Temporal Constraints in Reaching and Grasping Behavior

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Running head: TEMPORAL CONSTRAINTS

Abstract

Under specific task conditions, many types of human movement behavior such as speech, locomotion and handwriting exhibit a temporal constraint on the many potential degrees of freedom in the form of relative timing among movement components. In the present experiments, we show evidence of temporal constraints in the control of adult prehensile movement independent of transport duration (Exp. 1) and initial conditions (Exp. 2). In both experiments, subjects were required to reach and grasp a dowel, mounted vertically on a joystick over a distance of 23 cm. Using light emitting diodes (LEDs) placed on the subjects' finger, thumb and forearm, individual LED trajectories were captured on film and later kinematically analyzed. In Experiment 1, transport duration varied from 300 to 800 ms and in Experiment 2, initial conditions were manipulated by requiring subjects to adopt different initial grip postures. Regardless of these manipulations, little change was observed in the temporal occurrence of maximum aperture and onset of grip closure relative to overall movement duration. Functional coupling between fingers and forearm was indicated by high, within-trial co-variation between aperture size and forearm velocity. These results provide evidence for a temporal contraint on the individual components of prehensile action. Moreover, the spatiotemporal relationship between the hand and the object to be grasped may be viewed itself as a pattern formation process.

Temporal Constraints in Reaching and Grasping Behavior

The human hand is a most versatile and useful organ capable of performing a variety of functions. One categorization of hand function is based on the degree of mobility demanded in various tasks (Tubiana, 1981). A passive function can be identified in which the hand remains flat, or slightly cupped with perhaps only one finger extended for the purposes of carrying, scooping, pointing, pushing, etc. Much of the movement of the hand is indirectly controlled by the proximal part of the arm. The percussive function used in tapping the fingers, clapping the hands, or pounding the fist involves activation of the metacarpophalangeal articulators, the wrist and oftentimes the proximal joints. Functions that demand perhaps the most distal mobility are those which support expressive and prehensile gestures. Expressive gestures are wide-range, involving the hand in collaboration with other structures such as the mouth in speech and language (e.g. Leroi-Gourhan, 1964) and tactile contact during grooming and caressing. And finally, there are the prehensile functions involved in the reaching and grasping of objects with a single hand or two hands in collaboration. How the human hand is controlled has been the subject of several investigations (Jeannerod, 1981, 1984; Marteniuk, MacKenzie, Jeannerod, Athenes & Dugas, 1987; Wallace & Weeks, 1988; Wing & Fraser, 1983; Wing, Turton & Fraser, 1986). In the present study, we attempt to extend our previous work (Wallace & Weeks, 1988) on the problem of how the hand - arm linkage is controlled during the reaching and grasping of objects.

Our experimental paradigm requires the subject to simply reach forward and grasp a target object using a precision grip (Klatzky, McCloskey, Doherty, Pellegrino and Smith, 1987; Napier, 1956) with only the thumb and index finger. A measure of the reach (or transport) component has been the displacement and velocity of the forearm while changes in the aperture (the distance between the transport) component has been the displacement and velocity of the forearm while changes in the aperture (the distance between the index finger and thumb) represent adjustments in the grasp (or manipulation) component. The results from our work and others indicate that from a 'pinched' or small initial aperture, the aperture normally increases continuously to some maximum larger than the diameter of the target object before final closure occurs (von Hofsten & Ronnqvist, 1988; Jeannerod, 1981;1984; Wallace & Weeks, 1988; Wing & Fraser, 1983; Wing, et al., 1986). From our previous work, it appears that while the maximum aperture reached before the actual grasp is dependent on movement time (transport duration) and the size of the target object, the relative time of its occurrence maintains a stable value at roughly 70 % of the movement time. Relative timing, or the phase relation among articulatory components, proves to be a powerful constraint on complex, multidegree of freedom actions - from trajectory formation in the single limb (e.g. Soechting & Terzuolo, 1986) to discrete and rhythmical movements of two limbs (Haken, Kelso & Bunz, 1985; Kelso, Southard & Goodman, 1979) whether they operate at the same (Kelso, 1984) or different frequencies (Kelso & DeGuzman, 1988). A number of other activities, including speech (e.g. Nittrouer et al., 1988; Tuller & Kelso, 1984; in press; Tuller, Kelso & Harris, 1982), typing (Terzuolo & Viviani, 1980), locomotion (Shapiro et al., 1981) and handwriting (Hollerbach, 1981) exhibit stable temporal relationships among movement events, without necessarily obeying a constant proportion model (cf. Gentner, 1987; Heuer, 1988). Good reviews of this timing literature are provided by Schmidt (1988) and Kelso & Tuller (1984). One of the best reasons for claiming that the relative phase is a stable collective variable (cf. Haken, 1983; Haken, 1988) for certain multidegree of freedom movements is that stability can be lost at critical values of a parameter such as movement speed (see e.g. Jeka & Kelso, in press; Schoner & Kelso, 1988 for recent reviews) or spatial orientation (Kelso, Wallace, Buchanan & Murata, in preparation). A more modest test of temporal stability in the reaching and grasping behavior of humans is carried out here, namely, that if relative timing of maximum aperture (or grip closing) is a fundamental characteristic of the prehensile movement pattern, then it should be evident across a wide range of transport durations and be independent of initial conditions. This amounts to saying that an <u>attractor</u> for the collective variable can be identified, and opens the way to theoretical modelling of the phenomenon (see eg., Haken et al., 1985). In the present experiments, transport duration was manipulated by requiring subjects to produce reaching movements ranging from 300 to 800 ms (Exp. 1) and initial conditions were manipulated by requiring subjects to adopt different initial or starting grip postures (Exp. 2). In addition to relative timing measures of maximum aperture and grip closing, we observed how the kinematics of the reach and grasp components co-varied with respect to one another across variations of transport duration and initial grip posture.

