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Human Movement Science 18 (1999) 741–757

HUMAN MOVEMENT SCIENCE

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The effects of speed variation on joint kinematics during multisegment reaching movements

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Abstract

This study examined the effects of speed variation on the joint kinematic characteristics during multisegment reaching movements. An experiment was conducted in which six subjects performed a wide variety of seated reaching movements using two speed modes within a volitional range. Motions of the upper torso and right arm were measured by tracking markers on surface body landmarks using a four-camera opto-electronic movement analysis system. Joint angle profiles were derived from the measured locations of surface markers, based on a 7-DOF biomechanical linkage model. These angle profiles were then mathematically characterized by four-parameter hyperbolic tangent functions through a non-linear curve fitting process. Accurate characterization of the profiles (mean $R^2 = 0.99$) allowed subsequent statistical analysis including both multi- and uni-variate ANOVA to test the speed effects on the parameters collectively as well as individually. The study revealed the following: (1) neither the joint angle selection nor the amplitude of the selected angle motions was significantly influenced by the speed variation, (2) neither the time-scaling effect nor the symmetry of velocity profile in a strict sense was present, and (3) a faster speed induced a steeper rate (time-scaled) for the primary descending/ascending but a greater fraction of total time for accelerating phase where the velocity and acceleration are in the same direction.

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0167-9457/99/$ - see front matter
PII: S 0 1 6 7 - 9 4 5 7 (9 9) 0 0 0 3 8 - X

PsycINFO classification: 2240; 2260; 2330

Keywords: Speed effect; Multisegment reaching movement; Joint kinematics; Motion profile characterization

1. Introduction

There has been a considerable amount of interest and effort dedicated to investigating arm reaching movements. One of the objectives of these investigations was to identify common or invariant kinematic characteristics that underlie intact motor behavior (Flash, 1990). In that regard, many previous studies of point-to-point reaching motions have consistently yielded the following two conclusions: (1) the hand trajectory has a smooth, bell-shaped velocity profile (Abend, Bizzi & Morasso, 1982; Flash & Hogan, 1985; Kaminski & Gentile, 1986; Morasso, 1981; Soechting & Lacquaniti, 1981), and (2) this profile shape remains invariant when normalized with respect to the movement time and amplitude (Flash & Hogan, 1985; Hollerbach & Flash, 1982; Milner 1986; Ruitenbeek 1984). The latter characteristic coupling between the profile shape and speed (Morasso, 1983) manifests itself more explicitly in the displacement domain as a scaling effect of movement time on the hand trajectory displacement profile. As illustrated by Fig. 1, when the same movement is performed using a faster and a slower speed (in an average sense), the difference in movement completion time only

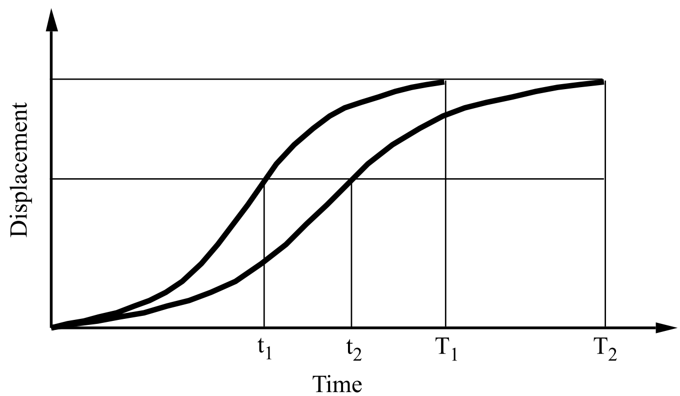

Fig. 1. Scaling effect of movement speed on displacement profiles. The two motions shown are of the same magnitude but completed in T_1 and T_2 of time.

exerts a scaling effect on the hand displacement profile: the two displacement profiles are of similar, typically sigmoidal shape, and if plotted on the same time scale, one would superimpose the other. An alternative way to interpret this time-scaling effect is that, regardless of the average speed used to perform the movement, identical hand positions are assumed at the same fraction of total movement time ($t_1/T_1 = t_2/T_2$ as in Fig. 1). Among many implications regarding arm movement control and organization (see Flash (1990) for a review), this scaling effect suggests that the hand trajectory planning is indifferent to movement speed variation, a mechanism used by the central nervous system (CNS) to simplify the motor command computation (Hollerbach and Flash, 1982).

