orienting the hip and trunk 30° to horizontal without any flexion of the ankle, knee, and lumbar spine. Similarly, the “high” target could be reached simply by orienting the hip and trunk 60° to the horizontal. The subject, however, never assumed the configurations shown in Fig. 1 since, in practice, this would necessitate backwards displacement of the pelvis given the mass of the trunk and the need to counteract forward displacement of that mass.

Movement speed

Subjects were instructed to reach for each target at a comfortable speed, and then were paced to reach the target at a fast speed. From pilot data it was determined that the average movement time for comfortable speed trials was 1,150 ms for the low target and 850 ms for the high target. Based on these data, we defined fast movement speed by the criterion of movement time to target. Subjects were trained to reach the low target with a movement time of 500±50 ms, and the high target with a movement time of 350±35 ms. The reason for adopting this procedure was that we wished to maintain the ratio of movement times for the slow and fast movements approximately constant (0.43 high target and 0.41 low target). In the fast-paced conditions subjects performed practice trials and were given verbal feedback on their movement time to target (e.g., “you were 2/10 of a second slow”). When the subject could reach the target in the specified movement time a trial was collected.

Subjects reached to the two target locations at comfortable and fast paced speeds. There were 6 trials at each experimental condition of target location (2) and movement speed (2) for a total of 24 movement trials. Subjects performed 12 reaching trials at a comfortable pace and the target location was alternated from low to high after each trial. Subjects then performed 12 reaching trials at

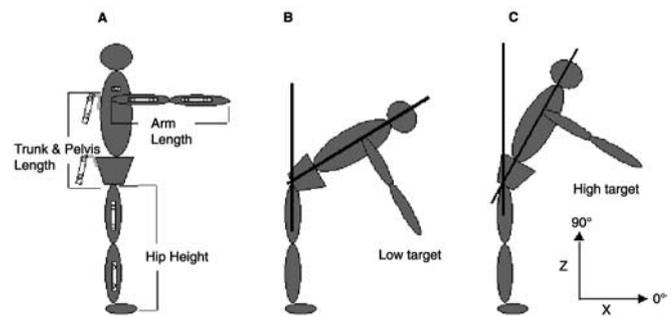


Fig. 1 A Diagrammatic representation of the segment lengths used to normalize the target location for each subject, and the location of the 13 infrared light-emitting diodes (IREDS). Pairs of IREDS were attached to the right shank, thigh, pelvis, thorax, humerus, and forearm. One IRED was attached to the right acromion process. B Subjects could reach the low target, in theory, by orienting their hips and trunk 30° with respect to the horizontal (with the elbow extended and the shoulder flexed 90°) without any motion of the ankle, knee, or spine. C The high target could be reached by orienting the hips and trunk 60° with respect to the horizontal. The local reference frame was set such that the horizontal vector pointing in an anterior direction as seen from the subject’s right side had an orientation of zero and sagittal plane angles were positive counterclockwise

the fast paced speed. Subjects were not given any instruction on the limb segment geometry to use while performing the reaching tasks.

Data collection

Movements of the shank, thigh, pelvis, trunk, humerus and forearm were recorded using a Selspot system. The Selspot system uses two infrared cameras to detect the positions of infrared-emitting diodes in three-dimensional space with a spatial resolution of 0.1 mm. Thirteen infrared-emitting diodes (IREDS) were used and the three-dimensional coordinates of these diodes were recorded at 100 Hz (see Fig. 1).

For the ground reaction force data the x -axis was defined as anteroposterior, the y -axis as mediolateral, and the z -axis as vertical. Force (F) and moment (M) outputs of the force platform were recorded and filtered with a second-order critically damped low-pass filter with a cutoff frequency of 10.5 Hz and A/D converted at 100 Hz with 12-bit resolution, using a separate computer. Center of pressure (COP) was determined from these force and moment data. For each reaching trial, the peak-to-peak displacement of COP position in the anterior-posterior direction was determined and normalized by the distance from the medial malleolus to the great toe. The same computer used to collect the force data also stored the contact-detector signals, and produced the synchronization pulse for recording the Selspot data.

Data analysis

Sagittal plane orientations of the six segments (shank, thigh, pelvis, trunk, forearm, and humerus) were defined as vectors directed from the “near” end of the segment to the “far” end. The near end was the one closer to the ankle in the linked chain of segments; thus for the shank the vector was directed from the ankle to the knee, for the thigh from the knee to the hip, and so on up to the forearm, for which it was directed from the elbow to the fingertip. The orientation angles (ϕ) of the vectors in the sagittal plane were defined as positive in a counterclockwise direction, as seen from the subject’s right side, with the anterior direction corresponding to zero degrees. For each segment the change in orientation angle from initial to final position, i.e., the excursion, was determined as

follows. The orientation angle was averaged over a 100-ms epoch at the beginning of the trial before the go signal, and another 100-ms epoch beginning 100 ms after target contact by which time the segment motions had settled. The difference of these two values determined the change in orientation angle ($\Delta\phi$).