Experiment 1

Method

<u>Subjects</u>. Six right handed male volunteers (ages 19-25) served as subjects. All subjects were naive as to the purpose of the experiment.

<u>Apparatus</u>. The apparatus consisted of two plexiglass dowel rods mounted vertically on a table top 23 cm apart. One dowel rod, 3.5 cm in diameter, and 14.5 cm in height, served as the starting point for each movement. A microswitch button was attached on the subject's side of the dowel 17 cm above the table. Depression and subsequent release of this button by the subject's index finger of the

right hand started a millisecond clock which represented initiation a trial. The target dowel to be grasped measured 3 mm in diameter and 14.5 cm in height with a 10 cm cleft running longitudinally down the center of the dowel. Within the cleft were two metallic contacts separated by an intercontact distance of .5 mm. When the contacts were forced together as a result of the subject grasping the dowel, the millisecond clock was halted thus providing movement time from trial initiation to dowel grasp. This second dowel was mounted on a "joystick" device which consisted of two potentiometers that measured displacement of the dowel after the grasp had occurred. A MINC PDP 11-23 computer (Digital Equipment Corporation), utilizing in-house software, recorded dowel movement information from each potentiometer as coordinates in X and Y planes at a sampling rate of 100 hz for 250 ms following closing of the metallic contacts (i.e., dowel grasp). This data was later analyzed to provide dowel movement information in the x-direction (parallel to the movement), y-direction (perpendicualr to the movement) and total resultant dowel movement.

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 lens was parallel 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.

Procedure. Subjects were seated comfortably in a chair with the right elbow flexed at 90 degrees. The right thumb and index finger, held in a pinched 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. No particular instructions or strategies about moving the index finger and thumb during the reaching movement were provided to the subject.

Three different MT conditions were examined in this experiment such that the subject was constrained to perform the entire reach and grasp of the target dowel within temporal limits of the presecribed MT. The three goal MT's were 300, 600, and 800 ms. Around each goal MT, a ±10% temporal bandwidth was allowed. Thus, trials were considered temporally acceptable for the 300 ms condition within a bandwidth of 270-330 ms, 540-660 ms for the 600 ms condition, and 720-880 ms for the 800 ms condition. Three blocks of five trials were recorded for each MT condition such that 15 trials were recorded consecutively per condition. All 15 trials were photographed to maintain a record of the kinematic information for each trial. Each subject participated in all MT conditions with the order of presentation of conditions randomized for each subject.

Subjects were instructed to perform trials within the temporal limits of the MT condition and to grasp and hold the dowel as accurately as possible for up to 1 s. Each trial was initiated by the subject following a ready cue by the experimenter. Immediately following each trial, the subject was provided with knowledge of results in the form of ms to complete the movement. Prior to trials collected for analysis, subjects practiced for the condition to be tested until ten consecutive trials within the temporal limits for that condition were achieved. The intertrial interval was approximately 10 s within which the subject received the MT 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 Theorem, a total resultant dowel movement measure was developed from sampling movement in the x and y directions to quantify grasping 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 the two adjacent samples. All individual hypotenuses during the 250 ms sampling interval were added together to form the total resultant dowel movement (or the total amount of movement of the dowel, regardless of direction during the 250 ms sampling period). In addition, total x-direction and y-direction dowel movement were considered separately for analysis.

Each photographed trial was mounted as a slide and the negative image of the movement was projected onto an x-y digitizer (Bid Pad One, Summagraphics Corp., resolution: .1 mm). Digitization converted the movement path of the forearm (wrist), finger, and thumb LEDS to x-y coordinates for each trial. This digitized raw data was then subjected to a cubic 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 were then analyzed by in-house software programs to obtain a variety of kinematic information about the finger/thumb aperture (and velocity) and forearm displacement (and velocity). The kinematic information was also averaged across the 5 trials per block to obtain mean scores for each subject per block within each condition.

Primary statistical analysis of average data was accomplished by employing multivariate analyses of variance (MANOVA) techniques to perform two way within subject ANOVA's for each dependent variable with MT condition and block (3 x 3 design) as within-subject independent variables. However, neither block effects nor any interactions involving blocks were significant. Therefore, the reported results represent means collapsed across blocks for each MT condition.

