Temporal Constraints in the Control of Prehensive Movement

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Running head: PREHENSIVE MOVEMENT

Abstract

Three experiments were conducted to investigate the control of the manipulation (i.e., finger-thumb aperture) and transportation (i.e., wrist velocity) components in prehensive movement (Jeannerod, 1981, 1984). In all experiments, subjects were seated and instructed to grasp a dowel mounted on a joystick following a discrete movement over a set distance. Thus, the amount of dowel movement following the grasp could be determined. In Experiment 1, the tolerance (i.e., amount of allowable dowel movement) was manipulated using a computer generated boundary around the dowel. The results indicated that the transportation component changed depending on the tolerance condition and there were trends that maximum aperture was also affected. Experiment 2 manipulated both tolerance and dowel size (i.e., diameter) factorially in a within-subject design. Dowel size affected only the manipulation component, supporting Jeannerod's (1981) earlier work but tolerance clearly influenced both components. Experiment 3 investigated Wing, Turton, and Fraser's (1986) proposition that speed of movement influences aperture size. Distance and movement time were combined factorially to produce conditions with different average velocities. Maximum aperture was dependent on the movement time, rather than the speed of movement. The functional relation between the components was examined by using within-trial correlations between aperture and wrist velocity in Experiments 2 and 3. The correlations were related to the temporal aspects of the movement with higher correlations in the low movement time conditions. Also, the temporal occurrence of maximum aperture remained invariant across the different movement conditions. In general, the results suggest a strong functional linkage between the two components which may be dependent on the temporal characteristics of the movement.

Temporal Constraints in the Control of Prehensive Movement

Prehensive movements compromise an important repertoire in human motor skills. There are an abundance of skills which require the use of both the arm and fingers to grasp stationary and moving targets. In adults, prehensive movements of the type requiring the grasping of a stationary object appear to be composed of two components (Jeannerod, 1981; 1984). The transportation component involves the use of the arm to propel the hand towards the target object and the manipulation component controls the fingers and thumb to grasp the object. The neurological mechanisms controlling arm movement appear to be distinct from those which control the hand and have different developmental rates in the infant with the former developing earlier (Kuypers, 1962; 1964).

Using kinematic data, Jeannerod (1981; 1984) examined the effects of object size and visual feedback on the dynamics of both the transportation and manipulation component. He found that only the manipulation component was sensitive to the size of the object in that a large maximum aperture (grip size) was produced with large objects. Velocity profiles of the transport component remained unaltered. Other evidence, however, suggested some functional linkage between the two components. The temporal occurrence of maximum aperture was highly correlated with what Jeannerod termed the "onset of a low velocity phase" of the transport component during the last third of the movement. Although he did not attempt to define the purpose of this low velocity phase, Jeannerod suggested it was not related to a "homing in" strategy using feedback because it was present even during non-visual trials. Jeannerod appeared to suggest that the low velocity phase was a programmed part of the movement and highly related to the temporal occurrence of maximum aperture. However, since movements in Jeannerod's (1981; 1984) experiments were slow (600 to over 1000 ms) allowing time for feedback processing, it may be premature to invoke a programming explanation of his data. Because he did not provide grasping error data for visual and non-visual conditions, it remains possible that the movements were visual feedback dependent (see Wallace & Newell, 1983). In the present study we show that faster prehensive movements may not show signs of a low velocity phase, thus negating Jeannerod's method of determining the linkage between the transport and manipulation components. However, we show evidence, using other methods, for a strong functional association between the components in more rapid movements.

Recent work by Wing (Wing & Fraser, 1983; Wing, Turton, & Fraser, 1986) extended some of Jeannerod's findings. For example, Wing found that subjects also produced greater apertures in anticipation of larger objects to be grasped. He showed that non-visual performance was accompanied by greater maximum apertures (a finding Jeannerod did not report). Finally, Wing et al. (1986) provided evidence that size of maximum aperture is positively related to transport speed. They had subjects reach for a wooden dowel at a fixed 28 cm distance from the start position at a normal (comfortable) speed and as fast as possible. Any trials in which the dowel was knocked over were repeated. Wing et al. found that in the fast condition, subjects maximum aperture increased by 1.3 cm over that of normal reaching. They interpreted this finding as an error-compensating adjustment that is anticipatory in nature.

The studies by Jeannerod (1981; 1984) and Wing et al. (1983; 1986) provide tentative evidence that the two components of prehension may, under certain circumstances, become functionally linked. We feel that there are a few shortcomings in their work, however, which limit the generality of the findings. First, neither Jeannerod or Wing et al. provide specific measures of grasping accuracy. If prehensive movement follow the principles of Fitts' Law (1954) for aiming movements, we would predict, for example, that limiting the tolerance for grasping error (i.e., less target object movement following the grasp) would result in slower movement time and different transport trajectories (see Langolf, Chaffin, & Foulke, 1976). How these changes might impact the simultaneous control of the manipulation component was investigated in the first two experiments of the present study. Target object size was held constant (Experiment 1) or was varied (Experiment 2) along with manipulations of tolerance for grasping error. Second, another limitation of the previous prehensive studies was that movements produced by subjects were slow, ranging from 376 ms to over 1000 ms. We felt that some of the results of previous studies (e.g., correlation of maximum aperture to a 'slow velocity phase,' Jeannerod, (1981, 1984)) may be related to the speed or temporal characteristics of the movements produced.

Specifically, in Experiment 3 we examined the strict interpretation of Wing et al.'s (1986) claim that speed of movement per se affects the size of maximum aperture by covarying movement time and movement distance. Finally, in Experiments 2 and 3 we investigate the functional relation between the transport and manipulation components using within-trial correlations between transport velocity and grip aperture. These, along with other measures (e.g., temporal occurrence of maximum aperture) allowed us to determine whether object size, tolerance of grasping error and movement speed affect how the two components are controlled during prehension.

