

Trunk-Assisted Prehension: Specification of Body Segments With Imposed Temporal Constraints

Rachael D. Seidler
George E. Stelmach
Motor Control Laboratory
Arizona State University

ABSTRACT. The authors used a trunk-assisted prehension task to examine intersegment coordination. Participants ($N = 7$) reached to grasp an object placed beyond full arm extension, thus requiring trunk flexion to achieve the target object, under 4 varying temporal constraints. Kinematic analyses were performed in which the motions of the arm, the trunk, and the endpoint were characterized. The spatial trajectories and the segments' peak velocity data revealed that under high temporal constraints the arm was more responsible for endpoint motion than the trunk, whereas in the unconstrained condition the trunk was more involved. In addition, the arm exhibited a decline in spatial variability toward the end of the movement in all conditions, whereas the trunk did not. The present study is the first to show that when temporal demand is increased for a trunk-assisted prehensile task, the arm plays a larger role than the trunk in the transport of the hand to the object. The data also suggest that the arm participates in the fine accuracy control of the reach, whereas the trunk does not.

Key words: coordination, prehension, synergy, trunk

People are often confronted with the task of reaching to grasp an object that is located beyond the reach of the fully extended arm. In those instances, the trunk must assist the arm so that it can reach the target object. It has indeed been shown that the trunk not only acts as a postural stabilizer but also contributes substantially to hand transport for both prehension (Saling, Stelmach, Mescheriakov, & Berger, 1996) and aiming tasks (Kaminski, Bock, & Gentile, 1995). How the control system coordinates the trunk with arm movement to achieve the transport of the hand to the object is not well understood. There are a multitude of potential combinations of arm and trunk motions that can transport the hand to any given object. Through investigation of the segment combinations that the control system selects under various constraints, the problem of how kinematic redundancy is solved by the control system can be understood (Flash, 1990).

In one theory put forth to explain how the control system solves the degrees of freedom problem, it is suggested that several segments (or muscles) are constrained to act as a unit, or synergy (Bernstein, 1967). In bimanual tasks, for instance, the two arms often perform movements with identical relative timing, such that movements for each arm are initiated and completed simultaneously despite differing constraints imposed for each arm (Kelso, Southard, & Goodman, 1979; Tresilian & Stelmach, 1997). Evidence for synergy control in reaching movements involving the trunk has come from Ma and Feldman (1995). They instructed participants to point to a target, using only the arm, the arm plus the trunk in phase, and the arm plus the trunk out of phase. Despite the changing involvement of the trunk across conditions, the fingertip trajectory remained smooth and unchanged. The authors thus inferred that the participants used two independent synergies to control the reaching movement, one that shifted the fingertip to the target and another that provided compensatory actions such that the fingertip trajectory remained unchanged from trial to trial despite the varying involvement of the trunk. Similarly, Wang and Stelmach (1998) found that, despite varying contributions of the arm and the trunk to the transport task, the aperture formation remained constant in a trunk-assisted prehension task.

Rosenbaum and his colleagues (Rosenbaum, Engelbrecht, Bushe, & Loukopoulos, 1993; Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995) have proposed a cost-based model that selects the body segments involved in a movement and determines to

Correspondence address: George E. Stelmach, Motor Control Laboratory, Arizona State University, P.O. Box 870404, Tempe, AZ 85287-0404. E-mail address: stelmach@asu.edu

what extent they contribute to motion of the endpoint to the target. This model is called the *knowledge model*. It is assumed in the model that the cost of segment involvement is determined by joint stiffness, friction, and the segment's inertia. Cost is determined in part by how well a segment's resonant frequency matches the desired amplitude and duration of the movement to be performed; differential weighting can be placed on the costs of spatial error and limb travel. The authors defined the level of involvement of each segment by its peak angular velocity and displacement that occurred during the task. In other words, body segments that travel farther, faster, or both are assumed to have a greater involvement in the task than those that do not. Thus, segment involvement is related to the role played in bringing the hand to the target. Predictions made on the basis of the model suggest that body segments with greater mass would be more involved for slower movements, whereas segments with less mass would become more involved for faster movements, because the resonant frequency for those segments would more closely match the desired movement duration. Data from cyclic movements have provided support for those predictions (Rosenbaum, Slotka, Vaughan, & Plamondon, 1991); however, the predictions appear to hold up only partially for discrete, goal-directed actions (Fischer, Rosenbaum, & Vaughan, 1997; Schillings, Meulenbroek, & Thomassen, 1996).

Recently, Saling et al. (1996) investigated the role of the trunk in prehensile actions by varying the size of the object to be grasped and therefore the spatial accuracy constraints. The object was placed such that the participant had to use the trunk to extend the reach. The investigators found that changing the size of the object to be grasped had very little effect on the trunk kinematics. Rather, adjustments were made in the timing of the arm movement. The trunk contributed the same amount to endpoint peak speed regardless of whether the reach was performed to the large or the small object. Those results suggest that the trunk plays only a general transport role in prehension tasks with differing levels of spatial accuracy.

Our purpose in this study was to use a trunk-assisted prehension task to examine whether body segments are differentially involved when various temporal constraints are imposed. We hypothesized that trunk movement would be smoothly coordinated with arm transport. In addition, we predicted that the arm would contribute more to the reach under conditions of high temporal constraint, regardless of whether the movement was fast or slow, because making corrections is easier with the lower inertia arm segment than with the trunk. If the arm is more involved with a slow but temporally constrained movement, that finding would imply that a segment's involvement is not determined solely by how well its resonant frequency matches the required amplitude and duration of the movement but rather by how precisely the segment can be positioned, both temporally and spatially. In addition to examining whether segment contributions vary with temporal constraints, we analyzed

spatial trajectories and variability in order to determine the nature of the roles played by the arm and the trunk in achieving endpoint motion to the target.

Method

Participants

Seven right-handed participants were recruited from the Arizona State University campus to participate. The participants were 29.7 ($SD = 4.7$) years old. After hearing an explanation of the experiment, the participants decided whether they wanted to volunteer. If they did, they provided written informed consent in accordance with human subjects policies. Their participation, which took an average of 1 hr, fulfilled class experimentation requirements.

Procedure

We recorded movements by using an Optotrak (Northern Digital, Inc., Waterloo, Ontario) optoelectronic recording system sampling at 100 Hz. Infrared light-emitting diodes were placed over the participants' thumb and index fingernails, the wrist (radial aspect of the distal styloid process), and the middle of the sternum. The target object (a cylindrical Plexiglas dowel, 12 cm high, 1 cm diameter) was placed 30 cm beyond the reach of their fully extended arm, 5 cm to the right of the body midline. Participants were instructed to begin each movement from the same posture, which was monitored closely by the investigator. They began the movement sitting upright in the chair, with their upper arm perpendicular and their lower arm parallel to the floor, resting on the table. The fingers were slightly flexed so that the thumb and index finger made contact.