While movement time based on a contact detector circuit was used for training purposes (i.e., to provide feedback during fast paced trials), it was not a sufficiently reliable method to determine movement time for each trial. This was because on some trials subjects moved their arm slightly prior to initiating the reaching task and thus broke contact with the electrode on the thigh and started the timer early. Alternatively, on some trials subjects began the reaching task by moving the trunk and lower limbs while the hand was still in contact with the electrode on the thigh and thus the timer was not started at the initiation of the reaching movement. Therefore, for subsequent analyses the movement times were determined from the time series trunk orientation data. The trunk was chosen for this determination because its motions were large, smooth, and always in the same direction (flexion). The time course of the trunk orientation was differentiated and peak velocity was determined. Movement onset (MO) was defined as the time where the velocity of the trunk was greater than 5% peak velocity. Movement cessation (MC) was defined as the time where trunk velocity fell below 5% of peak velocity. Movement time was defined as (MC–MO).

A linked-segment model consisting of six segments was used for kinetic energy calculations. The six segments were defined as follows: segment 1: the left and right shanks; segment 2: the left and right thighs; segment 3: the pelvis (greater trochanter to L3); segment 4: the trunk (comprising the thorax from L3 to the first thoracic vertebrae, the head and neck, and the stationary left humerus, forearm and hand); segment 5: the right humerus; and segment 6: the right forearm and hand.

The mass, location of the center of mass (COM), and radius of gyration of each segment were approximated using the regression equations provided by Plagenhoef et al. (1983) based on the subject's weight and sex, and the measured segment lengths. The moment of inertia about the COM for each segment was then calculated using the parallel-axis theorem.

We used the kinematic data and the location of the COM of each segment to determine the kinetic energy of the segment at each instant in time. First, for each segment we calculated at every instant in time the orientation angle (ϕ) with respect to the x -axis (anterior direction) and the position (x, z) of the COM. These data were then smoothed with a 61-point fourth-order Savitzky-Golay filter (Press et al. 1992). We then differentiated the 4th order polynomials derived for the orientation data to determine angular velocity (ω_i), as well as for the COM coordinates (in the anterior and vertical directions) to determine velocity of the center of mass (v_i) for each segment for each instant in time. The kinetic energy for each segment was derived using the following equation:

$$KE_{\text{segment}(i)} = \frac{1}{2} m_i v_i^2 + \frac{1}{2} I_i \omega_i^2$$

$$\text{Total KE} = \sum_{i=1}^6 KE_{\text{segment}(i)}$$

where m_i =mass of the i^{th} segment, v_i =velocity of the COM of the i^{th} segment, ω_i =angular velocity of the i^{th} segment, and I_i =moment of inertia of the i^{th} segment about its COM.

For each movement trial, peak kinetic energy was calculated from these data and then normalized by dividing by $(1/MT)^2$.

Horizontal ground reaction force was determined as follows:

$$\text{Horizontal ground reaction force} = \sqrt{(F_x^2 + F_y^2)}.$$

For each movement trial, the peak value of horizontal ground reaction force was then determined and this value was normalized by dividing it by $(1/MT)^2$. Additionally, peak horizontal GRF/vertical GRF was calculated for each trial and compared with the coefficient of friction to determine how close the subject might come to slipping. The static coefficient of friction between the

forceplate surface and the bare foot was estimated, using the inclined plane method, to be 0.53.

Statistical analysis

The changes in segment angles from initial posture to target contact (i.e., $\Delta\phi_{\text{shank}}$, $\Delta\phi_{\text{thigh}}$, $\Delta\phi_{\text{pelvis}}$, $\Delta\phi_{\text{trunk}}$, $\Delta\phi_{\text{humerus}}$ and $\Delta\phi_{\text{forearm}}$), as well as normalized peak kinetic energy, normalized peak horizontal GRF, and normalized peak-to-peak displacement of COP position were analyzed using mixed model ANOVAs. The within subject factors were Movement Speed (2), Target Location (2), and Trial (6). Gender was the between subject factor.

Results

Kinematic data recorded for a movement trial to the low target at a comfortable speed are presented in Fig. 2A as time series data, and in Fig. 2B as a series of stick figures from initial posture to target contact. As can be seen in Fig. 2A, the initial segment orientation angles of the shank, thigh, pelvis, and trunk are approximately 90° , while the initial orientation angles of humerus and forearm are approximately -90° and -75° respectively; the negative signs indicate clockwise orientations with respect to the anterior direction. It is clear from Fig. 2A that in order to reach the target this subject rotated the shank, pelvis, and trunk clockwise from the initial posture, and the thigh, humerus and forearm were rotated counterclockwise. Thus the changes in orientation angles