Results

Movement time. As shown in Table 1 , the mean movement times obtained were very near the desired goal movement times. As was expected, the movement time main effect was significant with $F(2,58) = 5909$, $p < .001$.

Insert Table 1 about here

Resultant dowel movement. The means for each condition displayed in Table 1 indicate an apparent speed-accuracy trade-off not only in total dowel movement, but also in dowel displacement both parallel and perpendicular to the direction of the reaching movement. Total resultant dowel movement was significantly affected by decreases in MT yielding an $F(2, 10) = 10.81$, $p < .005$. Dowel movement in the x-direction increased significantly as movement time decreased, $F(2,10) = 6.9$, $p < .05$ and the MT effect was significant in the y-direction with $F(2,10) = 15.9$, $p < .001$.

Forearm and aperture displacement. Figure 1 illustrates example individual trajectories of the index finger, thumb and forearm in the three movement conditions. Forearm trajectory was somewhat curvilinear in all conditions, and aperture between the finger and thumb opened to a different maximum (depending on movement time) before closing down on the target dowel (see Table 1). Figure 2 illustrates the kinematics of these three movements in terms of forearm and aperture displacement as well as their respective velocities.

Insert Figures 1 and 2 about here

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Forearm velocity analyses. As displayed in Table 1, the mean peak forearm velocity increased with decreased MT. This effect was significant with $F(2,4) = 278.3$, $p < .001$. The percent time and distance to achievement of peak forearm velocity varied little across all MT conditions with F's for both main effects less than 1. Table1 indicates that the temporal and spatial occurrence of peak forearm velocity was approximately midway through the movement.

Finger/thumb aperture analyses. Mean maximum apertures for each condition are displayed in Table1. Maximum aperture increased significantly as MT decreased, $F(2,4) = 54.1$, $p < .01$. The relative timing of maximum aperture did not significantly change across conditions, with $F(2,4) < 1$, and it occurred at approximately 70% of the movement time regardless of condition. For percent distance to maximum aperture, a small but significant MT effect occurred, $F(2,4) = 4.66$, $p < .05$. Maximum aperture was achieved after approximately 80-90% of the distance had been traversed in all MT conditions. Peak closing velocity (defined as the highest instantaneous aperture velocity following maximum aperture) increased significantly as MT decreased with $F(2,4) = 29.02$, $p<.01$ (see Figure 2).

Relationship between forearm velocity and aperture size.

A qualitative examination of the data revealed that the manner in which the forearm and aperture co-varied with respect to one another appeared to depend on transport duration. In the first half of the movement, the relationship between forearm velocity and aperture size was roughly linear regardless of transport duration. After peak forearm velocity, this relationship remained rather linear in the 300 ms condition, and became increasingly non-linear in the 600 and 800 ms conditions. Thus, we applied the Pearson product-moment correlation procedure to verify this qualitative description.[1] Within trial relations between peak forearm velocity and finger/thumb aperture before and after peak forearm velocity are displayed in Table 2 and graphic examples from each of the six subjects are shown in Figure 3 and 4. Before versus after (peak forearm velocity) was included as an additional within-subject factor in analysis of the correlations. In addition, the obtained Pearson correlations were transformed to Fisher's Z values prior to application of MANOVA procedures. The results from this analysis tended to confirm our qualitative descripition. Both MT and Portion of Movement main effects were significant. Higher correlations were found in the 300 ms condition and in the first half of the movement. A MT by before versus after interaction was only marginally significant, $F(2,4) = 6.48$, $p<.10$ and indicated that, on average, the lowest correlations were in the second half of the movement in the 800 ms condition.

Insert Table 2, Figure 3 and Figure 4 about here

Discussion

There were several features of the present experiment which replicated our earlier work (Wallace & Weeks, 1988). First, the size of maximum aperture during transport was related to the duration of the reaching movement. As the duration of transport reduced (speed increased), subjects produced larger maximum apertures and closed down on the target object with greater final peak closing velocities. However, the temporal occurrence of maximum aperture remained a fixed percentage of the movement time supporting earlier work (Wallace & Weeks, 1988). Second, grasping accuracy, as estimated by resultant target dowel movement, was inversely related to movement time. Dowel movement both perpendicular and parallel to the movement was equally effected by movement time although dowel movement parallel to the reaching movement was slightly greater. Third, movement time appeared to affect the manner in which the transport and manipulation components covaried with one another as reflected by the within-trial forearm velocity and aperture size correlations. Figures 3 and 4 illustrate that up to peak forearm velocity a strong linear relationship existed between the components regardless of transport duration. Following peak forearm velocity, the covariation of the components became more non-linear as transport duration increased. In particular, it appeared that motions of the two components became more independent in the later stages of the movement with significant reductions in aperture observed in the absence of comparable forearm movement.