However, evidence against the scaling effect has also emerged from several experimental investigations of simple arm motions (Zelaznik, Schmidt & Gielen, 1986; Nagasaki, 1989). In such investigations, movement time or speed was systematically varied and the effect rigorously analyzed. Zelaznik et al. (1986) demonstrated, for rapid aimed hand movements, the lack of the time rescalability in the acceleration-time functions, which implies the lack of the time scaling effect on the displacement or velocity profiles discussed above. The study by Nagasaki (1989) revealed that the velocity or acceleration profiles were largely asymmetric, particularly for slow and ballistic arm motions, and that the value of an asymmetry measure – the ratio of acceleration versus deceleration time – was speed-dependent. This again contradicts the scaling effect (note though the asymmetry alone does not necessarily violate the scaling). In addition to the empirical studies, a theoretical model based on neural networks (Bullock & Grossberg, 1991) was able to predict that velocity profiles should not be perfectly symmetric but rather be right-skew for short duration motions and left-skew for long duration motions. These predictions agree well with the empirical findings from Nagasaki's (1989) work.

A complete kinematic description of a reaching movement encompasses more than just the hand trajectory. In fact, a point-to-point reach with a straight hand path simply cannot be executed by moving a single segment but requires coordinated motions of at least the forearm and upper arm. Extended reaches towards targets that are more than an arm length away may also involve significant trunk motions (Kaminski, Bock & Gentile, 1995). While incorporation of multiple segments in a movement study entails complexities such as kinematic redundancy, it facilitates gaining more comprehensive insights into motion control and planning mechanism employed by the CNS (Flash & Hogan, 1985). In this context, a consequent question is whether or not the kinematic profiles of multiple joints exhibit the above described speed-insensitivity or time-scaling effect. This question has not been addressed in a quantitative and systematic fashion. In a few studies that considered multiple body segments (Kaminski & Gentile, 1989; Kaminski et al., 1995), movement time or speed was not an experimental factor systematically being varied. What these studies did show, nevertheless, was the similarity in appearance between hand and joint motion profiles, which inspires in-depth investigation of the time-scaling effect during multisegment movements.

Quantitative assessment of the speed effects on multisegment movement poses a methodological challenge. Such assessment must rely on a mathematical characterization of movement profiles, which itself merits exploration. Zhang and Chaffin (1997) demonstrated the voluminous nature of movement data, and proposed a polynomial regression scheme for data compression and characterization. Faraway (1997) developed a functional regression analysis method to model movement data as multiple curve-type responses. Spline functions have also been employed for fitting kinematic data or biomechanical data in general (Nagasaki, 1989; Wood & Jennings, 1979; Zernicke, Caldwell & Roberts, 1976). One limitation with these mathematical modeling techniques is that they do not allow further statistical analysis and physical interpretation. While the parameters in regression equations can be used for additional analysis, they hardly relate to any physical meaning. Ordinary spline fitting does not seem to facilitate further analysis due to the fact that the piece-wise fitting may yield too many parameters. Nevertheless, certain stereotyped forms (e.g., sigmoidal) of movement profiles can be well characterized using mathematical models with a manageable number of meaningful parameters. For instance, Boston, Rody, Mercer and Kubinski (1993) succeeded in utilizing hyperbolic tangent functions with four parameters (initial angle, final angle, midpoint time, and rise time) to accurately describe the lower extremity kinematics during lifting activities.

The purpose of this work was to quantitatively assess the effects of speed variation on the joint kinematics during multisegment seated reaching movements. These movements were discrete, volitional, non-ballistic reaches with simple hand trajectories but significant torso involvement. We conducted an experiment in which volunteers performed such movements using two distinct speed modes. We used hyperbolic tangent functions with four parameters to mathematically characterize the joint angle profiles, and employed analysis of variance to examine the speed effects on the resulting parameter values.

2. Methods

2.1. Experimental procedures

Six young adults (three males and three females; average age: 24 ± 2.7) volunteered to serve as the subjects. All subjects were right-hand dominant and none reported any neurological or muscular discomfort or abnormality at the time of experiment. The use of human subjects as well as the experimental protocol was approved by the University of Michigan Human Subject Review Committee.