Experiment 1

Method

Subjects. Four right handed male volunteers (ages 19-25) served as subjects. All subjects were naive to the purposes of the experiment.

Apparatus. The apparatus consisted of two dowel rods mounted vertically on a table 23 cm apart. One plexiglass dowel rod, 3.5 cm in diameter, and 14.5 cm in height, served as a starting point for each movement. A microswitch button was attached on the subject's side of the dowel 17 cm above the table. Release of this button by the subject's index finger initiated a trial. The target to be grasped was the second dowel measuring 1.27 cm in diameter and 14.5 cm in height. This second dowel was a part of a "joystick" device which consisted of two potentiometers that measured displacement of the dowel after the grasp. The target dowel had a 6 cm cleft running longitudinally down the center of the dowel and parallel to the direction of movement. Within the cleft were two metallic contacts separated by an intercontact distance of .5 mm. Interfaced with the starting position microswitch and the contacts within the dowel was a millisecond clock (Lafayette Instrument Co. Model 54035) which recorded movement time (MT) for each trial from release of the starting point microswitch to grasp of the dowel and subsequent closing of the metallic contacts within the dowel which stopped the millisecond clock.

Insert Figure 1 about here

In addition to movement time and dowel displacement information, the subject's movements were recorded on photographic film (Kodak FX 135-36) by using a 35 mm single lens reflex camera with the shutter on the bulb setting (F-stop 2.7) securely mounted 1 m above the table surface such that the camera angle was perpendicular to the plane of movement (for a similar technique see Kelso, Southard and Goodman, 1979). For each trial photographed, the shutter was opened by an experimenter with a remote bulb just prior to the commencement of movement and closed just after the dowel was grasped. Light emitting diodes (LED's) pulsing at a rate of 50 Hz were attached to the tip of the subject's right index finger and thumb, and to the subject's wrist over the styloid process of the ulna. Pulsing of the LED's was initiated by releasing the starting point microswitch and was terminated when the contacts within the dowel were closed. Lighting in the experimental chamber was dimmed sufficiently to increase the resolution of each pulse as recorded on film but not interfere with the subject's ability to accurately perceive the dowel. To insure that starting position of the right arm for each subject was identical for each trial, a microswitch was attached to the right side chair back of the subject's chair in such a position that the subject's right elbow would depress the microswitch thereby lighting a bulb just to the right of the chair within the subject's peripheral view prior to initiating each trial. This signalled to the subject and experimenter that the proper start position had been achieved.

A MINC PDP 11-23 computer (Digital Equipment Corporation), utilizing software developed in-house, monitored dowel movement information in each of three different error tolerance conditions. Following each trial, the subject was graphically provided with dowel movement information on the terminal screen in the form of a circle representing the error tolerance boundary for that condition, a dot in the center of the circle representing the dowel before grasping, and a trace within the boundaries of the circle representing the actual path of dowel movement for a 250 ms period following dowel grasp. The three tolerance conditions had error tolerance boundaries of 7.62 (3 in), 5.08 (2 in) and 2.54 cm (1 in). In addition to providing dowel movement information to the subject, the program also recorded resultant (total) dowel movement information on each trial for later analysis (sampling rate - 100 Hz).

Procedure. Subjects were seated comfortably in a chair with the right elbow flexed at 90 degrees so that the microswitch mounted to the right side chair back was depressed with the right elbow. The right thumb and index finger held in a pinch position, depressed the starting point microswitch with the third phalangeal articulation of the index finger. From this position, which represented the starting position for each trial, the subject extended the right arm forward toward the dowel and grasped the dowel between right thumb and index finger to complete the movement by closing the metallic contacts within the dowel.

Subjects were instructed to perform the entire task as rapidly as possible but stay within the error tolerance requirements for that particular condition. Each trial was initiated by the subject after a ready cue. Immediately following each trial, the subject was provided with the dowel movement information. Prior to the experimental trials, subjects practiced for the condition to be tested until ten consecutive trials within the error tolerance for that condition were achieved.

During experimental trials, the subject was presented each of the three tolerance conditions (small, medium and large) in 15 trial blocks and in an order determined by a Latin square. Thus, a totally within subject design with repeated measures on tolerance was employed. Ten of the fifteen trials were photographed to maintain a record of the kinematic information for those trials. The intertrial interval was approximately 20 s within which the subject received the graphic display of the dowel movement information.

Data Analysis. Dowel movement was essentially treated as linear displacement and was represented in centimeters. Sampling of dowel movement began at dowel contact and continued for 250 ms following dowel grasp. Using the Pythagorean Theorum, a resultant dowel movement measure was developed to quantify accuracy during the 250 ms sampling period. The movement of the dowel between successive samples was considered as the hypotenuse of a triangle formed from the x-y coordinates of two adjacent samples. All individual hypotenuse's during the 250 ms sampling interval were added together to form the resultant dowel movement (or, the total amount of movement of the dowel, regardless of direction, during the 250 ms sampling period).

Each photographed trial was mounted as a slide and the negative image of the movement was projected onto a digitizer bit pat (Bit Pad One, Summagraphics Corp., resolution - .1 mm). Digitization of each LED pulse for the wrist, finger, and thumb converted the movement path of each LED to x-y coordinates for each trial. This digitized raw data was then subjected to a spline function software program with a forcing function of 100 to smooth raw digitized points creating lines of best fit for the movement path of each LED for each trial.

Splined data was then analyzed by software programs again developed in-house to obtain a variety of kinematic information of the aperture and wrist. The kinematic information was also averaged across the ten trials per condition to obtain mean scores for each subject within each condition.

Primary statistical analysis of averaged data was accomplished by employing one-way analyses of variance (ANOVA) for each dependent variable with tolerance as a within-subject independent variable.