Trials were collected under four conditions of varying temporal instructions. Participants were instructed to move at a comfortable pace in Condition 1 (slow speed, no temporal constraint), following an auditory go signal from the experimenter, and as fast as possible in Condition 3 (fast speed, high temporal constraint). Participants in Conditions 2 and 4 were asked to pace their movements to the beat of a metronome such that they began the prehensile movement on one metronome beat and grasped the object as the next beat occurred. Participants were allowed to begin moving on either the first or second metronome beat following the imperative signal. Condition 2 was a slow-paced movement with a temporal target of approximately 950 ms (slow speed, high temporal constraint), whereas Condition 4 was a fast-paced movement with a temporal target of approximately 650 ms (high speed, high temporal constraint). Twenty trials were performed for each condition, with all participants following the sequence of C1, C3, C2, and C4. Participants were allowed to practice before each condition as desired.

Data Analysis

We used a residual analysis to estimate the appropriate cut-off frequency needed to smooth the data (Winter, 1990).

As a result, we smoothed all marker data with a dual-pass Butterworth digital filter, using a cut-off frequency of 8 Hz. The resultant speed of the wrist and trunk markers was computed with respect to an external reference frame. In addition, the resultant speed of the wrist marker relative to the trunk was computed. Movement of the wrist marker in the external reference frame thus reflected the combined actions of the trunk and the arm (termed *endpoint motion*), whereas movement of the wrist marker relative to the trunk reflected the actions of the arm musculature and any transfer of momentum from the trunk to the arm (termed *arm motion*). We obtained acceleration data by differentiating the speed profiles. We used the optimal algorithm of Teasdale, Bard, Fleury, Young, and Proteau (1992) to determine movement onset from the speed profiles. The algorithm works as follows: Locate the sample at which the velocity time series first exceeds 10% of its maximum value (V_{max}); working back from that point, stop at the first sample (call it S) that is less than or equal to $([V_{max}/10] - [V_{max}/100])$; find the standard deviation of the series between Sample 1 and Sample S (call this SD); working back from S , stop at the first sample that is less than or equal to $S - SD$; that is the onset sample. We used the same algorithm in reverse to determine movement offset for the trunk. Aperture formation and endpoint motion were considered to be completed at the time of object grasp (participants lifted the dowel upon grasping it).

Variables computed for the trunk, arm, and endpoint motion included amplitude of peak speed, acceleration, and deceleration, the absolute and relative time to each of those events, the total movement time for each segment, and the cumulative distance traveled in the x (lateral), y (anterior-posterior), and z (vertical) directions for each segment. The aperture formation was calculated as the difference between the finger and thumb markers. Variables computed to describe aperture formation included peak aperture amplitude and the absolute and relative time to this peak amplitude. The trial-to-trial spatial variability was computed for the trunk, arm, and endpoint paths as follows: After filtering, the spatial trajectories were time normalized to 100 samples, averaged across condition for each participant, and then the standard deviation was computed for the x , y , and z directions. The spatial variability was calculated as the square root of the sum of the variances in each direction. The within-participant spatial variability was then averaged across the participants for each condition. For each component, we computed a linear fit for the portion of the curve before and after the peak in order to characterize changes in spatial variability throughout the movement. We also computed the number of zero crossings in the acceleration profiles for each body segment to get an estimate of the number of corrective adjustments performed throughout the movement.

We used a within-participant univariate analysis of variance with repeated measures on condition (temporal constraints, four levels) to determine how performance varied

across condition for each measure. We evaluated the Huynh-Feldt epsilon (Huynh & Feldt, 1970) to determine whether the repeated measures data met the assumption of sphericity ($> .75$). Because the sphericity assumption was met for each variable, we used the univariate tests to maintain power. The observed power was computed for all variables, as was ω^2 , an estimate of the total population variance that is explained by the variation caused by the treatment (Keppel, 1991). Its value does not depend on sample size or power of the experiment. The magnitude can range between .0 and 1.0, with negative values a possibility when the associated F value is less than 1.0. Cohen (1977) suggested that a small effect is comparable to an ω^2 of .01, a medium effect is .06, and a large effect is .15 or greater. Those standards were employed in our assessment of treatment effect sizes.

We computed regressions between variables describing trunk and arm movement and the endpoint motion to determine whether the trunk or the arm contributed more to the transport for each condition. In addition, we computed regressions between the aperture formation landmarks and those of the arm, trunk, and endpoint to determine with which segment the aperture formation was the most tightly coupled. Those regressions were calculated on an individual participant basis for each condition, converted to z scores, and weighted for the degrees of freedom before averaging across participants. We conducted further repeated measures analyses on the z scores, using the values as a dependent measure, to allow for comparisons between conditions.

Results

The observed power for all significant effects reported ranged from .91 to .99. Values reported in the text are means and, in parentheses, standard deviations. Recall that the four temporal conditions were to move at a comfortable pace (C1), paced with a metronome to 950 ms (C2), as fast as possible (C3), and paced with a metronome to 650 ms (C4). Sample aperture and resultant speed data from each condition are shown in Figure 1. The trunk started moving before the arm in an average of 75% (14%) of the trials across the four conditions. As can be seen in Table 1, the number of trials on which the trunk started moving first varied significantly depending on the temporal condition; there was a significant main effect for condition, $F(3, 18) = 5.24, p < .01, \omega^2 = .49$. Follow up contrasts revealed that the frequency of trunk initiation was significantly less in C1 than in C3 and C4, but not in C2 ($p < .01$ and $p < .05$, respectively, for C1 vs. C2 and C4). Table 1 also shows the amount of time by which the trunk motion preceded arm motion, which varied depending on the temporal condition, $F(3, 18) = 8.25, p = .01, \omega^2 = .51$. The values for C1 and C3 were significantly less than those of the temporally paced conditions C2 and C4 ($p < .05$ in all cases). The trunk finished moving later than the arm on 98% (3%) of the trials across the four conditions. The amount of time by which the trunk motion outlasted the arm motion differed across the four conditions,

$F(3, 18) = 3.13, p = .05, \omega^2 = .23$. Follow up contrasts revealed that the duration was shorter for C1 and C2 than for C4 ($p = .05$ and $p = .06$, respectively).