The experiment incorporated three types of seated reaching task, distinguished by their general directions of hand motion – forward, rightward, and upward. As depicted in Fig. 2, each type was performed at four hand path locations created by varying the height, distance to the body, and asymmetry relative to the torso. The height for forward and rightward reaches was set at either the shoulder or hip height; the distance to the body at an upright

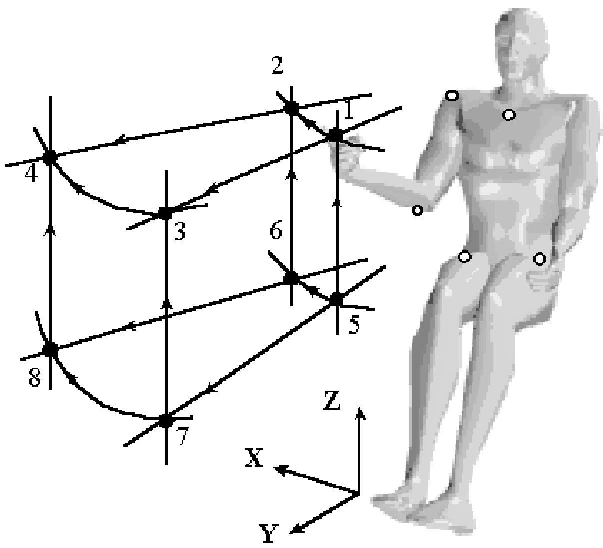

Fig. 2. Three types of seated reaching tasks completed by the subjects were distinguished by the general directions of hand motions – forward, rightward, and upward. Each type was performed at four different hand path locations. The arrows indicate the directions of 12 hand trajectories. Open circles represent the reflective markers placed over surface bony landmarks including the right wrist fold on the dorsal surface of the hand (invisible for particular posture shown), the right lateral epicondyle of the elbow, the right acromion process, the suprasternale notch, the right and left anterior–posterior iliac spine (ASIS). These markers were captured by a four-camera MacReflex™ motion analysis system.

resting position for rightward and upward motions was set in either 60% or 120% of a subject's arm reach; the angle of asymmetry was either 0° or 45° from the sagittal plane. Note that the former two dimensions were scaled with respect to the individual anthropometry of a subject. It was intended that these movements had diverse hand paths and covered an extensive portion of the normal right-hand maximum reach envelope. A wooden apparatus was built to facilitate guiding, without perturbation, the hand motions. The 12 hand paths roughly intersected with each other at eight points, as identified in Fig. 2. These numbered points were used for codifying the movements. For instance, a forward reach along a shoulder height path with 0° offset angle would be conveniently coded as '1–3'.

It was realized that to control and enforce an exact movement speed would be extremely difficult. Rather, the subjects were instructed to complete each movement along one of the hand paths using either a normal, self-paced speed mode or a faster, motivated speed mode. This latter speed mode was similar to the 'speeded-up' conditions as described in Schmidt (1980). But both speed modes were supposed to be within a volitional range. Two repetitions of identical movement conditions (hand path location and speed mode) were performed. Therefore, each subject completed a total of 48 movement trials (3 types × 4 hand paths × 2 speed modes × 2 repetitions) in a randomized order. Prior to the trials that were actually being recorded, there was a practice session for the subjects to acquire sufficient familiarity with the experiment.

Reflective markers were placed on subjects' surface bony landmarks including the right wrist fold on the dorsal surface of the hand, the right lateral epicondyle of the elbow, the right acromion process, the suprasternale notch, the right and left anterior–posterior iliac spine (ASIS). The 3-D coordinates of these markers during the movements were recorded at a sampling frequency of 25 Hz by a four-camera MacReflex™ motion analysis system.