Results

Movement time. Movement time increased as tolerance decreased and this effect was significant, $F(2,9) = 37.27$, $p < .001$. Tukey's post hoc test (Kirk, 1968) revealed that both MT in the medium and large tolerance condition was significantly smaller than in the small tolerance condition and not significantly different from each other.

Insert Table 1 about here

Resultant dowel movement. Resultant dowel movement significantly increased as tolerance increased, $F(2,9) = 5.63$, $p < .02$. Tukey's test revealed that resultant dowel movement for the large tolerance condition was greater than in the small tolerance condition.

Errors. Errors (which were considered to be a displacement of the target dowel outside the tolerance boundary within 250 ms after target dowel contact) tended to increase as tolerance decreased with the means ranging from .5 to 2.0 errors.

Wrist displacement and velocity. Figures 2 and 3 are representative wrist displacement and tangential velocity traces of splined data for single trials from each tolerance condition for one subject, respectively. Maximum (peak) wrist velocity was

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Insert Figures 2 and 3 about here

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greater as tolerance increased, an effect which was statistically significant, *F*(2,9) = 7.21, *p* < .01. Tukey's revealed that the peak wrist velocity of the large tolerance condition was significantly greater than the small tolerance condition. However, the tolerance main effects failed to reach significance for either the percentage of distance to reach peak wrist velocity, *F*(2,9) < 1, or the percentage of time to real peak wrist velocity, *F*(2,9) < 1. Peak wrist velocity occurred at roughly 50% of the distance and slightly over 40% of the movement time.

Insert Table 2 about here

Finger/thumb aperture displacement. Figure 4 shows representative displacement traces of splined aperture data for the same single trials. In general, aperture increased to a maximum and then rapidly "closed down" onto the target dowel. There was a trend for maximum aperture to increase as tolerance increased but this effect was not significant, *F*(2,9) < 1. The tolerance main effect for both the percent distance and time to peak aperture failed to reach significance, both *F*s(2,9) < 1.

Insert Figure 4 and Table 3 about here

Discussion

In anticipation of a given tolerance around the target dowel, subjects modified the transport component accordingly. As tolerance increased (i.e., lower accuracy constraint), peak wrist velocity also increased. However, in spite of significant changes in peak wrist velocity, the percentage of time and distance that it occurred remained relatively invariant across tolerance conditions. The wrist data, which represents in this study and others (e.g., Jeannerod, 1984) a description of the transport component, support the results found by Langolf et al. (1976) for discrete aiming movements.

The aperture data are more difficult to evaluate. From a statistical viewpoint, aperture dynamics appeared unaffected by changes in tolerance. A strict interpretation of Jeannerod's (1981) findings would indeed predict that changes in aperture dynamics would not be expected with constant object size. However, there were interesting trends in the aperture data which clearly warranted further investigation. For example, there was a tendency for maximum aperture to increase as tolerance increased. If this effect could be replicated and shown statistically significant, it would suggest that along with object size (Jeannerod, 1981), accuracy constraints of the object to-be-grasped may influence the manipulation component of prehensive movements.

These tendencies in the grasping component are coupled with significant changes in the transport component as a function of tolerance. Thus, it may be possible, as Jeannerod (1981,1984) has suggested, that transport and manipulation processes, while physiologically distinct, become functionally linked during prehension. Upon an extensive examination of the wrist velocity data we found no evidence of a low velocity component in the latter stages of the movement (see Figure 3). On average, the movements were much more rapid than those in either the Jeannerod (1981, 1984) or Wing et al. (1983, 1986) studies. Thus, it was not possible to correlate the temporal similarities between maximum aperture and the onset of a low velocity phase. However, in Experiment 2 we use a different correlational approach to investigate the linkage between the two components.

Experiment 2

In Experiment 2, the two variables of target dowel size and tolerance were factorially combined to determine their effects on each component of prehension. To examine the relation of the two components we developed a software program which performed within-trial correlations between wrist velocity and aperture size. In addition, the program calculated the correlation between wrist velocity and aperture size up to and following peak wrist velocity separately. We increased our sample size to further examine the tendency, shown in Experiment 1, that tolerance influenced aperture control.[1]

Method

Subjects. Six right-handed male college students (ages 19-25) volunteered to participate in this study. Each subject participated in all experimental conditions. All of the subjects were naive to the purpose of the experiment and did not participate in Experiment 1.

Apparatus. The apparatus was the same as in Experiment 1 with the exception that two dowel sizes were used, 3 mm and 25 mm in diameter. The dowels could be interchanged depending on the experimental condition.

Procedure. The procedures were similar to Experiment 1. Each subject participated in each of the four conditions (small tolerance/small dowel, small tolerance/large dowel, large tolerance/small dowel, large tolerance/large dowel) in an order which was randomly determined. A total of fifteen trials per condition were recorded for MT and dowel displacement information analysis. Ten of the fifteen trials were photographed to maintain a record of kinematic information for those trials. The intertrial interval was approximately 20s within which the subject received graphic display of the dowel movement information.

Data Analysis. The data analyses were similar to Experiment 1 with an additional statistical procedure utilizing Pearson correlations. Two correlations were obtained for each trial: one correlating velocity of the wrist and aperture size from movement initiation to peak wrist velocity, and a second correlating wrist velocity and aperture size beyond peak wrist velocity to termination of the movement. Both correlation coefficients from each trial were transformed to Fisher's Z values and averaged across the ten trials per condition. Finally, a 2x2x2 (dowel size x tolerance x portion of movement) analysis of variance was performed on the Fisher's Z values.

Results

Movement Time. Analysis of variance resulted in a significant tolerance effect, $F(1,5) = 54.59$, $p < .001$, but no dowel size main effect, $F(1,5) = 5.51$, $p > .05$, or dowel size by tolerance interaction, $F(1,5) = 2.607$, $p > .05$. Aggregate means for the tolerance effect were 390 ms and 251 ms, respectively for the small and large tolerance conditions.