In Figure 2 are three-dimensional spatial plots for 1 representative participant. The paths represent an average of the trials across each condition. The cumulative distance traveled by each segment in each of the three dimensions is presented in Table 2. Those distances varied across condition only for arm motion in the anterior direction; the arm traveled a greater distance with increasing temporal con-

straints, $F(3, 18) = 4.10, p < .05$, suggesting increasing arm involvement. In Figure 3 are plotted the resultant spatial variability of the endpoint, arm, and trunk motion for each temporal condition. Note that little or no change occurred in variability amplitude across the conditions. The plots reflect a group average of the within-participant variability for each condition. In Table 3, we present the r^2 values for the linear fit performed prior to and after the time of the peak spatial variability for each component. For the index finger, thumb, endpoint, and wrist, the r^2 values ranged from .87 to

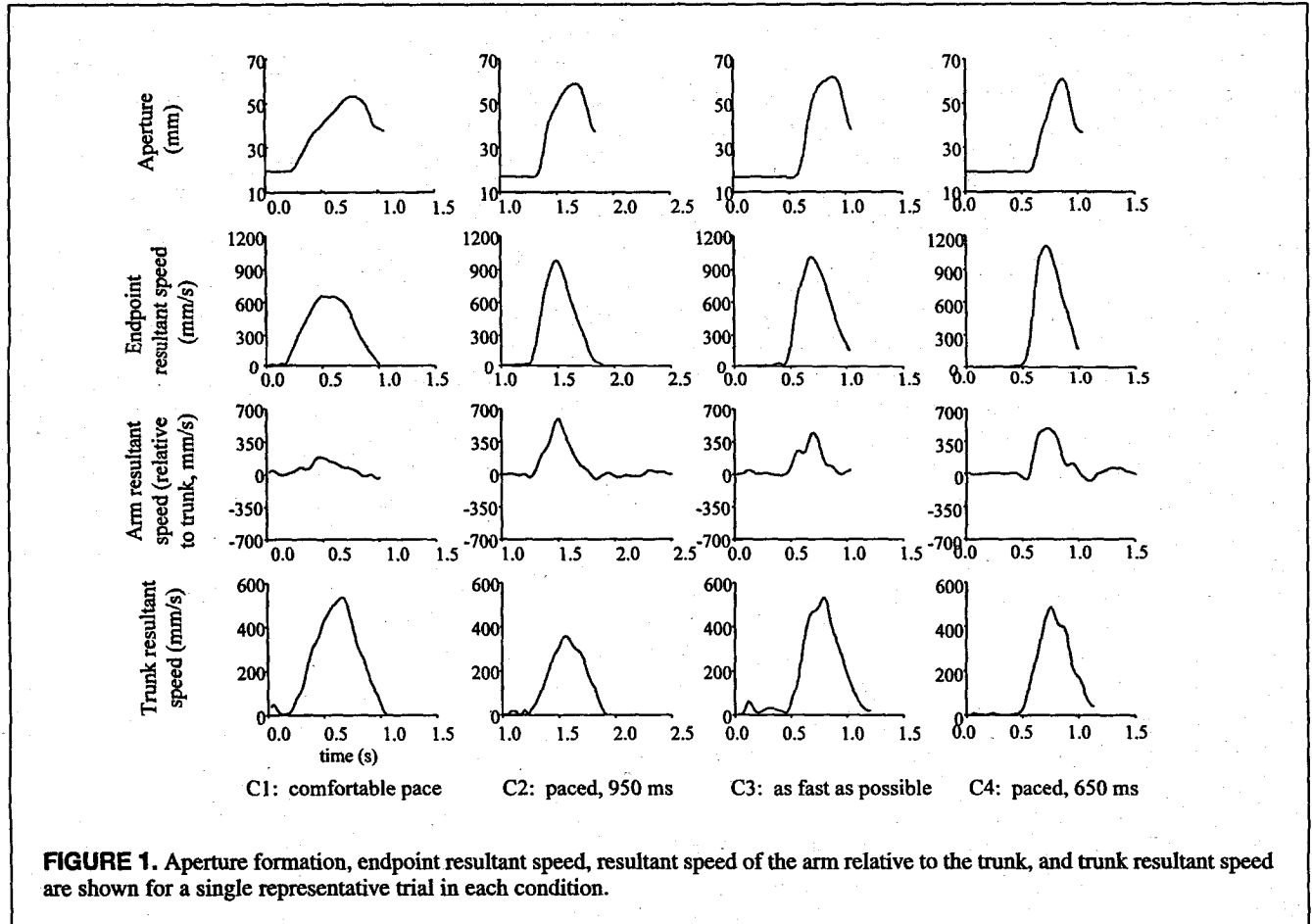


FIGURE 1. Aperture formation, endpoint resultant speed, resultant speed of the arm relative to the trunk, and trunk resultant speed are shown for a single representative trial in each condition.

TABLE 1
Segment Initiation Data: Means and Standard Deviations

Measure	C1		C2		C3		C4	
	M	SD	M	SD	M	SD	M	SD
Frequency of trunk initiation (%)	58	22	69	31	88	15	85	18
Trunk–endpoint onset delay (ms)	21	11	88	49	28	17	60	34
Frequency of trunk completion (%)	96	9	98	4	99	2	100	0
Endpoint–trunk offset delay (ms)	123	68	169	80	189	79	210	71

Note. C1 = comfortable pace, no temporal constraint; C2 = slow paced, 950-ms temporal constraint; C3 = as fast as possible, high temporal constraint; and C4 = paced, 650-ms temporal constraint.

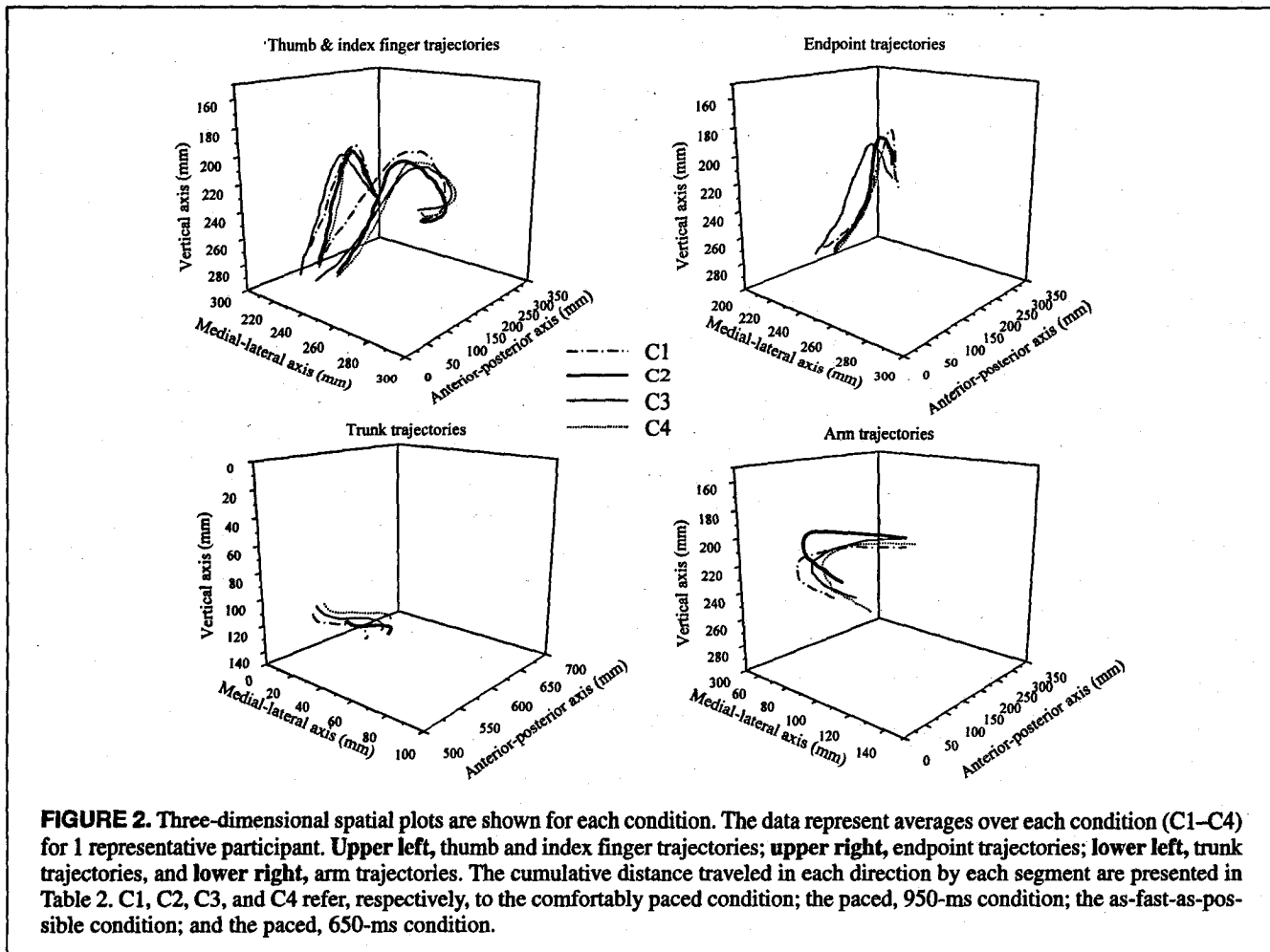
.99 both before and after the peak for all conditions, characterizing the unimodal shape of the curves. The r^2 values for the trunk were high before the peak in all conditions, but remained high after the peak only for the two temporally paced conditions (C2 and C4, see Table 2). Those values reflected the increase in spatial variability seen in the trunk in the first portion of the movement, with little or no decrease in variability in the latter portion of the movement.