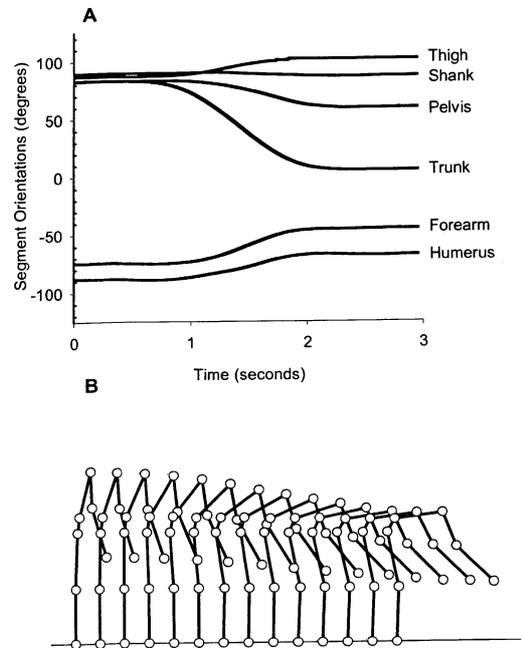


Fig. 2 **A** The time series changes in orientation of the shank, thigh, pelvis, trunk, forearm, and humerus segments of an individual subject reaching for the low target at a comfortable speed. Counterclockwise rotations as seen from the subject's right side are shown as increases. **B** Stick figures plotted every 100 ms from movement initiation until target contact are derived from the same time series illustrated above and the subject's anthropometric data

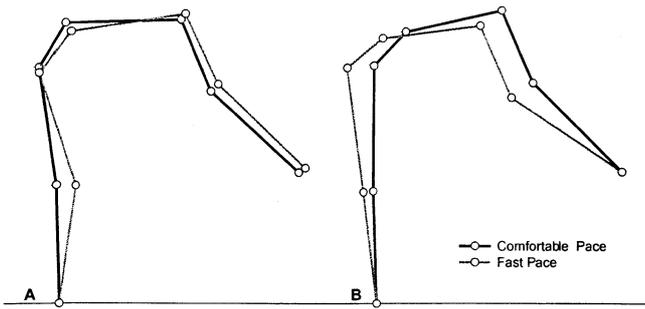


Fig. 3A, B Stick figures of the posture adopted at target contact for two different subjects reaching for the low target at a comfortable speed (*black*) and a fast paced speed (*gray*). **A** This subject is using an ankle dorsiflexion/knee flexion movement strategy to reach the target. **B** This subject is using an ankle plantarflexion/knee extension strategy to reach the target. As movement speed increases from a comfortable pace to fast pace both subjects have increases in the excursions of the shank, thigh and pelvis

($\Delta\phi$'s) of the shank, pelvis and trunk were negative, while the changes in orientation angles of the thigh, humerus and forearm were positive.

There were, however, substantial intersubject differences in the apportionment of the segmental motions as exemplified in Fig. 3. Parts A and B of the figure depict the final configurations adopted by two different subjects reaching for the low target at comfortable (black lines) and at fast paced speeds (gray lines). Two conclusions can be drawn from these figures. One is that these two subjects used different movement strategies to reach the target. The subject depicted in Fig. 3A used a knee flexion/ankle dorsiflexion strategy to reach for the target while the subject depicted in Fig. 3B used a knee extension/ankle plantarflexion strategy. Secondly, regardless of the movement strategy adopted by these two subjects, at the faster movement speed they increased the magnitude of rotations of the shank, thigh, and pelvis to perform the reaching task.

Movement speed

In the comfortable movement speed condition, subjects on average reached for the low target in 1,048 ms, and the high target in 991 ms. In the fast-paced condition they reached the targets in approximately half that time, namely 488 ms and 434 ms, respectively.

Figure 4 depicts, for both the low and high targets, the average values (and standard errors) of the angular excursions ($\Delta\phi$'s) of each of the six segments. Comparing trials at the fast speed with trials at comfortable speed, the effect of speed was absent for the shank and trunk angular excursions, but significant for the other segments. Specifically, with the increase in speed, subjects on average exhibited increased clockwise rotation of the pelvis ($\Delta\bar{X} = -5.9^\circ$; $F_{(1,18)}=55.2$, $P<0.05$) (Fig. 4C), and increased counterclockwise rotation of the thigh ($\Delta\bar{X} = 8.4^\circ$; $F_{(1,18)}=27.4$, $P<0.05$), humerus ($\Delta\bar{X} = 5.7^\circ$;

$F_{(1,18)}=39.1$, $P<0.05$), and forearm ($\Delta\bar{X} = 3.9^\circ$; $F_{(1,18)}=30.1$, $P<0.05$) (Fig. 4B, E, F). While there was no main effect of speed on the change in orientation of the shank or trunk (Fig. 4A, D), there was a significant interaction of target location and speed for $\Delta\phi_{\text{shank}}$ ($F_{(1,18)}=5.76$, $P<0.05$) and $\Delta\phi_{\text{trunk}}$ ($F_{(1,18)}=14.13$, $P<0.05$). Analysis of the simple effects of speed for $\Delta\phi_{\text{shank}}$ and $\Delta\phi_{\text{trunk}}$ at each target location was only significant for $\Delta\phi_{\text{trunk}}$ at the high target ($\Delta\phi_{\text{trunk}}$, $F_{(1,18)}=6.79$, $P<0.05$). On average, subjects increased trunk excursion 3.1° at the fast paced speed compared to the comfortable speed.