Insert Table 4 about here

Resultant dowel movement. There was a significant tolerance main effect, $F(1,5) = 29.63$, $p < .005$ with overall means for the small and large conditions of .63 and 2.44 cm, respectively. Both the dowel size and dowel size by tolerance interaction lacked significance, Fs(1,5) = 3.22 and < 1, respectively.

Errors. The number of errors (movement of the dowel outside of the error tolerance boundary) was roughly equivalent for all four conditions. There was a small tendency for more errors to be committed in the smaller tolerance conditions.

Wrist velocity information. The tolerance main effect for peak wrist velocity was significant, $F(1,5) = 27.63$, $p < .005$. However, neither the dowel size nor the interaction were significant, Fs(1,5) < 1. There was also a tendency for peak wrist velocity to occur further into the movement for the large tolerance conditions. The main effect for tolerance was significant $F(1,5) = 27.05$, $p < .005$ whereas the main effect for dowel size and the interaction were not, Fs(1,15) = 1.70 and 1.72, $p > .05$, respectively. For the percent of time to peak wrist velocity, the interaction between tolerance and dowel size was significant, $F(1,5) = 9.18$, $p < .05$ and superceded both significant main effects. Simple main effects revealed that the large tolerance/small dowel condition had a larger percent time of peak wrist velocity than the other three conditions, which did not differ significantly.

Insert Table 5 about here

Finger/thumb aperture displacement. Both main effects of tolerance and dowel size were significant for maximum aperture reached, Fs(1,5) = 11,32, $p < .05$ and 271.75, $p < .001$, respectively. Thus, maximum aperture increased as either the dowel size or tolerance increased. The interaction was not significant $F(1,5) < 1$. For percent distance to maximum aperture, there was a significant tolerance effect, $F(1,5) = 9.90$, p

$< .05$ revealing that percent distance to maximum aperture increased as tolerance decreased. No other effects were significant. Also, the percent of time to maximum aperture was similar for all conditions as evidenced by a lack of significance for both main effects and the interaction Fs(1,5) < 1.

Insert Table 6 about here

Table 7 illustrates the results of the within-trial correlations of wrist velocity and aperture size. Approximately 10-15 data pairs representing instantaneous velocity values were used for each correlation depending on the trial. Examination of table 7 reveals that the correlations, in general, were markedly high; nearly all of them were at or over .90. The tolerance by dowel size by portion of movement analysis of variance revealed that both the tolerance and portion of movement main effects were significant, Fs(1,5) = 10.54 and 6.38, ps < .05, however these were superceded by the tolerance-portion of movement interaction, $F(1,5) = 32.64$, $p < .01$. Simple main effects analysis showed that the Fisher's Z values in the small tolerance condition after peak wrist velocity were smaller than all others. No other effects were significant.

Insert Table 7 about here

Discussion

Several of the results in Experiment 1 were replicated in this experiment. As in Experiment 1, movements with short movement times resulted in greater target dowel movement supporting a speed-accuracy trade-off in prehensive movement. This type of result might not necessarily be expected if the manipulation component is functionally independent of the transport component. That is, it could be possible that variabilities in the transport component caused by, say, increases in wrist velocity, might be offset or compensated for by adjustments in the manipulation component. This was clearly not the case. Reductions in movement time, presumably caused by increased error tolerance, resulted in larger target dowel movement.

Also, in support of Experiment 1, tolerance affected both the transport and manipulation components. Larger tolerance allowed subjects to reach greater wrist velocities and also larger maximum apertures. This latter finding supports the trend evident in Experiment 1 and also confirms unpublished work by Douglas (1981), cited by Wing and Fraser (1983) and Wing et al. (1986) that aperture size appears to be positively related to movement speed.

The size of the target dowel appeared to primarily affect only the manipulation component, supporting Jeannerod's (1981) earlier work. It significantly influenced maximum aperture but not movement time, resultant dowel movement, or maximum wrist velocity.

Finally, there was a strong relation between wrist velocity and aperture size with the correlations ranging from .83 to .97 and somewhat higher in the large tolerance conditions particularly after peak wrist velocity. This result combined with the fact that maximum aperture varied as a function of tolerance condition suggests that the two components become more functionally linked as movement speed increases. Yet, in spite of these changes in aperture size, the temporal occurrence of maximum aperture in the movement remained invariant across all conditions and occurred at approximately 60% across all conditions.

Experiment 3

In the previous two experiments, maximum aperture increased as tolerance increased. A likely explanation for this result is that spatial tolerance affects the speed with which movements can be performed. Thus, changes in grip size could be due to movement speed as recently suggested by Wing et al. (1986). However, an equally plausible explanation is that movement time rather than speed determines grip dynamics and relations between the transport and manipulation components. In both the Wing et al. (1986) and the first two experiments of the present study, movement speed and movement time changes were confounded because distance was unaltered. Thus, in the third experiment we attempted to untangle this confounding by co-varying the distance and the movement time in a within-subject design. Subjects were required to perform grasping movements of either 200 or 400 ms over distances of 15 or 30 cm. Subjects were trained to produce these movements within 15%

temporal bandwidths around the 200 and 400 ms goal movement time. Thus, acceptable movement times were 170-230 and 340-460 ms, respectively. If movement speed determines the correlation between the two components then several predictions emerge. One, movements with greater speed, regardless of movement time, should be performed with larger apertures accompanied by higher within-trial correlations between wrist velocity and grip size. Two, there should be no differences in these dependent variables between movements with similar speed (e.g., the 15 cm-200 ms condition versus the 30 cm-400 ms condition).