Average movement times, peak speeds for each of the segments, and peak aperture amplitude for each of the conditions are plotted in Figure 4. Mean movement time for each condition was 908 ms (74 ms) for the comfortably paced condition (C1), 960 ms (71 ms) for the slow-paced condition (C2), 549 ms (54 ms) for the fast-as-possible condition (C3), and 661 ms (45 ms) for the fast-paced condition (C4). The main effect of condition on movement time was significant, $F(3, 18) = 70.22, p < .001, \omega^2 = .83$. Follow-up, pairwise comparisons revealed that movement time for each of the conditions differed significantly from each other, with the exception of the comparison of C1 with C2 (the two slower conditions).

Peak speed amplitudes, also shown in Figure 4, mirrored the movement time data. There was a significant main effect

of condition on endpoint peak speed, $F(3, 18) = 23.74, p < .001, \omega^2 = .76$, arm peak speed, $F(3, 18) = 10.89, p < .001, \omega^2 = .59$, and trunk peak speed, $F(3, 18) = 39.16, p < .001, \omega^2 = .84$. Follow-up contrasts revealed that endpoint peak speed did not differ between C1 and C2 (the two slower conditions), and differed only slightly between C3 and C4 (the two faster conditions, $p = .05$); all other comparisons for endpoint peak speed were significant. Trunk peak speed differed for each pair of conditions, except C1 and C2. Arm peak speed was significantly different between all pairs of conditions, except C3 versus C4 and C1 versus C2. Peak arm speed and peak trunk speed were significantly different from each other for C1 only ($p < .05$). Inspection of Figure 4 reveals that peak trunk speed was significantly greater than peak arm speed for that condition (366 mm/s [101 mm/s] and 210 mm/s [38 mm/s], respectively).

In Figure 5, correlations between endpoint peak speed and trunk or arm peak speed are plotted for each condition (regressions shown are for 1 representative participant). In Figure 6, we have plotted the mean correlation values for each condition. A repeated measures analysis on the z scores for those correlations revealed a difference in magnitude between z scores describing the relationship between



endpoint peak speed and arm speed compared with endpoint peak speed and trunk speed, $F(1, 12) = 23.19, p < .001$. Paired contrasts demonstrated that there was no difference between the values for C1, $F(1, 6) < 1.0$, whereas the values differed between trunk and arm for C2–C4 ($p < .05$ in all cases).

The peak aperture amplitude followed similar trends as the peak speed and movement time data. There was a significant main effect of condition, $F(3, 18) = 15.44, p < .001, \omega^2 = .67$. Follow-up contrasts revealed that the values for C1 and C2 did not differ from each other (the two slower conditions); nor did the values for C3 and C4 (the two faster

TABLE 2
Cumulative Distance Traveled (cm) in the x (Lateral), y (Anterior–Posterior), and z (Vertical) Dimensions by Each Segment

Segment	Direction	C1		C2		C3		C4	
		M	SD	M	SD	M	SD	M	SD
Arm	x	8.5	3.1	9.0	3.0	8.6	4.0	9.0	3.3
Arm	y	8.9	3.8	10.8	4.3	10.4	4.7	11.5	5.3
Arm	z	3.4	3.6	2.8	3.4	3.9	3.5	3.1	3.0
Trunk	x	1.3	4.1	1.5	.2	1.6	1.2	1.6	.5
Trunk	y	18.5	4.3	18.3	3.5	20.6	4.7	18.6	4.3
Trunk	z	3.2	1.7	3.1	1.7	3.8	2.5	3.6	1.8
End	x	2.5	8.7	2.3	7.0	2.4	9.0	2.2	6.0
End	y	27.1	1.9	27.0	1.6	28.0	1.8	27.6	1.6
End	z	8.3	3.1	8.4	2.3	7.2	3.1	7.7	2.6

Note. C1 = comfortable pace, no temporal constraint; C2 = slow paced, 950-ms temporal constraint; C3 = as fast as possible, high temporal constraint; and C4 = paced, 650-ms temporal constraint.