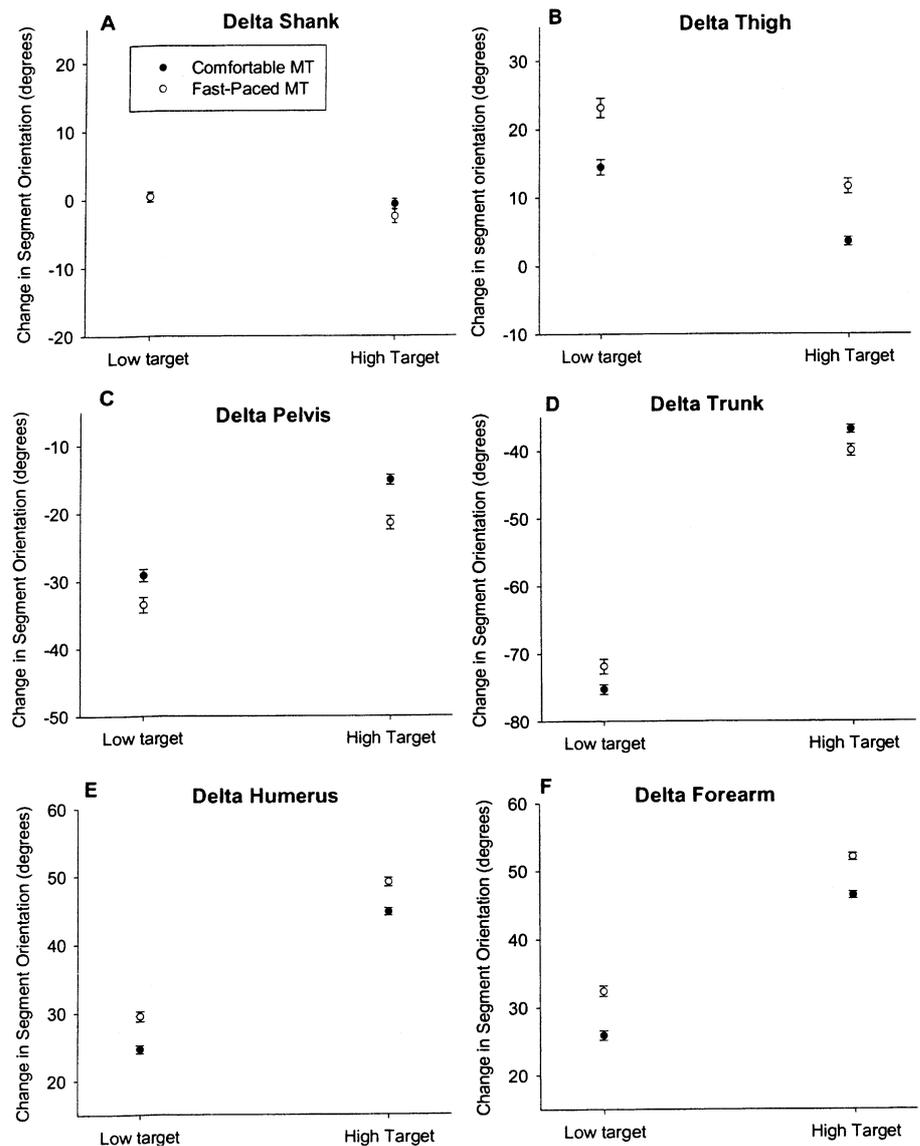
The effect of speed on the excursion of the shank was reported above as not statistically significant. This is due to the fact that the strategy used to reach the target determined the sign of $\Delta\phi_{\text{shank}}$. With a dorsiflexion (DF) strategy the $\Delta\phi_{\text{shank}}$ is negative (e.g., Fig. 3A) and with a plantarflexion (PF) strategy $\Delta\phi_{\text{shank}}$ is positive (e.g., Fig. 3B). If some subjects used a DF strategy and others a PF strategy, then any speed effects are lost when the data are averaged across subjects. To determine whether the *magnitude* of shank excursion changed with speed we ran an ANOVA on the absolute values of $\Delta\phi_{\text{shank}}$. This analysis revealed a significant speed effect ($F_{(1,18)}=19.5$, $P<0.05$); on average, during fast paced reaches subjects increased excursion of the shank 3.2° compared to comfortable paced reaches. The lack of speed effect on $\Delta\phi_{\text{trunk}}$, however, cannot be so explained, as all subjects exhibited trunk flexion in all trials.

While segment excursions increased at the fast movement speed conditions, there was no significant change in the peak-to-peak COP displacement ($F_{(1,18)}=1.47$, $P>0.05$). On average the peak-to-peak COP displacement (normalized to foot length) was 47.8% and 50.7% for the comfortable and fast paced movement times respectively.

Target location

The two target locations selected required some forward bending (i.e., clockwise rotation) of the trunk to reach the target, greater for the low target compared to the high target (Fig. 4D). For reaches to the low target compared to the high target (Fig. 4), when averaged across the two movement speeds, there was an increase in the counterclockwise motion of the thigh ($\Delta\bar{X} = 11.24^\circ$; $F_{(1,18)}=64.1$, $P<0.05$), and increases in the clockwise motions of the pelvis ($\Delta\bar{X} = -13.56^\circ$; $F_{(1,18)}=187.5$, $P<0.05$) and trunk ($\Delta\bar{X} = -35.16^\circ$; $F_{(1,18)}=436.8$, $P<0.05$). This was coupled with decreases in the counterclockwise motions of the humerus ($\Delta\bar{X} = -20.16^\circ$; $F_{(1,18)}=1,574.0$, $P<0.05$) and forearm ($\Delta\bar{X} = -19.85^\circ$; $F_{(1,18)}=795.1$, $P<0.05$) when comparing reaches to the low and high targets. While there was no significant effect of target location for the shank ($\Delta\phi_{\text{shank}}$, $F_{(1,18)}=3.0$, $P>0.05$), analysis of the absolute value of shank excursions showed a significant effect of target location ($F_{(1,18)}=14.7$, $P<0.05$) with a mean increase of shank excursion by 3.1° for reaches to the low target.