Experiment 2

This experiment examined the effect of initial grip posture, as reflected by size of aperture, on the relative motions of the two components. We required subjects to start their reaching movement in either a closed aperture (index finger and thumb pinched together) or an open aperture (index finger and thumb separated to approximately 75% of maximum) initial grip posture. From the open posture, aperture would clearly have to reduce to grasp the target dowel, however, we were particularly interested in whether this reduction would be related to within-trial changes in forearm velocity and whether movement time would influence the magnitude of this relationship. Also, the relative timing of final grip closure was investigated.

Method

Subjects. Six right-handed male volunteers served as subjects. None of the subjects participated in the first experiment, and all were naive as to the purpose of the experiment.

Apparatus. The apparatus was identical to that used in the previous experiment. Data collection and analysis procedures were also identical to those of the previous experiment.

Procedure. The grasping task utilized in this experiment was identical to that in Experiment 1. Following placement of light emitting diodes on the the subject's index finger, thumb and forearm (wrist), maximum aperture was determined by requiring the subject to spread his index finger and thumb as far as possible and using a centimeter ruler, this distance was recorded. In the open condition, the subject was instructed to initiate the grasping movement by assuming a pre-movement finger/thumb aperture of 75% maximum aperture. A second condition required the subject to adopt the closed pinch initial starting position utilized in the first experiment. As in

Experiment 1, no particular strategy for moving the index finger and thumb during the reaching movement was given to the subject in either condition. Movement time conditions of 300 and 800 ms were used, again with a ± 10% bandwidth for acceptable MT's. Following a minimum of 10 practice trials, 15 experimental trials were collected per condition and later divided into blocks of five to be included in statistical analyses. A grip by MT by block design (2 x 2 x 3) was used. However, again no statistically significant blocks effects or interactions were observed. Therefore, reported means per MT and grip type condition were again collapsed across blocks. All subjects participated in all experimental conditions which were randomized across subjects.

Results

Movement time. As shown in Table 3, the two movement time conditions were different from one another. No other main effects or interactions were significant.

Table 3 about here

Resultant dowel movement. A decrease in MT caused a significant increase in dowel movement in the x-direction, $F\ (1,5) = 97.1$, $p<.01$. Neither the grip manipulation (open or closed) nor any interactions were significant (all F's<1). Decreased MT also significantly increased the amount of dowel movement in the y-direction $F\ (1,5) = 39.43$, $p<.01$. Neither the grip type effects nor interactions were significant (F's<1). Total resultant dowel movement was again signficantly affected by MT manipulation, $F\ (1,5) = 61.39$, $p<.01$. Neither the grip type effect nor any interactions reached significance.

Figure 5 and 6 about here

Forearm velocity analyses. Forearm velocity was significantly affected by grip type with the open grip forearm velocities slightly higher than the closed grip velocities, $F(1,5) = 50.08$, $p<.01$. As would be expected, MT manipulation also significantly affected forearm velocity, $F(1,5) = 308$, $p<.001$. The MT by grip interaction reached signficance, $F(1,5) = 41.1$, $p<.01$. The highest velocities were achieved in the open grip, 300 ms condition as determined by a simple main effects test (Kirk, 1982).

The percent time and percent distance to peak forearm velocity were both significantly affected by MT with $Fs(1,5) = 33.3$, $p<.01$ and $F(1,5) = 65.6$, $p<.001$, respectively. Time to peak velocity occurred at about 47 percent for the 300 ms condition and about 43 percent for the 800 ms condition. No other significant main effects or interactions were obtained.

Table 4 about here

Closed grip finger/thumb aperture analyses. As MT decreased, maximum aperture in the closed condition increased significantly, $F(1,5) = 16.6$, $p<.05$. The closed grip peak finger/thumb closing velocity also significantly increased as MT decreased, $F(1,5) = 65.2$, $p<.001$. The percent distance and percent time of maximum aperture occurrence was not significantly different across MT conditions with all F's<1.5.

Open grip finger/thumb aperture analyses. In the open condition, it was difficult to use aperture displacement in determining percent of movement time. To quantify the point in time at which this increase in closing velocity occurred, points at which final closing velocity onset occurred were digitized via interactive computer analysis. Table 5 indicates that the times to initiation of final aperture closing velocity were roughly 70% of the movement time in both movement time conditions and not significantly different from one another, $F(1,5)=5.59$, $p>.05$. These times were also not significantly different than the times to maximum aperture in the closed conditions, $F(1,5)<1$.

Table 5 about here

Relationship between forearm velocity and aperture size. In the closed grip condition, the correlations were similar to those in Experiment 1. High positive correlations were found in the first half of the movement regardless of transport duration. In the second half of the movement the correlations were lower, particularly in the 800 ms condition.

Table 6 and Figures 7 and 8 about here

In the open grip condition many negative, but high correlations were obtained in the first half of the movement (up to peak forearm velocity) due to decreasing aperture size accompanied by increasing forearm velocity. Following peak forearm velocity, the correlations were slightly lower but positive. The grip type effect was significant, $F(1,5) = 56$, $p<.01$, with slightly higher absolute values for correlations occurring in the open grip condtion. Correlations were signficantly larger before peak forearm velocity than after with $F(1,5) = 2.41$, $p<.05$

and the MT effect was also significant, $F(1,5) = 22.4$, $p<.01$. No interactions were significant (all F's<2.6).