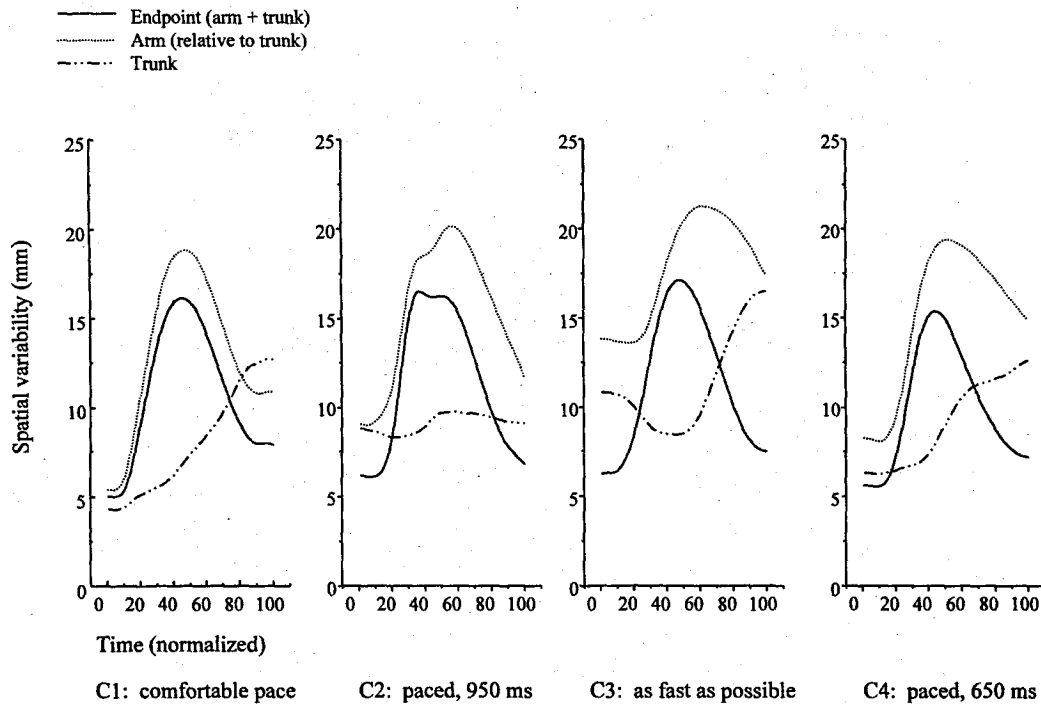


FIGURE 3. Resultant spatial variability has been plotted for the endpoint, arm, and the trunk for each condition. The data shown are the average across participants of the within-participant variability. Note that variability declined toward the end of the movement for all components in all conditions except for the trunk, which showed declines toward the end of the movement only in the temporally constrained conditions (C2 and C4).

conditions). All other pairwise contrasts were significant, however ($p < .01$ in all cases). Correlations were also computed between the time to peak aperture and the time to peak deceleration of the arm, the trunk, and the endpoint. Mean correlation values describing the relationship between aperture and endpoint ranged from .21 to .37 across the four conditions. Mean correlations between the aperture and the arm ranged from .33 to .45, and those between aperture and trunk ranged from .10 to .48.

The average number of acceleration zero crossings for the trunk, arm, and endpoint are shown in Figure 7. Pairwise comparisons revealed that the number of zero crossings was lower for the endpoint than for the arm or the trunk in each condition ($p < .01$, $\omega^2 > .45$, in all cases). In addition, the arm exhibited a greater number of zero crossings than the trunk for the two slower conditions, C1 and C2 ($p < .01$, $\omega^2 > .50$, in both cases).

Discussion

Relative Contributions of the Trunk and the Arm

The arm traveled a greater distance in the direction of the target object for both the fast and the temporally paced

movements than it did for the comfortably paced condition (Table 2), suggesting an increase in the arm's contribution to endpoint motion with increasing temporal constraints. Although only a small increase in distance was observed, that conclusion was supported by the changes in segment peak speed across condition. The peak speed of the trunk was greater than that of the arm in the comfortably paced condition only. That result supports the prediction of the knowledge model that segments with larger inertia play a larger role in slow movements (Rosenbaum et al., 1995). It may be that their larger inertia produces a more stable movement at slower velocities or that their resonant frequency more closely matches the duration of the task. It should be pointed out, however, that stiffness and therefore stability can be modulated at each joint, effectively changing the resonant frequency of the limb (Feldman, 1980; Hogan, 1984; Karst & Hasan, 1987; Seidler-Dobrin, He, & Stelmach, 1998).

For the other three conditions, the arm and the trunk peak speeds were not significantly different, suggesting that both segments played an equal role for the faster and the temporally paced conditions. We computed regression analyses correlating peak speed of the trunk or the arm with the endpoint motion to further explore the contribution of those segments to the movement. The results for the comfortably paced condition supported the peak speed comparisons, with the trunk and the arm playing approximately equal roles for this slow, unconstrained condition. In contrast, the arm was more highly correlated than the trunk with the endpoint in the fast movements and in the temporally paced movements. That analysis extends our understanding of the mechanisms of interjoint coordination by demonstrating that segments with lower inertia play a large role not only in fast movements but also in those movements with specific temporal constraints, regardless of movement speed. Furthermore, the spatial plots demonstrated that arm motion is not entirely in the direction of the reach, but may rather be responsible for orienting the hand to grasp the object, as was suggested by Soechting and Flanders (1993).

The high correlation between arm and endpoint motion in the slow but highly constrained movement suggests that joint precision, in both space and time, should be accounted for in any theory of segment contribution to task performance. What, therefore, is the benefit of using smaller inertia segments for fast or temporally constrained movements? Their lower inertia would allow for faster corrections, if needed (Langolf, Chaffin, & Foulke, 1976). Whereas the knowledge model supports this point for fast movements (Rosenbaum et al., 1993; Rosenbaum et al., 1995), our data suggest that it holds for slow movements with high constraints as well. Indeed, it does appear from our data that the arm plays more of a corrective or compensatory role. In all conditions, the absolute and relative time to peak speed of the arm was more correlated than that of the trunk with endpoint motion, suggesting that arm motion has more of an impact on the temporal profile of endpoint motion. In addi-

TABLE 3
 R^2 Values for the Linear Fit to the Spatial Variability Profiles

	C1	C2	C3	C4
<i>Index finger</i>				
Fit before peak	.95	.97	.98	.98
Fit after peak	.96	.98	.98	.95
<i>Thumb</i>				
Fit before peak	.94	.97	.98	.98
Fit after peak	.96	.98	.97	.95
<i>Endpoint</i>				
Fit before peak	.95	.95	.89	.93
Fit after peak	.98	.99	.98	.98
<i>Arm</i>				
Fit before peak	.96	.95	.88	.87
Fit after peak	.99	.99	.99	.99
<i>Trunk</i>				
Fit before peak	.92	.95	.99	.95
Fit after peak	.25	.87	NA*	.83

*Peak variability occurred at the last sample. C1 = comfortable pace, no temporal constraint; C2 = slow paced, 950-ms temporal constraint; C3 = as fast as possible, high temporal constraint; and C4 = paced, 650-ms temporal constraint. Fits were computed for the data before and after the time of the peak magnitude.

tion, the time to peak aperture of the arm was more correlated than the trunk with time to peak deceleration. Those timing correlations did not vary significantly with movement speed or for the paced versus the nonpaced conditions, suggesting that the relative temporal roles of the arm and the trunk do not vary by condition. We quantified compensatory actions by computing the number of acceleration zero crossings per movement. As can be seen in Figure 7, the number of zero crossings was larger for the arm than for the trunk in the two slow conditions, suggesting that the arm plays a compensatory role for slower movements (Lacquaniti, Ferrigno, Pedotti, Soechting, & Terzuolo, 1987).