Fig. 4A–F The effect of movement speed on the change in segment orientation angle for the two target locations is depicted for each segment. **A** Shank; **B** thigh; **C** pelvis; **D** trunk; **E** humerus; **F** forearm



Additionally, peak-to-peak COP displacement was greater for reaches to the low target ($\bar{X} = 52.1\%$) compared to reaches to the high target ($\bar{X} = 46.3\%$), $F_{(1,18)}=47.1$, $P<0.05$.

Speed scaling and kinetics

Figure 5A, B illustrates for a representative trial the effect of movement speed on the kinetic energy (KE) and horizontal ground reaction force (H_GRF) at comfortable (black) and fast (gray) paced speeds to the high target. The direction of H_GRF is not shown, as only the magnitude is relevant for testing Hypothesis 2.2, which concerns the possibility of slipping. The multiple peaks stem from non-coincident timings of the F_x and F_y peaks (not shown). As might be expected, both the peak kinetic energy and peak horizontal ground reaction force are greater at the faster speed. The values of peak KE and

peak H_GRF for the 24 movement trials of an individual subject are plotted against movement time in Fig. 6A, B, and illustrate that both variables are larger when the movement time is smaller, for reaches to high as well as low target locations.

If the same segment motions are used to perform a reaching task at comfortable and fast speeds, i.e., if time scaling is followed, then one would expect the peak kinetic energy to scale by $(1/MT)^2$. Thus, we normalized peak KE for each trial by $(1/MT)^2$ and tested for speed effects. While segment motions changed with movement speed, there was no significant effect of movement speed on normalized peak KE ($F_{(1,18)}=0.386$, $P>0.05$).

Peak horizontal ground reaction force should also scale by $(1/MT)^2$ if the same segment motions are used to perform a reaching task at comfortable and fast speeds. There was no effect of movement speed on normalized peak horizontal GRF ($F_{(1,18)}=2.23$, $P>0.05$). The actual values of peak horizontal GRF and peak horizontal GRF/

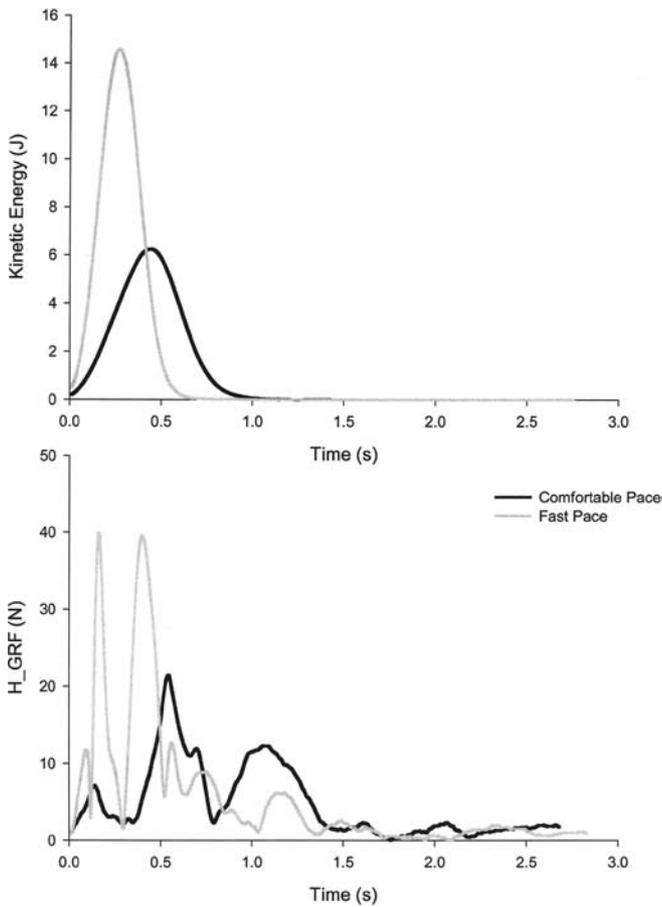


Fig. 5 **A** Time series kinetic energy (KE) data from an individual subject reaching for the high target at comfortable (*black*) and fast paced (*gray*) movement speeds. **B** Time series horizontal ground reaction force data of the same movement trials illustrated in **A**. The data from the comfortable and fast paced movement trials were aligned by movement onset times

Table 1 Peak horizontal ground reaction force (H_GRF) and peak H_GRF normalized by vertical ground reaction force (V_GRF) for reaches to the low and high targets at a comfortable pace and fast-paced movement speed (means \pm SE). The estimated coefficient of friction for this experiment was 0.53. Even for the fast-paced reaches, subjects were well below the threshold for slipping

| | Peak H_GRF (N) | Peak HGRF/V_GRF |
|-------------------|-----------------|--------------------|
| Low target | | |
| Comfortable speed | 14.8 \pm 0.62 | 0.024 \pm 0.0009 |
| Fast paced speed | 53.4 \pm 2.1 | 0.089 \pm 0.004 |
| High target | | |
| Comfortable speed | 12.5 \pm 0.47 | 0.02 \pm 0.0006 |
| Fast paced speed | 42.2 \pm 1.8 | 0.068 \pm 0.003 |

vertical GRF are summarized in Table 1. For reaches to both target locations, the ratio of peak H_GRF to V_GRF was such that even for fast-paced movements subjects remained below the estimated coefficient of friction.