A linkage representation of the upper torso and right arm, as illustrated in Fig. 3, was constructed from the measured locations of the markers. In doing that, the coordinates of surface markers on the wrist, elbow, and acromion process were translated into those of the corresponding internal joint centers using a technique developed by Nussbaum, Zhang and Chaffin (1999). The bottom of the torso segment was assumed to be at the bisection of the two ASIS markers. Seven degrees of freedom (DOF) were embedded in the linkage to describe the joint kinematics: torso flexion/extension (θ_1), torso lateral bending (θ_2), torso twisting (θ_3), shoulder flexion/extension (θ_4), shoulder abduction/adduction (θ_5), humeral rotation (θ_6), and elbow flexion/

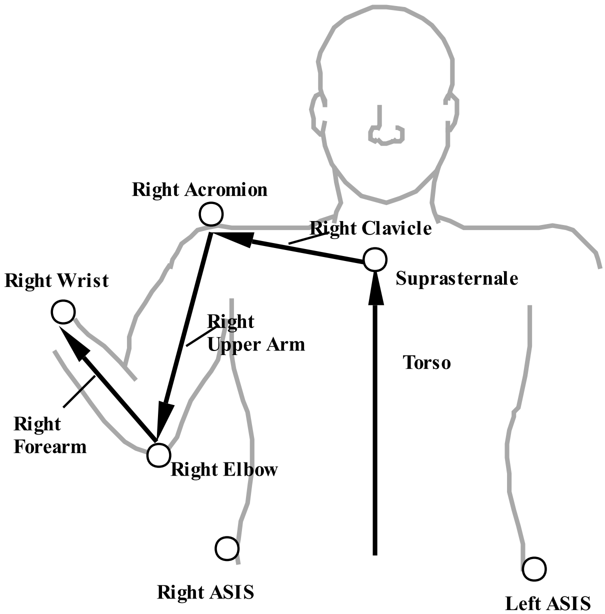

Fig. 3. A linkage representation of the upper torso and right arm. Based on this linkage, seven joint angles were derived from the measured locations of 6 surface markers placed at the right wrist, right elbow, right acromion, suprasternale, right and left ASIS.

extension (θ_7). Based on this linkage representation, profiles of seven joint angles, defined as Euler angles quantifying the seven DOF, were derived for the measured movements.

2.2. Joint angle profile characterization

Our initial inspection of the angle profiles revealed that they mostly were of a sigmoidal form. Two alternative models could be possibly used to mathematically characterize such a form: one derived using dynamic optimization (Flash & Hogan, 1985), and one based on hyperbolic tangent (tanh) functions (Boston et al., 1993). The first model allows only two parameters and is restrictive in that it implies a perfect symmetry in the bell-shaped velocity profile – this symmetry was found to be absent in joint kinematics (Abend et al., 1982; Kaminski & Gentile, 1989; Morasso, 1981) and even in hand motion trajectories (Nagasaki, 1989; Zelaznik et al., 1986). In contrast, the second model has less constraints and affords the flexibility of accommodating various sigmoidal forms. Therefore, we elected to apply the latter model as described in the following.

If we use $\theta_i(t)$ to represent a joint angle at a time frame t ($i = 1, \ldots, 7$; $t = 0, \ldots, T$), the mathematical model can then be expressed as

$$\theta_i(t) = c_1 + c_2 * \tanh\left(\frac{t - c_3 T}{c_4 T}\right), \quad (1)$$

where c_1 is the constant offset that determines the absolute values of the angles, c_2 the span of the profile that characterizes the total angular displacement, c_3 determines the time to reach the peak velocity, and c_4 characterizes the rate of angular change (i.e., the 'slope') for the primary ascending or descending portion of a sigmoidal profile. In other words, c_1 and c_2 determine the position of the profile on a 2-D angle-versus-time coordinate system, while c_3 and c_4 characterize the shape of the profile. For a profile that has an idealized symmetric sigmoidal shape, c_1 equals the average of the initial and final angles $(\theta_i(0) + \theta_i(T))/2$; c_3 equals 0.5; c_2 equals $(\theta_i(0) - \theta_i(T))/(2 * \tanh(0.5/c_4))$ and becomes asymptotically close to half of the total angular displacement $(\theta_i(0) - \theta_i(T))/2)$ when c_4 is sufficiently small. [1] Notice that the c_3 value essentially quantifies the degree of symmetry in the profiles, particularly in the velocity domain – the velocity profile is left-skew if c_3 is less than 0.5, and right-skew if greater than 0.5.