Method

Subjects. Six right handed male college students (ages 19-22) volunteered to participate. All subjects were naive to the purpose of the experiment. None of the subjects participated in the previous experiments.

Apparatus. The same apparatus was used. Only the small target dowel (3 mm in diameter) was used in this experiment, while the start position dowel was moved to create the 15 and 30 cm conditions.

Procedure. Subjects participated in each of four movement time/distance conditions. The two movement times were 200 and 400 ms and the two distances were 15 and 30 cm. A long slot parallel to the direction of movement in the baseboard of the apparatus allowed the start position dowel to be easily moved to the appropriate distance from the target dowel. As in the previous two experiments, subjects started with their index finger and thumb in a pinched position with slight pressure on the starting button. After a cue to begin the trial, subjects were instructed to initiate the movement and grasp the target dowel as accurately as possible within the designated movement time bandwidth. No graphic display of dowel movement was presented to the subject in this experiment but the computer recorded resultant dowel movement as in the previous experiments. Subjects received a minimum of 20 practice trials with knowledge of results regarding movement time before each experimental session. Each movement time/distance session continued until 10 trials within the movement time bandwidth were collected. All 10 trials were photographed and used in the analysis.

The presentation order of the four movement time-distance conditions across the six subjects was randomized.

Design and data analysis. A 2 x 2 (movement time x distance) within-subject design was used. Movement times were 200 ms and 400 ms and distances were 15 and 30 cm. Data analysis was identical to the previous experiment.

Results

Movement time. As shown in Table 8, the mean movement times obtained were very near the desired goal movements. Not surprising, the movement time main effect was significant, $F(1,5) = 2140.63$, $p < .001$.

Resultant dowel movement. There were clear trends for dowel movement to be related to the speed of movement. For example, dowel movement in the slowest condition (400 ms - 15 cm) was much smaller than in the fastest condition (200 ms - 30 cm). However, the distance main effect, $F(1,5) < 1$, the movement time main effect, $F(1,5) = 5.10$, $p > .05$, and the interaction, $F(1,5) < 1$ all lacked significance.

Insert Table 8 about here

Wrist velocity information. Peak wrist velocity increased as the velocity required by the movement condition increased. Both movement time and distance main effects were significant, however, they were superceded by a significant interaction, $F(1,5) = 41.36$, $p < .001$. Simple main effects indicated that the peak wrist velocity of the 200 ms - 30 cm condition was significantly greater than all other conditions. The two conditions with similar average velocities (200 ms - 15 cm and 400 ms - 30 cm) were not different but greater than the 400 ms - 15 cm condition.

The percent distance and time to peak wrist velocity remained invariant across all conditions (all p's > .05). The spatial and temporal occurrence of peak wrist velocity was, on average, 50% through the movement.

Insert Table 9 about here

Finger/thumb aperture information. Maximum aperture appeared to be more related to movement time than speed or distance. The movement time main effect was significant, $F(1,5) = 5.99$, $p < .05$. Maximum aperture was greater for the 200 ms conditions. The lack of a distance main effect or interaction suggests that speed of movement, per se, does not accurately account for aperture size. Also, all main effects and interactions lacked significance for percent distance and time to maximum aperture (p's > .05).

Insert Table 10 about here

Table 11 shows the within-trial correlations of wrist velocity and aperture size. In general, the correlations were high except in the slow movement time condition, particularly after peak wrist velocity. The only significant effects were the MT, $F(1,5) = 53.92$, $p<.001$, and MT by portion of movement interaction, $F(1,5) = 160.48$, $p<.001$. Simple main effects analysis of the interaction showed that the Fisher's Z values were higher in the 200 ms conditions. Also, the Fisher's Z values in the 400 ms condition after peak wrist velocity was significantly smaller than all others. One interesting comparison between the two conditions with similar average velocities (200 ms-30 cm and 400 ms-15 cm) showed higher Fisher's Z values in the former condition. Thus, the functional relationship between the components appears more to be due to temporal constraints than distance or velocity, per se.

Insert Table 11 about here

Discussion

This experiment provided two lines of evidence for temporal factors affecting the relation between the manipulation and transport components of prehension. One, maximum aperture was significantly affected by the movement time. Movements of shorter durations had larger maximum apertures. Two, the correlations between aperture size and wrist velocity were greater in the shorter duration movements. Speed of movement did not affect these relations. Larger maximum apertures and larger correlations between aperture size and wrist velocity were obtained in movements with shorter durations regardless of movement speed. In spite of dramatic changes in velocity across the four MT - distance conditions, invariance in the temporal location of peak wrist velocity and maximum aperture was shown. The values of these temporal invariances were similar to those obtained in the first two experiments.

Lastly, there were strong trends for a speed-accuracy tradeoff in that larger target dowel movement accompanied movements of greater velocity. The variability in the dowel movement data however, prevented any significant differences.

General Discussion

In the present study we have demonstrated that tolerance of grasping error has marked effects on both the transport and manipulation components in prehensive movements (Experiments 1 and 2). Greater tolerance allows for concomitant increases in transport velocity and results in systematic increases in maximum grip aperture. The changes shown in transport trajectory (i.e., velocity profile) as a function of tolerance in the present study fit nicely with the results of Langolf et al. (1973) in simple aiming movement. Langolf et al. showed that target width (as in the Fitts, 1964 task) affected the velocity pattern toward the target. Larger target width allowed for greater transport velocities to be reached. In the first two experiments of the present study, we can safely argue that our tolerance manipulation has analogous effects on transport velocity in prehensive movements.