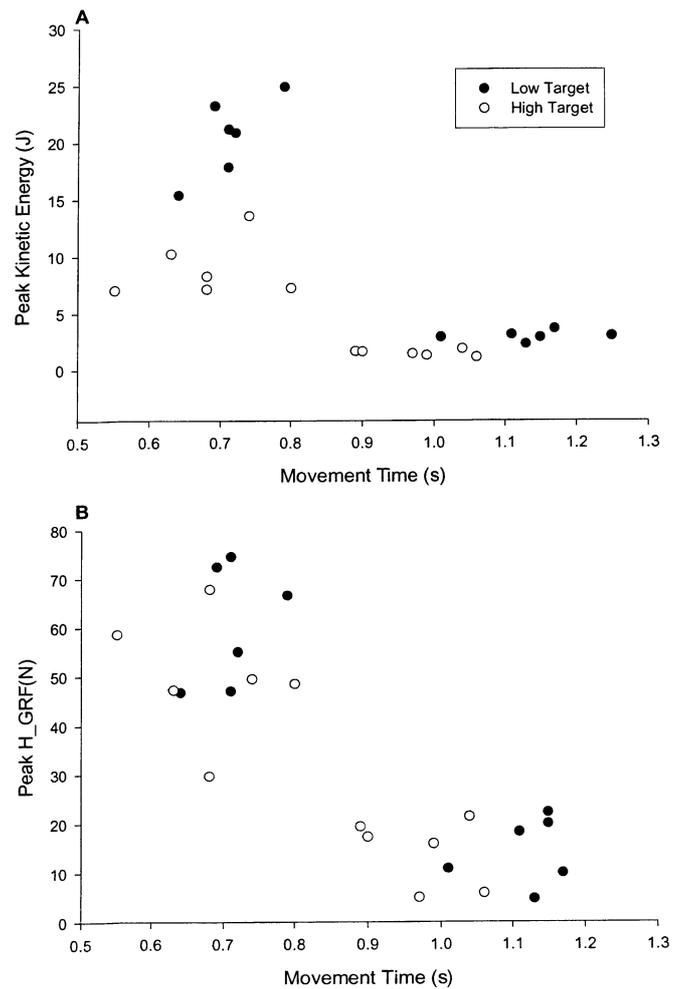


Fig. 6 **A** The peak KE for all 24 trials of an individual subject is plotted against the movement time. As movement time decreased peak kinetic energy increased. **B** The peak horizontal GRF for all 24 trials of an individual subject plotted against movement time. As movement time decreased peak horizontal GRF increased

Intersubject differences

The stick diagrams in Fig. 3 demonstrate two different movement strategies utilized to perform the reaching tasks. Subjects need to move their hips backwards to offset the forward motion of the trunk during the forward reaching task, yet they can accomplish this by adopting either a knee flexion/ankle dorsiflexion strategy (Fig. 3A) or a knee extension/ankle plantarflexion strategy (Fig. 3B). A post hoc analysis was performed to quantify the prevalence of dorsiflexion (DF) and plantarflexion (PF) strategies utilized by individuals in this study, and whether the strategy depends on speed. These findings are summarized in Table 2. While some subjects did switch from a PF to a DF strategy at the fast movement speeds, most subjects used the same strategy at both movement speeds. Thus there was no convergence of movement strategies noted at the fast speeds.

Table 2 The prevalence of ankle dorsiflexion and ankle plantarflexion movement strategies used by subjects to perform reaches to the low and high targets

| | No. trials of dorsiflexion | No. trials of plantarflexion |
|-------------------|----------------------------|------------------------------|
| Low target | | |
| Comfortable speed | 80 | 40 |
| Fast paced speed | 78 | 42 |
| Prevalence | 65.8% | 34.2% |
| High target | | |
| Comfortable speed | 89 | 31 |
| Fast paced speed | 78 | 42 |
| Prevalence | 69.6% | 30.4% |

Table 3 The influence of gender on segment excursions is summarized. The data are averaged across target heights and movement speeds (means \pm SE)

| Segment | Males | Females |
|----------------------|-------------------|-------------------|
| $\Delta\phi$ shank* | -4.08 \pm 0.42 | 2.89 \pm 0.57 |
| $\Delta\phi$ thigh | 17.38 \pm 0.73 | 8.99 \pm 0.95 |
| $\Delta\phi$ pelvis* | -20.88 \pm 0.64 | -29.25 \pm 0.90 |
| $\Delta\phi$ trunk* | -52.88 \pm 1.24 | -59.66 \pm 1.28 |
| $\Delta\phi$ humerus | 36.50 \pm 1.26 | 37.51 \pm 0.82 |
| $\Delta\phi$ forearm | 39.80 \pm 0.83 | 38.59 \pm 0.80 |

* Significant gender effect ($P < 0.05$)

The influences of gender on segment excursions are summarized in Table 3. Male subjects used significantly larger amounts of shank motion, coupled with less motion of the pelvis and trunk, when compared to female subjects. Examination of movement strategy by gender revealed that males used the DF strategy in 80.0% of the trials and the PF strategy in the remaining 20.0%, whereas females used the DF strategy in 55.4% of the trials and PF in 44.6%.