Figures 9 and 10 about here

Discussion

In the closed grip condition, the relative time to maximum aperture was not significantly different in the 300 and 800 ms conditions. These results are consistent with those found in Experiment 1. In the open grip condition, this type of measurement was not possible since maximum aperture actually occured at the start of the reaching movement. However, the relative time to final closing velocity was similiar in the two movement time, open grip conditions and this kinematic event was not significantly different from the relative time to maximal aperture in the closed conditions.

The within-trial aperture size and forearm velocity correlational analysis suggested that regardless of initial grip posture, there was a strong statistical association between these two variables especially in the first half of the movement (up to peak forearm velocity). In the open condition, the correlations were high, but negative, indicating that as forearm velocity increased, aperture size decreased in a highly related manner. In the closed condition, as in Experiment 1, both of these variables increased until the occurrence of peak forearm velocity. In the second half of the movement, the correlations for both conditions were smaller, particularly in the slower movement time condition.

General Discussion

The present study provided additional support for our view (Wallace & Weeks, 1988) of the existence of temporal constraints on the control of prehensile movement. In the first experiment, we showed that the temporal duration of the reach affects not only the kinematics of the forearm (or transport component) but also influences several kinematic features of the grasp, as measured by aperture displacement and velocity. As the duration of the reach reduces (with distance constant), the maximum aperture prior to the grasp also increases, supporting earlier work by Wing et al., (1986). We demonstrated earlier (Wallace & Weeks, 1988) that this effect is due to changes in the duration of the reach and not necessarily due to its velocity as suggested by Wing et. al. However, it remains a possibility, as hypothesized by Wing and colleagues that the size of maximum aperture reflects an anticipation on the part of the subject of the expected size of the grasping error. The resultant target dowel movement data provided in the present study can be considered as one type of grasping error. As transport duration reduces (and speed increases), the finger and thumb apparently impact the object harder, thus displacing it farther following more rapid aperture closing velocities. The subject may learn through experience to widen maximum aperture to increase the likelihood of a successful grasp of the object.

The kinematic scaling of both the reach <u>and</u> the grasp components as transport duration is reduced may be taken as evidence for some type of functional coupling (as opposed to that of a mechanical or inertial type, see Lacquaniti & Soechting, 1982). Further support for this coupling comes from the high within-trial correlations between changes in aperture and forearm velocity (Experiment 1) regardless of initial conditions (Experiment 2). As transport duration reduced, the correlation between these measures increased, reflecting an <u>increase</u> in the covariation of the reach and the grasp. In slower movements (greater transport durations), the individual trajectories of the reach and grasp components can be dissociated from one another and the components moved independently. For example, this can be seen in Figures 3 and 4 in the 800 ms condition, particularly in the second half of the movement. Von Hofsten & Ronnqvist (1988) have recently argued that this type of control is rare, even in infants, yet our data, generated of course in a rather different paradigm, suggest that it is observable in slower reaching movements. In many natural acts, the degrees of freedom appear to be functionally, though not mandatorily, coupled. Functional coupling may take the form of a temporal constraint on the many degrees of freedom.

In spite of the transport duration effects on the within-trial association of the reach and grasp, certain features remained stable in that relative timing to maximum aperture (both experiments) and time to onset of final grip closing (Experiment 2) changed little across different transport durations. The fact that these two kinematic events occurred close to one another in relative time may be due, in part, to our sampling rate (50 Hz). A higher sampling frequency may help to quantitatively distinguish the two events in time. Using a sampling frequency of 300 Hz for example, von Hofsten & Rönnqvist (1988) were able to independently measure both maximum aperture and the onset of final closing in infant and adult reaching. Their data suggest that onset of final closing is delayed relative to maximum aperture but the extent of this delay is unclear from their analysis because relative times to both maximum aperture and final closing were not reported on a within-trial basis. Although our data indicate that the two events normally occur close in time, exceptions were observed. In Figure 6, it can be seen that the subject reached maximum aperture in the closed condition much earlier in the reach relative to final closing aperture velocity (approximately 40% and 80% of relative time, respectively). This early attainment of maximum aperture characterized the grip displacement of this subject across most trials. It could be that the temporal occurrence of maximum aperture is not as critical as the time to final closure for a successful grasp. Another possibility is that the critical feature for a successful grasp is the size of the aperture at the onset of final closing. Further research is needed to explore these speculations.