We utilized a non-linear least square curve fitting approach to determine the parameter values of angle profiles for the measured movements. This approach searches a set of four parameters that results in the best fit, as indicated by a maximum R^2, between the model and the actual profile. Essentially a non-linear optimization routine, the search is facilitated by setting good initial estimates of the parameters. We consulted the results presented by Boston et al. (1993) and set the initial values as: $c_1 = (\theta_i(0) + \theta_i(T))/2$, $c_2 = (\theta_i(0) - \theta_i(T))/2, c_3 = 0.5$, and $c_4 = 0.25$. Our approach, however, differed from the approach used by Boston et al. (1993) in that they allowed only two variables (c_3 and c_4) in the curve fitting process. By allowing more parameters to vary, the current approach can potentially fit the movement profiles more accurately.

We developed a Mathematica® computer program to execute the above data characterization procedures in a batch processing mode. Individual

[1] $\tanh[2] = 0.964, \ \tanh[3] = 0.995$.

angle profiles were the input to this program. The output for each profile included the resulting model parameters and the coefficient of determination (R^2). In order to be included in subsequent statistical analysis, an individual angle profile had to meet at least one of the following two criteria: (1) the angular change is greater than 5°; (2) the R^2 is greater than 0.9. Failure to meet either of the criteria would suggest the corresponding joint motion was unlikely to be involved in a particular movement – it had not only an insignificant magnitude but also an erratic, uncharacterizable pattern.

2.3. Statistical analysis

The parameter values resulting from characterization procedures and subjected to statistical analysis formed a complex and possibly unbalanced data structure. Every movement, performed by a specific subject along a specific hand path (see Fig. 2) using either a self-paced or a faster speed mode, comprised multiple (up to seven) angle profiles. Each angle profile corresponded to four parameters, suggesting a multivariate nature for the analysis. Among the parameters, c_1 and c_2, which define the initial and final postural angles, are more position-dependent than c_3 and c_4. The complexity was further compounded by the fact that the set of active joint angles (which met at least one of the above two criteria) for a movement along the same path might vary from trial to trial when performed by a different subject or using a different speed mode, or even when repeated by the same the subject. A change in the active joint angle set for the same movement (along the same path by the same individual) implies a re-apportionment of displacement among the angles. On the other hand, if the apportionment remains consistent for the same movement, c_1 and c_2 parameter values are unlikely to be affected by speed mode or repetition.

We analyzed the data in two ways. We conducted multivariate analysis of variance (MANOVA) in an attempt to examine whether the speed variation significantly affected the overall profile shape. This MANOVA treated the four parameters as the collective dependent variable, the subject and speed mode as the independent variables, and used Wilk's lambda as test statistic. Consequently, the analysis was administered in an angle-by-angle fashion for each hand path location. In the event that different sets of joint angles were activated, it was done only on the subset of angles that were common to all subjects and both speed modes. Whenever the MANOVA detected a significant (P-value < 0.05) or marginally significant (P-value < 0.1) overall effect, the P-values for individual parameters were further inspected to determine which specific parameter(s) mainly contributed to the difference. Additionally, recognizing that the MANOVA might not discern statistically significant effects on individual parameters, we also performed uni-variate analysis of variance (ANOVA). The analysis was separate for each general type of reaching movement, provided that there existed some degree of consistency in the participating joint angle sets across four hand paths within each type. Otherwise, the analysis was further divided into different hand paths. For the former situation, hand paths would be one of the independent variables, along with the speed mode and subject.

3. Results

First of all, a *t*-test confirmed that the average speed used to complete a reaching motion under a normal, self-pace mode was significantly different ($P < 0.0001$) from the one under a faster, motivated mode. The average movement time was 0.83 s ($\pm$0.13 s) for the former speed mode and 0.55 s ($\pm$0.09 s) for the latter. This ensured that two distinct levels of speed were generally achieved.

In general, neither speed mode nor repetition affected which joint angles were involved in a particular movement. There were only two exceptions, both caused by speed difference, out of 144 pair-wise comparisons. In other words, regardless of speed variation, the same set of joint angles was being activated (according to the criteria established earlier) when the same movement was performed by the same individual. Fig. 4 graphically depicts the active joint angles involved in different reaching movements performed by different subjects. As can be seen from the figure, forward reaches involved almost all the seven joint motions, whereas the rightward and upward reaches mainly relied on torso twisting and arm motions. Within each general type of movement, while the active angle set depended on where and by whom a movement was performed, there was a high degree of consistency across various hand paths. This consistency seemed to facilitate the uni-variate ANOVA being conducted at a movement type level.