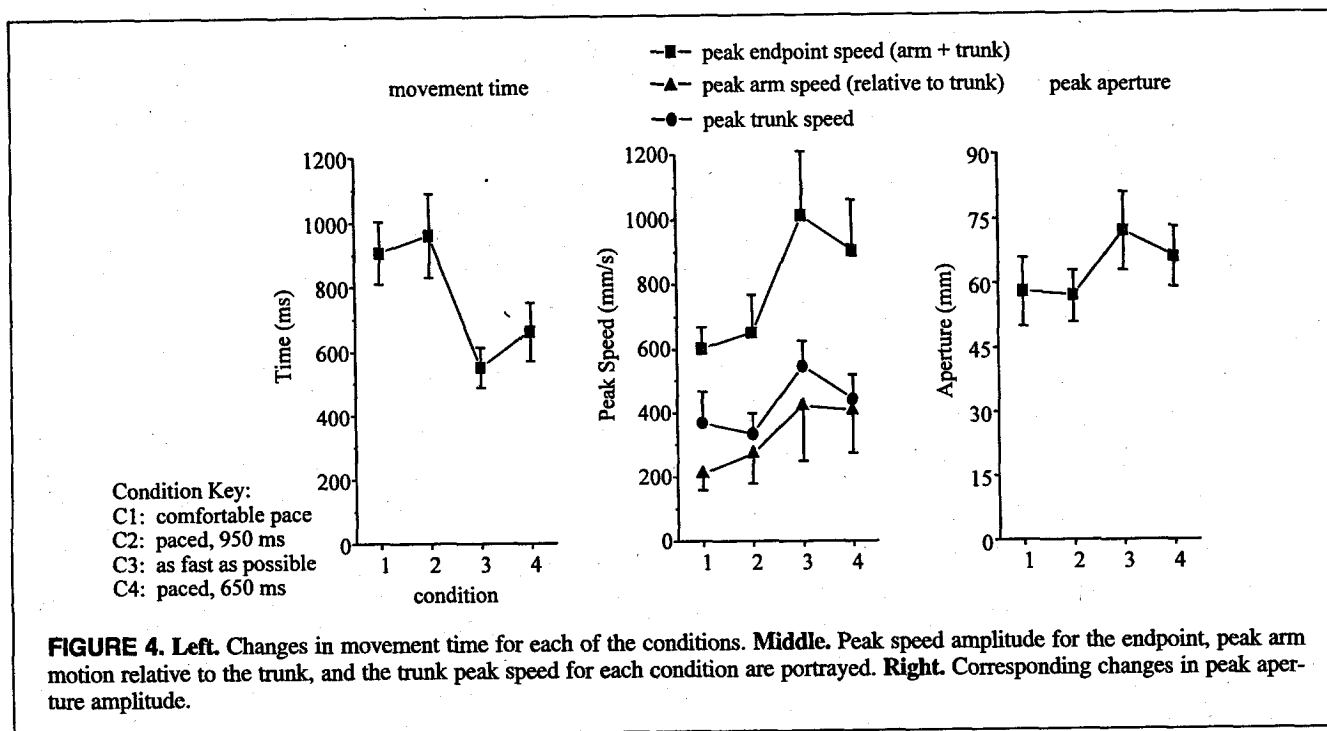
It appears that the arm is crucial in reducing variability as the hand approaches the target object. The patterns of spatial variability found were similar to those obtained by Kudoh, Hattori, Numata, and Maruyama (1997). The spatial variability pattern of the endpoint was unimodal, exhibiting a peak near the time of peak velocity. Spatial variability for the aperture effectors showed an earlier peak, followed by a plateau period. Our data revealed that the arm motion contributed to the decline in endpoint spatial variability toward the end of the movement across all four conditions. In contrast, the trunk contributed to that decline in variability toward the end of the movement only in the temporally paced conditions (C2 and C4). The trunk variability likely remained high toward the end of the movement because trunk motion continued for some time after grasp of the object.

Proximal and Distal Synergies of Control

The notion of a proximal synergy whose goal is general movement toward the target and a more distal synergy con-

trolling end-effector accuracy is congruent with the findings of Lacquaniti and his colleagues (Lacquaniti et al., 1987; Lacquaniti & Soechting, 1982) for whole-arm drawing movements. They found that wrist motion was more correlated than either elbow or shoulder motion with the actual figure drawn. Moreover, the separate innervation of axial and distal segments may allow the central nervous system to assign different goals so that this complex task can be achieved more easily. The proximal musculature is innervated by the ventral corticospinal tract for voluntary movement control and the distal musculature by the lateral corticospinal and the rubrospinal tracts (Martin, 1989). Those tracts do not simply run in parallel but also have hierarchical connections between them, potentially coordinating the proximal and distal segments together.

The overall goals of those two synergies may be similar to those observed by Ma and Feldman (1995): In an arm aiming task combined with trunk motion, they revealed one synergy for controlling the shifting of the endpoint to the target and another for maintaining endpoint smoothness by compensating for trunk motion. In their task, however, participants did not require trunk motion to achieve the target, but rather they were instructed to move the trunk either in phase or out of phase with the arm. In the task used in the present experiment, though, participants required trunk motion to achieve the target; thus, it is unclear how much arm motion they would have needed to compensate for trunk motion. Pigeon and Feldman (1998) have hypothesized that the degree of compensation is modulated to meet task requirements; that is, when the trunk is required to extend the reach, compensation is reduced. Furthermore, it seems likely that the distal synergy would be involved with



on-line correcting for errors in the movement plan, for external perturbations, and to orient the hand to grasp the object.