Tolerance of grasping error also had significant impact on the manipulation component. In general, when tolerance was large, transport velocities increased which resulted in larger maximum apertures. The results in Experiment 1 and 2 suggest that aperture increases are sensitive to the speed of movement, an interpretation in line with that of Wing et al. (1986). They argued that this type of result is a reflection of an error-compensating adjustment since a larger aperture gives "increased tolerance for positioning errors just prior to contact" (pg. 257). In support of this view, Wing et al. found increased variabilities in the thumb position at maximum aperture as well as at one sample period prior to contact in faster transport conditions. The variabilities were even greater under non-visual conditions. Presumably, in an anticipation of these increased variabilities, the manipulation component increases maximum aperture to insure the grasp of the object. In summary, tolerance of target object movement appears to effect both the transport and manipulation components in prehensive action.

In contrast, size of target dowel only affected the manipulation component (Experiment 2). Greater apertures were observed in the large dowel conditions. The fact that size of dowel had no effect on the transport component supports earlier work by Jeannerod (1981) but also extends the generality of this finding to faster movements.

There is strong evidence, based on the results in Experiment 3, that control of the manipulation is dependent on movement time and not movement speed. In anticipation of a shorter movement duration, the motor system produced a larger aperture regardless of speed or movement distance. Maximum wrist velocities effectively doubled for each MT condition by increasing movement distance from 15 to 30 cm (see Table 9). Yet, maximum aperture was not affected within each MT condition. In addition, in the two conditions with similar average and peak velocities, maximum aperture was greater in the 200 ms condition. Perhaps with less time to perform the grasp, the system anticipates larger target dowel movement following the grasp and produces a larger aperture to insure a successful grasp. While not significant, there were trends in Experiment 3 for dowel movement to be larger in the 200 ms compared to the 400 ms conditions.

The results from the within-trial correlation analyses between wrist velocity and aperture size support the existence of functional coupling between the transport and manipulation components which is sensitive to the temporal characteristics of the movement. In Experiment 2, the correlations were particularly high in the first half of the movement but were significantly smaller in the second half of the movement for the small tolerance conditions. These results give some indication that the correlation between the two components is sensitive to changes in either the movement speed or movement time. Experiment 3 provided evidence for the movement time viewpoint and thus, it would appear the functional association between the components is dependent on the temporal characteristics of the movement. If this were so, what would happen if movements were performed at much slower movement times? To provide preliminary data we asked two subjects from Experiment 3 to perform a few extra trials at long movement times over the 30 cm distance. Subject 1's average movement time was 531 ms and Subject 2's was 585 ms. For Subject 1, the correlation in Fisher's Z values between instantaneous wrist velocity and aperture size up to and following peak wrist velocity was .69 and .55, respectively. For Subject 2, the correlations were .55 and .34, respectively. Thus, not only were the correlations much lower than in faster movements, the correlations in the first part of the movement were also considerably lower. These preliminary data support the view that the association between the transport and manipulation is, in part, dependent on the movement time of the prehensive activity. Of course, while it is possible that a phase shift between the components in the long movement time (slower) conditions might lower the correlations, the fact that the temporal occurrence of maximum aperture remained invariant across conditions tends to discount this interpretation.

The transport and manipulation components, as operationally defined in the present study, are not inertially coupled (Lacquaniti & Soechting, 1982) because their respective planes of movement are perpendicular to each other. That is, a torque applied solely to one component does not necessarily result in movement of the other component. It is obvious that when the transport component is at rest, the manipulation component can operate independently. Alternatively, we can move our arm without activating the manipulation component. Given the results of our correlational analysis, there appears to be an independence in the control of these two systems at slow movement times. That is, the velocity of transport is unrelated to the size of the aperture. At these long movement times, the subject is likely to be using visual feedback to accurately carry out the movement (e.g., Wallace & Newell, 1983). As movement time reduces, greater anticipation is needed in controlling grip dynamics, perhaps shifting the type of control from feedback processing to programmed action (see Schmidt, 1982, pg. 285-332 for a review). Also, the data suggest that to successfully grasp the object in a shorter duration, the two components become functionally linked, as evidenced by high correlations, before as well as after peak wrist velocity, even though they are not inertially coupled.

To further explore this functional relation, we had one of our subjects in Experiment 3 perform a few additional trials under different task constraints. Instead of starting with the index finger and thumb tips together, the subject started with a wide aperture (near maximum). The distance to the target dowel was 30 cm and the subject was told to move at a comfortable pace. The average movement, over nine trials was 380 ms. With a wide aperture at the beginning of the movement the subject could adopt several strategies to grasp the object, many of which could markedly affect the correlation between the components. Interestingly, the correlations prior to and after peak wrist velocity were -.93 and .74, respectively. From the data it is clear that as wrist velocity increased to its peak, aperture decreased in a highly related way. The correlation after peak velocity was moderately high - similar to previous results with this movement time. Of course, more work needs to be done to verify these preliminary data. However, the results thus far suggest a strong functional coupling between the two components of prehension at least within the constraints of the task and procedures we have used.

Other aspects of the data also suggest some functional coupling such as the invariance of the temporal occurrence of maximum aperture. This type of invariance has been used to support a generalized motor programming concept in other types of movement (Schmidt, 1982, but see Kelso & Tuller, 1987 for a different interpretation). In the generalized programming view, invariant features of a movement performed at different speeds, for example, signify governance by the same motor program. In prehensive movement, the speed (or time) of the movement and the size of the aperture can vary but the relative time of maximum aperture is invariant. Using this view, we might model prehensive activity as the two components of transport and manipulation contained in the same program whose variant features such as movement speed (or time) and aperture size can vary from task to task, whereas the temporal occurrence of maximum aperture remains invariant.