Profiles of the involved joint angles were accurately characterized by the mathematical model based on hyperbolic tangent functions. The R^2 values resulting from the non-linear curve fitting processes had the following descriptive statistics ($n = 1280$): mean = 0.99; standard deviation = 0.028; median = 0.998. Such a superior level of accuracy endorsed the use of four

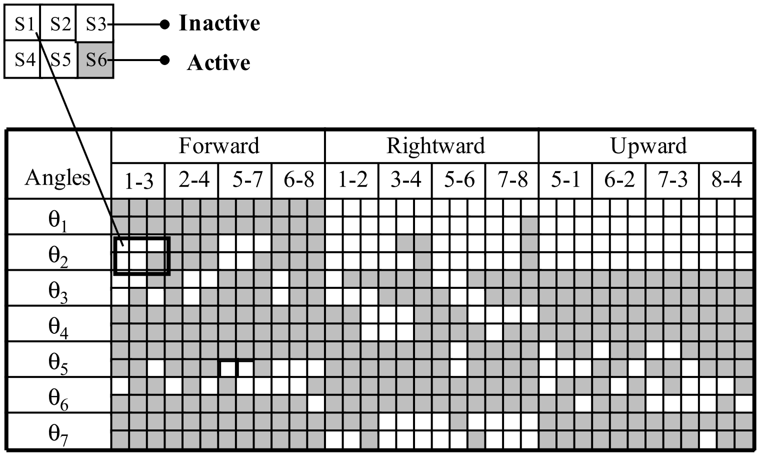

Fig. 4. Joint motions that were actively involved in different reaching movements when performed by different subjects. Each six-square unit contains the binary information for six subjects. Two criteria with regard to an individual angle profile were used to assess whether the corresponding joint motion was active or not.

parameters to represent the reaching movements considered in this study, and also justified further statistical analysis on the parameter values.

The MANOVA, using four parameters as either a collective or individual dependent measure, was conducted only on the angles that were common to at least five subjects (i.e., at least five squares within the six-square unit were highlighted in Fig. 4). Table 1 presents the angles qualified for the analysis and ones found to be significantly affected by the speed mode. There were eight cases (asterisked in Table 1) out of 42 (highlighted in Table 1) in which speed variation had a significant or marginally significant effect on the four parameters as a whole. For six out of these eight cases, the significant difference in overall shape seemed to be chiefly reflected in c_3 and c_4. More specifically, a faster speed mode caused an increase in c_3 value and/or a decrease in c_4 value.

Table 2 summarizes the significant effects identified by the uni-variate ANOVA on individual parameters. Note that the parameters for multiple joint angles were grouped in this analysis, which makes the test less discriminating in detecting significant difference. This influenced largely the more heterogeneous c_1 and c_2 values but minimally the c_3 and c_4 values which were fairly homogenous across the joint angles. The emphasis, therefore, was placed on the effects found to be significant. Both subject and hand path affected one or more parameter values, particularly on c_3 and c_4. The speed was found to

Table 1
Angles selected (shadowed) for statistical analysis and the ones found to be significantly affected by the speed variation

	Forward				Rightward				Upward			
Angles	1-3	2-4	5-7	6-8	1-2	3-4	5-6	7-8	5-1	6-2	7-3	8-4
θ_1	(shaded)	(shaded)	(shaded)	(shaded) **								
θ_2		(shaded)		(shaded)								
θ_3			(shaded)			(shaded)		(shaded)	(shaded)	(shaded)	(shaded)	(shaded) *
θ_4	(shaded)	(shaded)	(shaded)	(shaded)			(shaded)		(shaded) **	(shaded) *	(shaded)	(shaded)
θ_5	(shaded)	(shaded)			(shaded)	(shaded)		(shaded)				(shaded)
θ_6	(shaded)				(shaded) *	(shaded)	(shaded)	(shaded) **		(shaded)		
θ_7	(shaded)	(shaded)	(shaded)	(shaded)					(shaded)	(shaded)	(shaded) **	(shaded) **

Note: **Significant at a $P < 0.05$ level; *Significant at a $0.05 < P < 0.1$ level.