Nevertheless, if some type of relative timing is consistently observed, characterization of the reaching and grasping pattern might shift from the 'metering out' of time by a stored, motor program (e. g., Schmidt, 1988) or a "centrally generated temporal template" (Jeannerod, 1984, pg. 252), to one in which the spatiotemporal relationship between hand and object is viewed itself as a kind of pattern formation. Only certain temporal relationships between hand and object may be stable, if the hand is to make a soft collision with an object. The infant feeding herself/himself or being fed by an adult offers a useful image of what we mean. All degrees of freedom may be subservient to the temporal relationship between mouth opening and the handheld spoon. On a less metaphorical note, recent work by Kelso and collegues shows that a small set of temporal relations is stable when the hand must track a periodic event whose frequency is changed over a wide range (1 to 3.5 Hz in steps of .25 Hz; Kelso, DelColle, Schöner, in press). Supporting this claim was the abrupt, nonlinear shift from one temporal pattern to another at a critical tracking frequency. All the results were reproduced by a simple model of the collective variable dynamics, in this case where the collective variable was the relative phase between actor (hand) and environment (visual tracking frequency). Following the synergetic or dynamic pattern strategy (Haken, et al., 1985; Kelso & Scholz, 1985; Schöner & Kelso, 1988) all observed patterns at the <u>pattern</u> level of description were derived by cooperatively coupling the components at a lower level of description (cf. Kelso et al., in press). Identifying collective variable(s) for hand-object patterns and their dynamics (stability, loss of stability) in the present paradigm may be crucial to understanding how other (e.g., articulatory) degrees of freedom are organized that subserve these patterns. Experiments motivated by this shift in focus are underway, with the aim of establishing a closer theory - experiment relation for reaching and grasping objects and for hand function in general.

References

Gentner, D. R. (1987). Timing of skilled motor performance: Tests of the proportional duration model. Psychological Review, 94, 255-276.

Haken, H. (1983). Advanced synergetics. Springer-Verlag. New York.

Haken, H. (1988). Synergetics. IEEE Circuits and Devices Magazine. Nov. 3-7.

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. Biological Cybernetics, 51, 347-356.

Heuer, H. (1988). Testing the invariance of relative timing: Comment on Gentner (1987). Psychological Review, 95, 552-557.

Hofsten, C. von. & Rönnqvist, L. (1988). Preparation for grasping an object: A developmental study. Journal of Experimental Psychology: Human Perception and Performance, 14, 610-621.

Hollerbach, J. (1981). An oscillatory theory of handwriting. Biological Cybernetics, 39, 139-156.

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

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

Jeka, J. J. & Kelso, J. A. S. (in press). The dynamic pattern approach to coordinated behavior: A tutorial review. In S. A. Wallace (Ed.). Perspectives on the coordination of movement. Advances in Psychology series, North - Holland publishers.

Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. American Journal of Physiology: Regulatory, Integrative and Comparitive Physiology, 15, R1000-R1004.

Kelso, J. A. S., & de Guzman, G. C. (1988). Order in time: How the cooperation between the hands informs the design of the brain. In H. Haken (Ed.), Neural and synergetic computers. Springer - Verlag, Berlin, Heidelberg.

Kelso, J. A. S., DelColle, J. D. & Schöner, G. (in press). Action - perception as a pattern formation process. in M. Jeannerod (Ed.), Attention and Performance XIII. Erlbaum, Hillsdale, N.J.

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., & Scholz, J. P. (1985). Cooperative phenomena in biological motion. In H. Haken (Ed.), Complex systems: Operational approaches in neurobiology, physical systems and computers. Springer-Verlag, Berlin, 124-129.

Kelso, J. A. S., Wallace, S. A., Buchanan, J. J., & Murata, T. (in preparation). Phase transitions and trajectory formation in single, multijoint limb patterns.

Kirk, R. E. (1982). Experimental design: Procedures for the behavioral sciences. Brooks/Cole Publishing Co., 2nd edition.

Klatzky, R. L., McCloskey, B., Doherty, S., Pellegrino, J. & Smith, T. (1987). Knowledge about hand shaping and knowledge about objects. Journal of Motor Behavior, 19, 187-213.

Lacquaniti, F., & Soechting, J. F. (1982). Coordination of arm and wrist during a reaching task. Journal of Neuroscience, 2, 399-408.

Leroi-Gourhan, A. (1964). Le Geste et la Parole. Paris, Albin Michel.

Marteniuk, G.G., MacKensie, C. L., Jeannerod, M., Athenes, S. & Dugas, C. (1987). Constraints on human arm trajectories. Canadian Journal of Psychology, 41, 365-378.

Napier, J. R. (1956). The prehensile movements of the human hand. Journal of Bone and Joint Surgery, 38 B, 902-912.

Nittrouer, S., Munhall, K., Kelso, J. A. S., Tuller, B. & Harris, K. (1988). Patterns of interarticulator phasing and their relation to linguistic structure. The Journal of the Acoustic Society of America, 84, 1653-1661.

Schmidt, R. A. (1988). Motor and action perspectives on motor behavior. In O. G. Meijer & K. Roth (Eds.), Complex movement behavior: The motor-action controversy. Advances in Psychology series, 50, 3-44, North-Holland.

Schoner, G., & Kelso, J. A. S. (1988). Dynamic pattern generation in behavioral and neural systems. Science, 239, 1513-1520.