In contrast, we might view the muscles involved in prehension as organized into functional synergies or coordinative structures in which movement is a result of the functional relation between two coupled limit cycle oscillators (e.g., Kelso, et al., 1980; Kelso, Holt, Rubin, & Kugler, 1981) - one for the manipulation component and one for the transport component. The oscillator controlling the manipulation component might be responsible for opening and closing the aperture while the transport oscillator would control movement of the arm. A discrete prehensive movement could be viewed as the interaction of the two oscillators during only a part of a complete cycle. It could be that the high correlations shown in the present study between the two components represent some form of entrainment. We might also speculate that the temporal constraints of the task serve to "potentiate" (activate) or depotentiate (deactivate) the coordination between the two components. At long movement times (slow movements), oscillator circuits controlling the two components could operate independently but short movement times (fast movements) might cause potentiation of the coupling between the oscillators (see Gallistel, 1980, for a discussion of the potentiation concept).

Finally, we might ask what are the critical features or aspects of the prehensive activity to be capitalized on for a successful grasp of the object? In this regard, our results impact on a model of grasping developed by Arbib (1981). In the model, prehension is viewed as a two component process. The first component deals with the analysis of visual input to locate the object to be grasped and the second component involves the processes necessary to reach and grasp the object. Arbib suggests that the critical visual input are the visual location, size and orientation of the object in space. Our results suggest that the tolerance of grasping error also needs to be appreciated in advance by the performer. The influence of tolerance on prehensive control is, no doubt, analogous to picking up a coffee cup 'filled to the brim' versus half-filled. The task of the performer is not only to grasp the cup, but to do so with minimal cup movement following the grasp. Arbib further speculates that visual location directly effects the ballistic movement towards the object whereas the object size and orientation affect the finger and hand rotation, respectively. Our data show that tolerance affects both the characteristics of the ballistic movement (transport component) and finger movement (manipulation component) whereas object size affects only finger adjustments. What other types of visual information are important and the nature of the relationship between the transport and manipulation components appear to us to be important research questions in future work on prehensive movement.

References

Arbib, M. (1981). Perceptual structures and distributed motor control. In V. B. Brooks (Ed.), Handbook of physiology, Section 1: The nervous system, Volume 2: Motor Control. Bethesda, MD: American Psychological Society.

Douglas, G. (1981). Coordination during reaching movements. Honours Thesis, Cambridge University.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47, 381-391.

Fitts, P. M. (1964). Information capacity of discrete motor responses. Journal of Experimental Psychology, 67, 103-112.

Gallistel, C. R. (1980). The organization of action: A new synthesis. Hillsdale, NJ: Lawrence Erlbaum Associates.

Jeannerod, M. (1981). Intersegmental coordination during reaching at natural visual objects. In J. Long & A. Baddeley (Es.), Attention & performance IX. Hillsdale, NJ: Erlbaum.

Jeannerod, M. (1984). The timing of natural prehension movements. Journal of Motor Behavior, 16, 235-254.

Kelso, J.A.S., Holt, K. G., Kugler, P. N., & Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures: II. Empirical lines of convergence. In G. E. Stelmach & J. Requin (Eds.), Tutorials in motor behavior (pp. 48-70). Amsterdam: North Holland.

Kelso, J.A.S., Holt, K. G., Rubin, P., & Kugler, P. N. (1981). Patterns of human interlimb coordination emerge from the properties of non-linear, limit cycle oscillatory processes: Theory and data. Journal of Motor Behavior, 13, 226-261.

Kelso, J.A.S., Southard, D. L., & Goodman, D. (1979). On the coordination of two-handed movements. Journal of Experimental Psychology: Human Perception and Performance, 5, 229-238.

Kelso, J.A.S., & Tuller, B. (1987). Intrinsic time in speech production: Theory, methodology, and preliminary observations. In E. Keller & M. Gopnik (Eds.), Motor and sensory processes of language. Hillsdale, NJ: Lawrence Erlbaum Associates.

Kirk, R. E. (1968). Experimental design: Procedures for the behavioral sciences. Wadsworth Publishing Company.

Kuypers, H.G.J.M. (1962). Cortico spinal connections: Postnatal development in the rhesus monkey. Science, 138, 678-680.

Kuypers, H.G.J.M. (1964). The descending pathways to the spinal cord, their anatomy and function. In J. C. Eccles, & J. C. Shade (Eds.), Organization of the spinal cord. Amsterdam: Elsevier.

Lacquaniti, F., & Soechting, J. F. (1982). Coordination of arm and wrist 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.

Schmidt, R. A. (1982). Motor learning and control: A behavioral emphasis. Champaign, IL: Human Kinetics.

Wallace, S. A., & Newell, K. M. (1983). Visual control of discrete aiming movements. Quarterly Journal of Experimental Psychology, 35A, 311-321.

Wing, A. M., & Fraser, C. (1983). The contribution of the thumb to reaching movements. Quarterly Journal of Experimental Psychology, 35A, 297-309.

Wing, A. M., Turton, A., & Fraser, C. (1986). Grasp size and accuracy of approach in reaching. Journal of Motor Behavior, 18, 245-260.

Author Notes

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Footnote

[1] Because of a different format of the data files, it was not possible to retroactively perform the correlational analysis on the data from Experiment 1.

Table 1

Means and standard deviations (in parentheses below each mean) for MT and resultant dowel movement across tolerance conditions (Experiment 1).

	Tolerance Condition		
	Small	Medium	Large
Movement time (ms)	410 (28.66)	289 (18.46)	253 (31.75)
Resultant dowel movement (cm)	.65 (.11)	1.66 (.38)	2.21 (1.09)
Number of errors	2 (0)	1.25 (.43)	.5 (.37)

Table 2

Means and standard deviations of splined wrist data (Experiment 1).

	Tolerance Condition		
	Small	Medium	Large
Maximum wrist velocity (cm/s)	117.1 (7.48)	140.6 (19.37)	165.3 (23.13)
Distance maximum wrist velocity achieved (%)	49.7 (4.0)	52.0 (4.2)	51.5 (4.6)
Time maximum wrist velocity achieved (%)	41 (2.9)	45.2 (5.9)	43.5 (4.3)

Table 3

Means and standard deviations of splined finger/thumb aperture data (Experiment 1).