Table 2
Significant effects identified by uni-variate analysis of variance (ANOVA) on individual parameter values

Effect	Forward				Rightward				Upward			
	c_1	c_2	c_3	c_4	c_1	c_2	c_3	c_4	c_1	c_2	c_3	c_4
(1) Subject			**	**	*	*	**	**			**	**
(2) Hand path				**	**				*	**		**
(3) Speed			**				*	*			**	*
Interaction 1 × 2			**	**								
Interaction 1 × 3			*									
Interaction 2 × 3												

* Significant at a $0.05 < P < 0.1$ level.
** Significant at a $P < 0.05$ level.

significantly affect c_3 and/or c_4 throughout the three types of movement, but not c_1 nor c_2. Fig. 5 compares the mean c_3 and c_4 values between the two speed modes. As the figure shows, the faster speed mode resulted in a greater c_3 value for all the three types of reach, and a smaller c_4 for the rightward and upward reaches. Of further note is that, while the c_3 values varied in a range (SD = 0.09–0.15), the means for the normal, self-paced speed mode across all the three types of movement were approximately equal to 0.5 (which corresponds to a symmetric velocity profile).

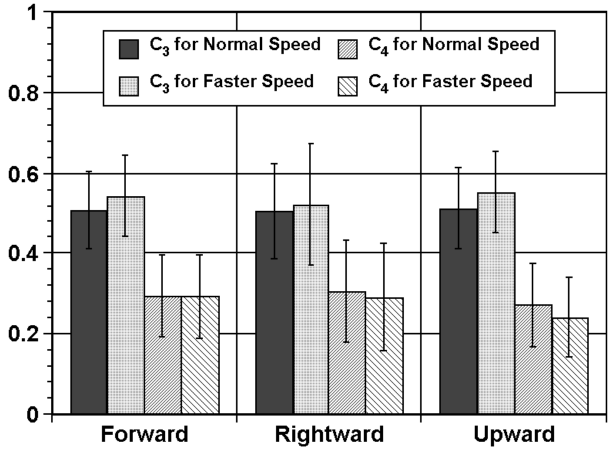

Fig. 5. A comparison of mean c_3 and c_4 values between two speed modes as summarized across each type of reaching movements. Whiskers indicate the standard deviation.

4. Discussion

This study quantitatively assessed the effects of speed variation on the kinematics during multisegment seated reaching movements. It is important to recapitulate the scope of the study: the speed variation was within a volitional, non-ballistic range; the reaching movements were discrete, undisturbed and one-directional (i.e., no reversal motion was involved). This latter stipulation was the basis for employing the particular means of characterizing the movement data. As we have demonstrated, though multisegment reaching movements incur complex postural changes in a three-dimensional space, the joint kinematics of such movements can still be well represented by angle profiles that maintain a sigmoidal form similar to that of the hand trajectory. The representation, nevertheless, has to rely on a biomechanical linkage model that possesses adequate degrees of freedom to account for the major motions involved. We have shown that the sigmoidal angle profiles can be described in an accurate and compact fashion by four-parameter hyperbolic tangent functions, with each of these parameters characterizing one specific kinematic aspect of an angle profile.

The speed variation may possibly exert its effect on a multisegment movement at several levels: (1) which joint angles are selected to complete the movement, (2) the amplitude of the joint motions that are involved, and (3) the pattern of how joint angles change over time (i.e., the profile shape).

The results from this study indicated that neither the joint angle selection nor the amplitude of the selected angle motions was significantly influenced by the speed variation. In other words, movement organization at these two levels was robust or indifferent to the changes in task variables such as speed. This indifference may however hinder the detection of significant change(s) occurring at a lower level. In our MANOVA intended to examine the effects on the overall shape of the profiles, since two out of the four parameters (c_1 and c_2) were unaffected, the significant effects on c_3 and c_4 were elusive and only partially revealed. More discerning was the subsequent uni-variate ANOVA on the individual parameters. However, the difference in time-normalized displacement profile, caused by a statistically significant speed effect, may not seem salient qualitatively. Fig. 6 presents the reproduced profiles (from the parameters averaged across subjects) under two speed modes for one particular joint motion for which the effect was significant and most pronounced. The largest discrepancy between the two normalized displacement profiles was 4° (8% of the total displacement). In the velocity or acceleration domain, the effect is likely to be more conspicuous.