Shapiro, D. C., Zernicke, R. F., Gregor, R. J., & Diestel, J. D. (1981). Evidence for generalized motor programs using gait pattern analysis. Journal of Motor Behavior, 13, 33-47.

Soechting, J. F., & Terzuolo, C. (1986). An algorithm for the generation of curvilinear wrist motion in an arbitrary plane in three-dimensional space. Neuroscience, 19, 1393-1405.

Terzuolo, C., & Viviani, P. (1980). Determinants and characteristics of motor patterns used for typing. Neuroscience, 5,1085-1103.

Tuller, B. & Kelso, J. A. S. (1984). The timing of articulatory gestures: Evidence for relational invariants. The Journal of the Acoustical Society of America, 76, 1030-1036.

Tuller, B. & Kelso, J. A. S. (in press). Phase transitions in speech production and their perceptual consequences. In M. Jeannerod (Ed.), Attention and Performance, XIII, Erlbaum.

Tuller, B., Kelso, J. A. S., & Harris, K. S. (1982). Interarticulatory phasing as index of temporal regularity in speech. Journal of Experimental Psychology: Human Perception and Perception, 8, 460-472.

Tubiana, R. (1981). Architecture and functions of the hand. In R. Tubiana (Ed.), The hand, 1, Philadelphia: W. B. Saunders, 19-93.

Wallace, S. A. & Weeks, D. L. (1988). Temporal constraints in the control of prehensile movements. Journal of Motor Behavior, 20, 81-105.

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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Footnotes

1. We should indicate our caution in using the linear correlation procedure on data which, when taken as a whole, are non-linear. Also, it is arbitrary as to where one applies two correlations to fit the total curve. We used the linear correlation procedure to simply verify our qualitative observations that the covariation of aperture size and forearm velocity is clearly different in the first versus the second half of the reaching movement. The functional significance of this difference in covariance must await further study.

Table 1

Means and Standard Deviations for Various Kinematic Measures in the Three Movement Time Conditions for Experiment 1

	Movement Time		
	300	600	800
Movement Time (ms)	303 (16)	601 (28)	800 (41)
X- Direction Dowel Movement (cm)	3.1 (2.1)	1.0 (.3)	0.9 (.3)
Y- Direction Dowel Movement (cm)	3.1 (1.7)	0.9 (.5)	0.7 (.21)
Total Resultant Dowel Movement (cm)	4.5 (2.5)	1.4 (.4)	1.2 (.3)
Peak Forearm Velocity (cm/s)	117 (9)	74 (6)	57 (5)
Time to Peak Forearm Velocity (%)	48 (6)	48 (5)	46 (3)
Distance to Peak Forearm Velocity (%)	50 (6)	47 (4)	45 (4)
Maximum Aperture (cm)	8 (.9)	6 (.5)	6 (.6)
Time to Maximum Aperture (%)	69 (9)	74 (7)	73 (8)
Aperture Peak Closing Velocity (cm/s)	72 (19)	30 (10)	22 (5)

Table 2

Correlation Coefficients Between Forearm Velocity and Finger/Thumb Aperture Before and After Peak Forearm Velocity. Fisher's Z Transformations are in Parentheses.

	Movement Time		
Portion of Movement	300	600	800
Before	.913 (1.57)	.917 (1.58)	.920 (1.60)
After	.812 (1.14)	.533 (0.60)	.473 (0.52)

Table 3

Means and Standard Deviations for Movement Time and Resultant Dowel Movement of the Open and Closed Grip Conditions in Experiment 2

	Movement Time	
	300	800
Closed Grip MT (ms)	301 (12)	800 (32)
Open Grip MT	304 (16)	798 (29)
Closed Grip X-Direction Dowel Movement (cm)	2.5 (.9)	1.1 (.1)
Open Grip X-Direction Dowel Movement	2.4 (1.2)	1.1 (.4)
Closed Grip Y-Direction Dowel Movement	2.4 (.8)	.9 (.4)
Open Grip Y-Direction Dowel Movement	2.1 (.7)	1.0 (.3)
Closed Grip Total Resultant Dowel Movement	3.6 (.9)	1.4 (.4)
Open Grip Total Resultant Dowel Movement	3.3 (1.4)	1.5 (.4)

Table 4

Means and Standard Deviations for Forearm Velocity in Experiment 2

	Movement Time	
	300	800
Closed Grip Peak Forearm Velocity (cm/s)	109 (12)	55 (6)
Open Grip Peak Forearm Velocity	129 (10)	60 (10)
Closed Grip Time to Peak Forearm Velocity (%)	47 (4)	43 (5)
Open Grip Time to Peak Forearm Velocity	44 (5)	38 (5)
Closed Grip Distance to Peak Forearm Velocity (%)	47 (4)	42 (5)
Open Grip Distance to Peak Forearm Velocity	47 (4)	42 (4)

Table 5

Means and Standard Deviations for Aperture Analysis in Experiment 2

	Movement Time	
	300	800
Closed Grip		
Maximum Aperture (cm)	7.1 (1.5)	5.4 (1.6)
Distance to Maximum Aperture (%)	76 (12)	75 (18)
Time to Maximum Aperture (%)	74 (8)	63 (14)
Peak Aperture Closing Velocity (cm/s)	74.5 (19.4)	28.5 (9.1)
Open Grip		
Time to Initiation of Final Aperture Closing Velocity	71 (5)	64 (8)

Table 6

Correlation Coefficients Between Forearm Velocity and Finger/Thumb Aperture Before and After Peak Velocity in Experiment 2. Fisher's Z Transformations are in Parentheses.