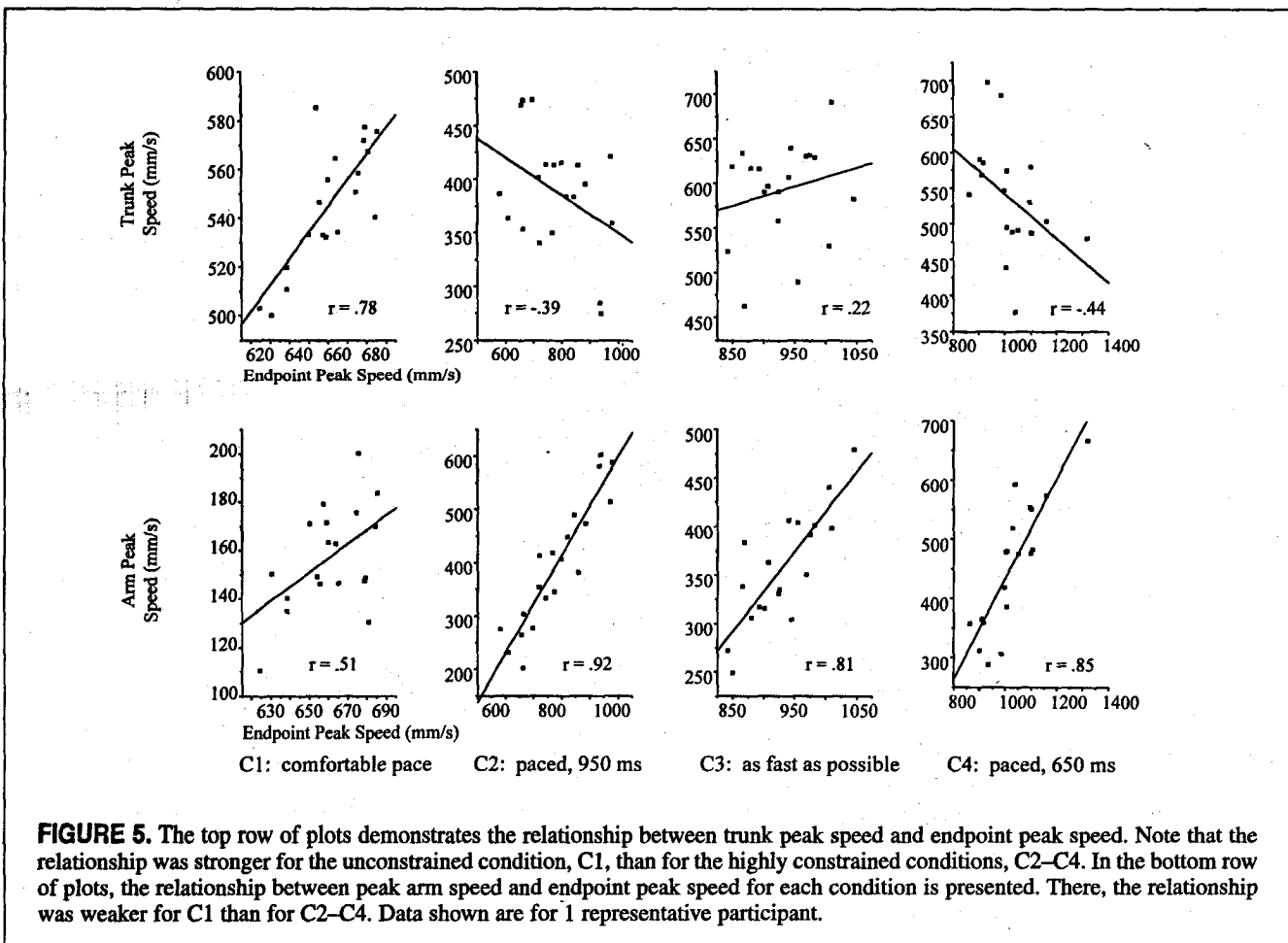
Our finding that the trunk was nearly always the last segment to complete the movement has been shown by other investigators studying trunk-assisted reaching (Saling et al., 1996) and aiming tasks (Kaminski et al., 1995). Kaminski and colleagues concluded from that observation that trunk motion is used preferentially in the final stage of the movement to bring the hand to the target. That conclusion, however, was not supported by our data. The participants in the current investigation grasped the object within a couple of milliseconds after the completion of arm motion, with trunk motion continuing for up to 200 ms after that time. The continuation of trunk motion after the grasp has been completed may serve to increase stability during lift and manipulation of the target object.

One limitation of our approach is that we did not compute arm motion by using the dynamic equations of motion and thus could not determine the portion of the arm movement that resulted from actions of the arm musculature and the portion that resulted from transfer of momentum from the trunk. Clearly that transfer may have a big impact on the control of this prehension movement, as reflected by the

fact that the trunk began the movement first and finished last in the majority of the trials. The transfer may serve to aid the acceleration and deceleration of the arm. However, increasing transfer of momentum from the trunk to the arm did not appear to be responsible for the increasing involvement of the arm across conditions in the present experiment. If that were the case, the arm would have contributed more only in the faster conditions and not under the slow, temporally constrained condition, as we found. Regardless, an analysis of the data in joint space could provide additional insights into the relative contributions played by each segment.

Parallel Control of Endpoint Trajectory and Aperture Formation

Evidence that the reach is planned in terms of the endpoint trajectory comes from the observation that endpoint motion is smoother than either trunk or arm motion (Flash, 1990; Morasso, 1981). That finding again highlights the fact that some type of compensatory action occurs between the trunk and the arm so that smooth endpoint transport can be maintained, and supports the hypothesis that the roles of the distal musculature in goal-oriented movements are to reduce variability and increase accuracy in the endpoint



motion (Lacquaniti et al., 1987; Lacquaniti & Soechting, 1982). Clearly, endpoint planning is a functional necessity in prehension; it allows endpoint transport to be coordinated with aperture formation. It was somewhat surprising, however, that the time to peak aperture was slightly more correlated with the time to peak deceleration of the arm rel-

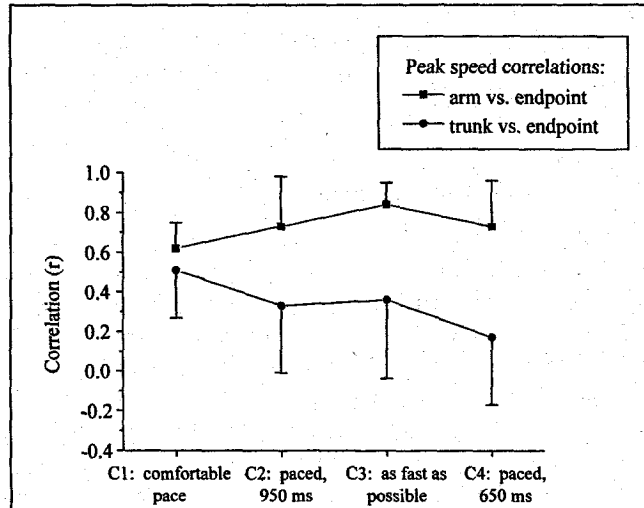


FIGURE 6. Mean correlations between the endpoint and the arm peak speed and between the endpoint and the trunk peak speed are plotted for each condition. A repeated measures analysis of variance performed on the z scores for those correlations revealed that the values were similar for C1 only (comfortable pace). For the remaining three conditions, the values for the arm z scores were greater than those for the trunk ($p < .05$ in all cases).

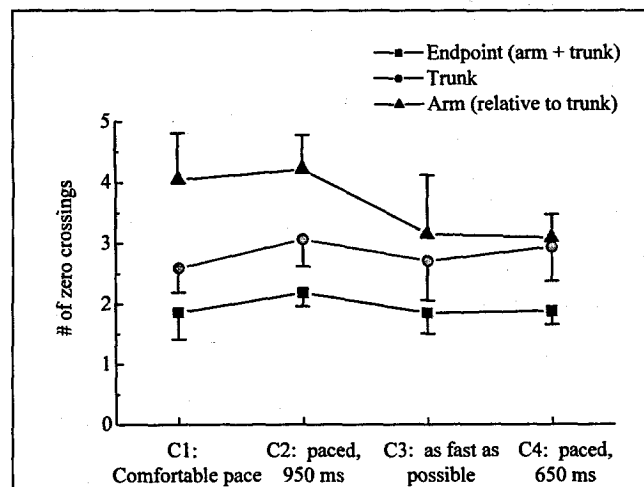


FIGURE 7. The number of acceleration zero crossings for the endpoint motion, arm motion relative to the trunk, and trunk motion are plotted for each condition. The number of zero crossings for the endpoint motion was lower than that of both the arm and the trunk in all conditions. The number of zero crossings was greater for the arm than for the trunk for the two slower conditions (C1 and C2).

ative to the trunk than with endpoint motion. That finding suggests that aperture formation occurs while the compensatory actions that the arm is making are taken into account. It also may be that aperture formation and endpoint transport do not become fully coupled until after the time of peak deceleration of the endpoint. Indeed, several authors have suggested that the two tasks of hand transport and aperture formation become more coordinated as the movement progresses (Saling et al., 1996; Timman et al., 1996). It appears that, in the case of trunk-assisted prehension, the transport channel is further broken down into two basic synergies of control, one controlling the proximal segments and the other the more distal, with some type of hierarchical arrangement allowing for coordination between the two.