Discussion

Given the large number of segments involved in the free standing reaching task, there are an infinite number of movement patterns that could be used to successfully reach a target, due to the inherent kinematic redundancy. Despite intersubject differences in how motions were apportioned among the six segments, we found certain regularities. For instance, in reaching for the low compared to the high target, there was on average an increase in the magnitudes of the motions of the shank, thigh, pelvis, and trunk, and a concomitant decrease in the motions of the arm segments.

Effect of speed on segment motions

Hypothesis 1, that the rotational excursions of the shank, thigh, pelvis, trunk, upper arm, and forearm segments are affected by instructed speed when reaching for the same target, was supported for the most part by our observations. The change in orientation angle from initial posture to the post-target contact period was affected significantly by movement speed for five of the six segments, namely,

the shank, thigh, pelvis, humerus, and forearm. For the shank the effect was significant only for the absolute magnitude of the excursion. These observations are contrary to the idea of time scaling.

Interestingly, we found that all the angular excursions except that of the trunk were significantly larger in magnitude at the higher speed. This finding is consistent with the data of Alexandrov et al. (1998) for voluntary trunk flexion movements, showing increases in ankle and knee joint angle excursions as trunk flexion speed increased. Similarly, Stapley et al. (1999) found during full body reaching tasks that the translational motion of the hip in the posterior direction increased with speed, which is consistent with the increased counterclockwise excursion of the thigh that we observed. While segment excursions increased at the fast movement speed conditions, there was no significant increase in the normalized peak-to-peak COP displacements, which is inconsistent with the findings by Pozzo et al. (2002). These authors had subjects perform full body reaching tasks at a comfortable pace and as fast as possible. The differences in target location and movement speeds (i.e., as fast as possible versus twice comfortable pace) between these two experiments could account for this inconsistency.

Are the increased angular excursions at higher speed specific to movements performed from a standing position? In seated subjects reaching to kinesthetically defined targets using the arm segments alone, Adamovich et al. (1999) found significant increases in segment motions, and consequent overshoot in the final hand position, when fast movements were compared to comfortable-speed movements. In discrete drawing movements using the elbow, wrist, and fingers, Schillings et al. (1996) report that when they compared the fastest and slowest movement trials, all segmental contributions increased at the higher speed, contrary to their expectation. Furthermore, for single-joint movements it has been reported that across the range of speeds exhibited by subjects instructed to perform as-fast-as-possible movements, the transient overshoot at the end is positively correlated with the peak velocity during the movement (Milanovic et al. 2000). Thus, it appears that increased angular excursions at higher movement speeds are not unique to our standing reaching task.

Hypotheses concerning lack of time scaling

Kinetic energy

Hypothesis 2.1 was that peak kinetic energy normalized by $(1/MT)^2$ would be less for fast movements to the same target. However, there was no speed effect observed for peak kinetic energy normalized by $(1/MT)^2$. While peak kinetic energy must scale at $(1/MT)^2$ if the same segment excursions are used to complete a particular task at different movement speeds, the converse is not true in a kinematically redundant system. Kinetic energy is determined by the sum of angular as well as translational contributions of all the segment masses in the system. Thus an increase in KE from increased angular excursions can be offset by decreased translational motion of some of the segment COMs, resulting in comparable peak KEs for quite different motions. While Soechting et al. (1995) and Nishikawa et al. (1999) suggest that the final configuration of the arm during reaching tasks can be predicted by minimization of the peak kinetic energy required to move the arm from its initial position to the target location, this expectation is contradicted by our findings. In other words, minimization of peak KE may not be a good predictor of segment motions across all movement speeds.

Horizontal ground reaction force

Hypothesis 2.2, that peak horizontal GRF [normalized by $(1/MT)^2$] will be less for fast movements to the same target, was not supported by the data. This hypothesis was based on the idea that slippage may become a problem at the higher speeds because of the requirement of increasing horizontal ground reaction force if time scaling of segment motions were followed. The contradiction of this hypothesis is a reflection of the fact that the force platform had sufficient friction so that the threshold of slipping was never approached even for the fast movements.

Differences in strategy

Hypothesis 2.3, that the two strategies, exemplified by plantarflexion (PF) or dorsiflexion (DF) at the ankles seen at the slower speed, will converge at the higher speed to the same strategy for all subjects, also was not supported by the data. Subjects tended to adhere to the same strategy at the higher speed as at the comfortable speed, and although some switching between strategies did occur, it could occur in either direction. Again, this negative result may reflect the fact that we did not force the subjects to extreme tasks, for example, by having the subject stand on a narrow beam and move at the fastest possible speed.