	Tolerance Condition		
	Small	Medium	Large
Maximum aperture (cm)	10.4 (.97)	10.7 (1.9)	11.8 (1.65)
Distance maximum aperture achieved (%)	77.5 (6.3)	78.2 (3.0)	76.7 (2.2)
Time maximum aperture achieved (%)	55 (8.4)	59 (3.3)	58.2 (2.6)

Table 4

Means and standard deviations (in parentheses below each mean) for MT and resultant dowel movement for each condition (Experiment 2).

	Condition (Tolerance/Dowel Size)			
	Small/Small	Small/Large	Large/Small	Large/Large
Movement time (ms)	345 (54.33)	435 (72.71)	242 (39.87)	260 (47.70)
Resultant dowel movement (cm)	0.54 (0.07)	0.71 (0.08)	2.16 (0.83)	2.69 (1.06)
Number of errors	1.6 (.81)	.33 (.76)	1.16 (.92)	1.16 (.96)

Table 5

Means and standard deviations (in parentheses below means) of splined wrist data (Experiment 2).

	Condition (Tolerance/Dowel Size)			
Analysis	Small/Small	Small/Large	Large/Small	Large/Large
Maximum wrist velocity (cm/s)	127.25 (22.37)	114.43 (16.09)	160.13 (33.40)	172.4 (34.78)
Distance maximum wrist velocity achieved (%)	47.74 (3.80)	45.86 (5.30)	53.38 (4.49)	48.71 (4.04)
Time maximum wrist velocity achieved (%)	45.15 (5.96)	42.04 (5.20)	51.96 (5.32)	42.94 (5.71)

Table 6

Means and standard deviations (in parentheses below means) of splined finger/thumb data (Experiment 2).

	Condition (Tolerance/Dowel Size)			
Analysis	Small/Small	Small/Large	Large/Small	Large/Large
Maximum aperture (cm)	8.29 (1.40)	12.04 (1.47)	9.26 (1.09)	13.23 (2.18)
Distance maximum aperture achieved (%)	81.38 (2.27)	83.66 (3.87)	77.19 (5.89)	80.69 (3.08)
Time maximum aperture achieved (%)	61.75 (9.57)	63.37 (6.23)	62.19 (8.19)	61.51 (3.54)

Table 7

Means and standard deviations (in parentheses below means) of Fisher's Z values for the correlation of wrist velocity with aperture size of finger and thumb. The Z values are accompanied by their respective correlations* (Experiment 2).

	Condition (Tolerance/Dowel Size)			
Portion of Movement	Small/Small Z/r	Small/Large Z/r	Large/Small Z/r	Large/Large Z/r
To peak wrist velocity	1.85/.95 (.33)	2.15/.97 (.44)	1.96/.96 (.44)	1.77/.94 (.40)
After peak wrist velocity	1.31/.86 (.55)	1.19/.83 (.30)	1.95/.96 (.16)	1.75/.94 (.24)

*All correlations significantly different from zero.

Table 8

Means and standard deviations for MT and dowel movement for each condition (Experiment 3).

	Condition (MT/Distance)			
	200/15	200/30	400/15	400/30
Movement time (ms)	201 (4.7)	204 (8)	395 (11)	397 (12)
Resultant dowel movement (cm)	1.8 (2)	2.03 (1.9)	.65 (.6)	1.00 (.8)

Table 9

Means and standard deviations of splined wrist data (Experiment 3).

	Condition (MT/Distance)			
	200/15	200/30	400/15	400/30
Maximum wrist velocity (cm/s)	109 (8.6)	205 (16)	66 (5.7)	125 (8.1)
Distance maximum wrist velocity achieved (%)	53 (10)	51 (5)	46 (13)	45 (4)
Time maximum wrist velocity achieved (%)	51 (10)	46 (7)	47 (14)	45 (6)

Table 10

Means and standard deviations of splined finger/thumb data (Experiment 3).

	Condition (MT/Distance)			
	200/15	200/30	400/15	400/30
Maximum aperture (cm)	11.2 (2.6)	11.3 (1.5)	9.7 (2)	9.5 (1.2)
Distance maximum aperture achieved (%)	73.5 (9.6)	79.6 (11)	72 (12)	80 (11)
Time maximum aperture achieved (%)	61 (7)	63.9 (11.4)	63 (10)	67.8 (9.1)

Table 11

Means and standard deviations of Fisher's Z values for the correlation of wrist velocity with aperture of finger and thumb. Z values are accompanied by their respective correlations* (Experiment 3).

	Condition (MT/Distance)			
Portion of Movement	200/15 Z/r	200/30 Z/r	400/15 Z/r	400/30 Z/r
To peak wrist velocity	1.45/.89 (.50)	1.79/.94 (.18)	1.35/.87 (.49)	1.37/.88 (.32)
After peak wrist velocity	1.70/.93 (.45)	1.87/.95 (.44)	.6/.54 (.16)	.63/.56 (.16)

*All correlations significantly different from zero.

Figure Captions

Figure 1. In A, a camera view of the finger, thumb and wrist trajectories and in B, the experimental set-up. In Experiments 1 and 2, the inter-dowel distance (dashed line) was 23 cm.

Figure 2. Representative examples of wrist displacements from single trials for one subject in the small (———), medium (-----), and large (— —) tolerance conditions (Experiment 1).

Figure 3. Tangential wrist velocity traces from the same trials as in Figure 2. For graphic purposes, a straight line was drawn from the origin to the first data point for each trace. Notice that there were no signs of a 'low velocity phase' at the end of these movements, unlike Jeannerod (1984).

Figure 4. Aperture changes in the three tolerance conditions (same trials as in Figures 2 and 3).