Conclusions

With our data, we have established that smaller segments are more involved in movements with a specific temporal goal, even if the movement duration is relatively long. The results suggest that there may be very practical implications for such a control strategy. Specifically, it appears that the more proximal trunk segment plays the role of general mover in this trunk-assisted prehension task, whereas the arm plays more of a compensatory or corrective role in the movement. That relationship became quite evident for the temporally constrained conditions; in those conditions, any corrections would have to be made quite quickly and would be more efficient if made with the arm and not the trunk. Despite the changing involvement of effectors in response to task constraints, the aperture formation remained coordinated with the endpoint motion.

ACKNOWLEDGMENTS

This work was supported by National Institute of Neurological Diseases and Stroke Grant NS 17421, National Institute of Aging Grant AG 15018, and Flinn Foundation grants awarded to G. E. Stelmach; and a National Aeronautics and Space Administration Grant NGT9-21 awarded to R. D. Seidler. The authors wish to thank the two reviewers for their insightful contributions to the article.

Portions of these data were presented in poster format at the 1997 annual meeting of the Society for Neuroscience, New Orleans, LA.

REFERENCES

Bernstein, N. A. (1967). *The coordination and regulation of movement*. Oxford, UK: Pergamon Press.
 Cohen, J. (1977). *Statistical power analysis for the behavioral sciences* (rev. ed.). New York: Academic Press.
 Feldman, A. G. (1980). Superposition of motor programs—I. Rhythmic forearm movements in man. *Neuroscience*, 5, 81–90.
 Fischer, M. H., Rosenbaum, D. A., & Vaughan, J. (1997). Speed and sequential effects in reaching. *Journal of Experimental Psychology: Human Perception & Performance*, 23, 404–428.
 Flash, T. (1990). The organization of human arm trajectory control. In J. M. Winters & S.-L. Y. Woo (Eds.), *Multiple muscle systems* (pp. 282–301). New York: Springer-Verlag.
 Hogan, N. (1984). Adaptive control of mechanical impedance by coactivation of antagonist muscles. *IEEE Transactions in Automatic Controls*, AC-29, 681–690.

- Huynh, H., & Feldt, L. S. (1970). Conditions under which the mean square ratios in repeated measurements designs have exact F -distributions. *Journal of the American Statistical Association*, *65*, 1582-1589.
- Kaminski, T. R., Bock, C., & Gentile, A. M. (1995). The coordination between trunk and arm motion during pointing movements. *Experimental Brain Research*, *106*, 457-466.
- Karst, G. M., & Hasan, Z. (1987). Antagonist muscle activity during human forearm movements under varying kinematic and loading conditions. *Experimental Brain Research*, *67*, 391-401.
- Kelso, J. A. S., Southard, D. L., & Goodman, D. (1979). On the coordination of two-handed movements. *Journal of Experimental Psychology: Human Perception & Performance*, *5*, 229-238.
- Keppel, G. (1991). *Design and analysis: A researcher's handbook* (3rd ed.). Edgewood Cliffs, NJ: Prentice-Hall.
- Kudoh, N., Hattori, M., Numata, N., & Maruyama, K. (1997). An analysis of spatiotemporal variability during prehension movements: Effects of object size and distance. *Experimental Brain Research*, *117*, 457-464.
- Lacquaniti, F., Ferrigno, G., Pedotti, A., Soechting, J. F., & Terzuolo, C. (1987). Changes in spatial scale in drawing and handwriting: Kinematic contributions by proximal and distal joints. *Journal of Neuroscience*, *7*, 819-828.
- Lacquaniti, F., & Soechting, J. F. (1982). Coordination of arm and wrist motion during a reaching task. *Journal of Neuroscience*, *2*, 399-408.
- Langolf, G. D., Chaffin, D. B., & Foulke, J. A. (1976). An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior*, *8*, 113-128.
- Ma, S., & Feldman, A. G. (1995). Two functionally different synergies during arm reaching movements involving the trunk. *Journal of Neurophysiology*, *73*, 2120-2122.
- Martin, J. H. (1989). *Neuroanatomy*. New York: Elsevier Science.
- Morasso, P. (1981). Spatial control of arm movements. *Experimental Brain Research*, *42*, 223-227.
- Pigeon, P., & Feldman, A. G. (1998). Compensatory arm-trunk coordination in pointing movements is preserved in the absence of visual feedback. *Brain Research*, *802*, 274-280.
- Rosenbaum, D. A., Engelbrecht, S. E., Bushe, M. M., & Loukopoulos, L. D. (1993). Knowledge model for selecting and producing reaching movements. *Journal of Motor Behavior*, *25*, 217-227.
- Rosenbaum, D. A., Loukopoulos, L. D., Meulenbroek, R. G. J., Vaughan, J., & Engelbrecht, S. E. (1995). Planning reaches by evaluating stored postures. *Psychological Review*, *102*, 28-67.
- Rosenbaum, D. A., Slotta, J. D., Vaughan, J., & Plamondon, R. (1991). Optimal movement selection. *Psychological Science*, *2*, 86-91.
- Saling, M., Stelmach, G. E., Mescheriakov, S., & Berger, M. (1996). Prehension with trunk-assisted reaching. *Behavior Brain Research*, *80*, 153-160.
- Schillings, J. J., Meulenbroek, R. G. J., & Thomassen, A. J. W. M. (1996). Limb segment recruitment as a function of movement direction, amplitude, and speed. *Journal of Motor Behavior*, *28*, 241-254.
- Seidler-Dobrin, R. D., He, J., & Stelmach, G. E. (1998). Coactivation to reduce variability in the elderly. *Motor Control*, *2*, 314-330.
- Soechting, J. F., & Flanders, M. (1993). Parallel, interdependent channels for location and orientation in sensorimotor transformations for reaching and grasping. *Journal of Neurophysiology*, *70*, 1137-1150.
- Teasdale, N., Bard, C., Fleury, M., Young, D., & Proteau, L. (1992). Determining movement onsets from temporal series. *Journal of Motor Behavior*, *25*, 97-106.
- Timmann, D., Stelmach, G. E., & Bloedel, J. R. (1996). Grasping component alterations and limb transport. *Experimental Brain Research*, *108*, 486-492.
- Tresilian, J. R., & Stelmach, G. E. (1997). Common organization for unimanual and bimanual reach-to-grasp tasks. *Experimental Brain Research*, *115*, 283-299.
- Wang, J., & Stelmach, G. E. (1998). The coordination among body segments during reach-to-grasp action involving the trunk. *Experimental Brain Research*, *123*, 346-350.
- Winter, D. A. (1990). *Biomechanics and motor control of human movement* (2nd ed.). New York: Wiley.

Submitted June 4, 1999

Revised September 20, 1999

Second revision October 29, 1999