Gender was found to have an influence on the apportionment of segment excursions, yet our findings are not entirely consistent with those previously reported

by Thomas et al. (1998). A consistent gender finding across these two studies is that female subjects tend to use greater amounts of flexion at the pelvis compared to male subjects performing the reaching task (see Table 3). However, in Thomas et al. (1998) female subjects tended to use a DF movement strategy while male subjects used a PF strategy. While differences in experimental conditions between the two studies might account for the different results (e.g., wearing gym shoes versus barefoot), the fact that male and female subjects used both DF and PF strategies in this current investigation suggests that gender is not a good predictor of movement strategy for these tasks.

A speculative control scheme

A speculative control scheme that is consistent with these observations is as follows. In single, as well as multijoint, movements the instruction to increase movement speed elicits changes in the motor output according to certain rules (described for single-joint movements by Corcos et al. 1989). The rules, we propose, are such that they would result in greater angular excursions. Moreover, in the absence of visual feedback of the error, the increased excursions would not be fully corrected, resulting in significant constant errors in reaching as observed by Adamovich et al. (1999). Visual feedback of the error, however, acts to correct the motion so that only a transient overshoot is observed instead of a maintained error, as reported for one-joint movements (Milanovic et al. 2000). When kinematic redundancy allows the target to be attained despite increased motions of the segments, there is no need then to fully correct the increased motions, but only to modify them, under visual control, to the extent necessary for the hand to reach the target. We speculate that this is the reason underlying the increased segment excursions with speed in movements involving redundant degrees of freedom that we and others have found.

The excursion of the trunk, however, did not increase significantly with speed (although for the high target there was a simple effect of speed on trunk excursion). This finding of reduced speed dependence for the heaviest segment may seem to be supportive of the "Knowledge Model" (Rosenbaum et al. 1995; Fischer et al. 1997). The model predicts that as movement speed increases one should observe an increase in excursions of segments with less inertia and a decrease or smaller increases in the excursions of the segments with the greatest inertia. This prediction is a consequence of reducing the "travel cost" associated with the movement, which in the model makes it more efficient at higher speeds to apportion greater amounts of motion to segments with smaller inertia. The "Knowledge Model" would predict that as movement speed increased in our experiments the angular excursions of the forearm and humerus, which are the lightest segments, would increase by the largest amount, and the shank, thigh, pelvis, and trunk would exhibit either a decrease or smaller increases in excursions. We found

instead that individuals on average increased the angular excursion of the forearm by 3.9° , and of the humerus by 5.7° at the higher speed, but the excursions of the thighs and the pelvis, which are heavier than the arm segments, increased by greater amounts, namely 9.3° and 5.9° respectively.

Inertia, however, is not the only important mechanical property that the CNS controller needs to take into account. The elastic and viscous properties of active muscles (and of passive tissues) are equally important, especially at lower velocities of movement. Indeed, the concept of time scaling can be seen as a simplifying feature only if muscles are assumed to be ideal torque generators, for which the torque output is specified uniquely by the CNS drive to the muscles, unaffected by the movement itself. In fact, the CNS drive serves partly to overcome the viscoelastic resistance to movement, and partly to accelerate (and decelerate) the inertia. It is conceivable, however, that for a heavy segment the inertia dominates the viscoelasticity of the joints to such an extent that time scaling holds approximately true. This would be consistent with the lack of speed effect on the trunk excursion that we observed. As for the other segments, the departures from time scaling would be expected to depend not so much on the inertias of the segments relative to each other, but rather on the relative importance of inertia and viscoelasticity in resisting the motion of each particular segment. Thus, the speed dependence of the excursions need not vary strictly in order of the inertias of the segments. Whether this speculation accounts for the actual values of the speed dependencies that we observed cannot be determined in the absence of information about the viscoelastic properties of the different joints during movement. Such measurements have so far only been carried out for the arm (Lacquaniti et al. 1993).

Conclusions

We have shown that at different speeds of movement the segmental kinematics are not simply scaled in time, but exhibit changes in the angular excursions. Concerning the possible advantage of altering the excursions with speed, the data did not support any of the possibilities we considered, namely, reduction of mechanical work (as measured by peak kinetic energy), avoidance of slipping (as measured by peak horizontal ground reaction force), or convergence to a single movement strategy. We favor the possibility that the changes in excursion, instead of representing optimal choices for achieving any specific advantage, may simply be a reflection of how the control system operates.

We propose instead a speculative scheme in which increases in angular excursions of the segments with speed may be a consequence of the rules underlying the generation of the motor output, the increases being greater when viscoelastic resistance to movement is more significant in comparison with inertial resistance. Full correc-

tions for the increased angular excursions, governed by visual feedback, are crucial for systems without kinematic redundancy, whereas a system with kinematic redundancy can perform the task without full correction of the increased excursions. Kinematic redundancy also makes it possible for different individuals to employ different apportionments of segmental motions, of which they take advantage. But the extent to which these differences can be explained by variations in the relative importance of inertial and viscoelastic properties remains to be elucidated.

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