Thus, the scaling effect of movement time or average speed, in a strict sense, was not present in the joint kinematics. More specifically, the current study provides evidence suggesting that a faster speed induces a steeper rate (time-scaled) for the primary descending/ascending but a greater fraction of total time for accelerating phase (where the velocity and acceleration are in

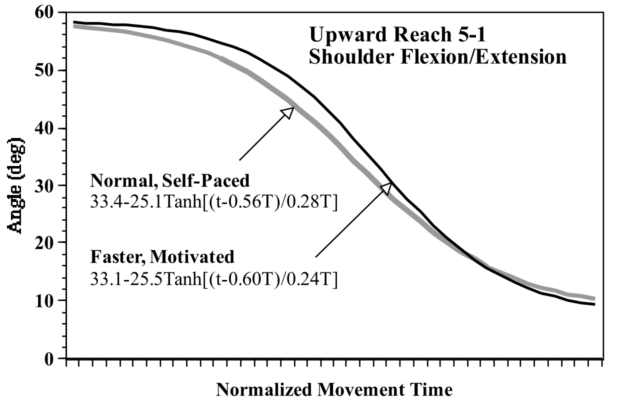

Fig. 6. A comparison of the displacement profiles under two speed modes for one particular movement for which the speed effect was statistically significant and most pronounced. The profiles were reproduced from the parameters averaged across six subjects.

the same direction). In the velocity domain, such a change is manifested as a narrower but taller time-scaled velocity profile with the inflection point more to the right. Although for the faster speed mode there were both left-skew and right-skew velocity profiles, the latter were predominant – about 65% of the c_3 values for the faster speed mode were greater than 0.5. The right-skewness means that the accelerating phase is longer than the decelerating phase. In fact, regardless of the speed mode, a symmetric bell-shaped velocity profile was generally not retained for the multiple joint angular motions. The variability in c_3 values was substantive for both speed modes (see Fig. 5).

The lack of both speed scaling effect and profile symmetry in joint kinematics disclosed in this study converges nicely with what was found for hand trajectories by Zelaznik et al. (1986) and Nagasaki (1989). The general trends of speed-dependent profile characteristics were resoundingly consistent, particularly between the current study and the one by Nagasaki. For instance, the k values (equivalent to the c_3 in this study) presented in Nagasaki's (1989) work not only revealed a greater fraction of total time for acceleration during a faster reaching motion, but also formed a distribution comparable to that of the c_3 values in this study. The converging evidence collectively may lead to a conjecture in a broader context. That is, under 'speeded-up' conditions during reaching movements, the motor system tends to temporally over-accelerate the entire dynamic system in a synergetic fashion.

Abundant previous studies have either concluded or endorsed the symmetry and speed-scaling effect for hand trajectories during reaching motions (Abend et al., 1982; Flash & Hogan, 1985; Kaminski & Gentile, 1986, 1989; Morasso, 1981; Soechting & Lacquaniti, 1981). Some of these studies and others nevertheless have presented data suggesting the absence of symmetry in joint kinematics (Abend et al., 1982; Kaminski and Gentile, 1989; Kaminski et al., 1995; Morasso, 1981). Flash & Hogan (1985) even pointed out that a perfect symmetry signifies invariances in joint motions which would be incompatible with the invariances in hand trajectory. Seemingly, there exists a contradiction with respect to the speed effects on hand motion characteristics between these studies and the ones by Zelaznik et al. (1986) and Nagasaki (1989). While our findings favor the latter two studies given the convergence discussed above, we attribute the contradiction to a lack of systematic variation of speed factor and a lack of quantitative analysis with the former studies. As demonstrated in the current study, the effect of speed variation on movement profiles can be subtle and somewhat elusive, and might not have been discerned by qualitative assessment.

It is recognized that the use of parametrized hyperbolic tangent functions for movement data characterization is restricted to the sigmoidal profile form. While such a form seems typical for smooth non-reversal movements, there are a plethora of forms of movement profile for which our mathematical model is not applicable. On the other hand, demonstration the scaling effect or the lack of does not require a stereotyped form of the movement profiles. Therefore, using novel mathematical models for movement characterization, in conjunction with the framework outlined in the current study, it is possible to quantitatively examine the speed effects extensively for more diverse human movements.

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