		Movement Time	
Grip Condition	Portion of Movement *	300	800
Closed	Before	.94 (1.75)	.89 (1.44)
	After	.85 (1.25)	.46 (.5)
Open	Before	-.97 (-2.07)	-.96 (-1.9)
	After	.95 (1.80)	.89 (1.44)

* In relation to peak forearm velocity

Figure Captions

Figure 1. Photographs from the same subject grasping the target dowel from an initial 'closed' or pinched finger-thumb aperture under three transport durations. In A, B, and C, transport durations are 800, 600 and 300 ms, respectively. Sampling frequency was 50 Hz.

Figure 2. Forearm displacement, forearm velocity, aperture and its velocity of the three movements shown in Figure 1. Notice that maximum aperture and maximum peak closing velocity is dependent on transport duration although the difference between the 600 and 800 ms conditions, in this case, is small.

Figure 3. Within-trial correlations between forearm velocity and aperture size across the three transport durations in subjects A, B and C. Open squares are correlations up to peak forearm velocity and closed diamonds are correlations following peak forearm velocity. In most cases, the correlations up to peak forearm velocity are high but systemmatically reduce in the second half of the movement as a function of transport duration. Exceptions to these results were noteable (see subject D - 300 ms condition and subject E - 800 ms condition in Figure 4).

Figure 4. Within-trial correlations between forearm velocity and aperture size across the three transport durations in subjects D, E and F.

Figure 5. Forearm displacement and its velocity in the open and closed grip conditions across both transport durations in Experiment 2. Trials are from the same subject.

Figure 6. Aperture and its velocity in the open and closed grip conditions across both transport durations in Experiment 2. Data are from same trials shown in Figure 5. Notice that in this subject, maximum aperture is reached prior to final closing velocity in the 300 ms, closed condition.

Figure 7. Closed grip within-trial correlations between forearm velocity and aperture size across both transport durations from subjects A, B and C in Experiment 2.

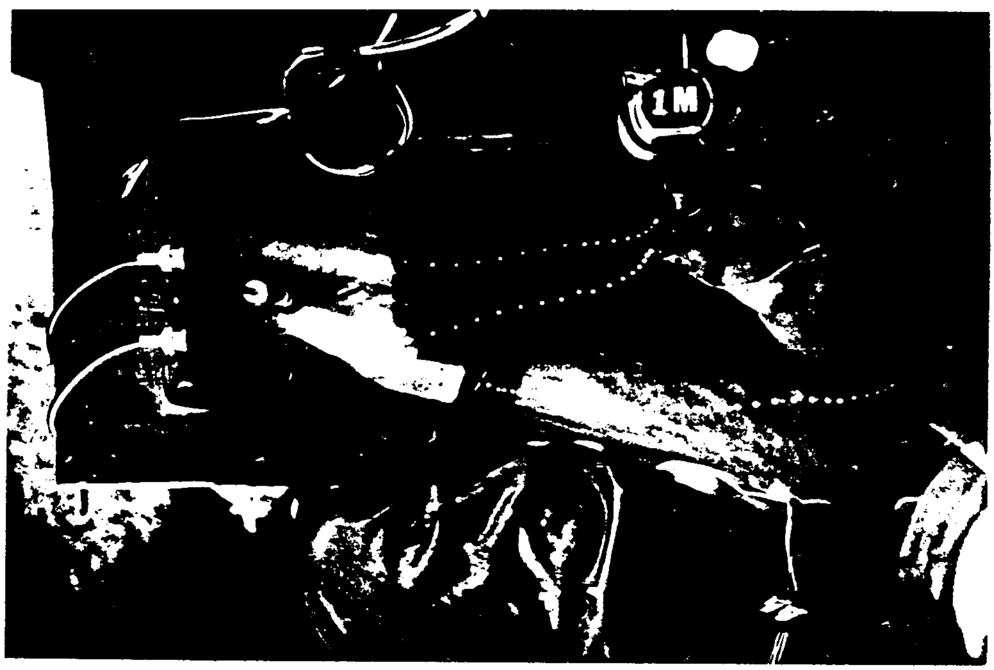
Figure 8. Closed grip within-trial correlations between forearm velocity and aperture size across both transport durations from subjects D, E and F in Experiment 2.

Figure 9. Open grip within-trial correlations between forearm velocity and aperture size across both transport durations from subjects A, B and C in Experiment 2.

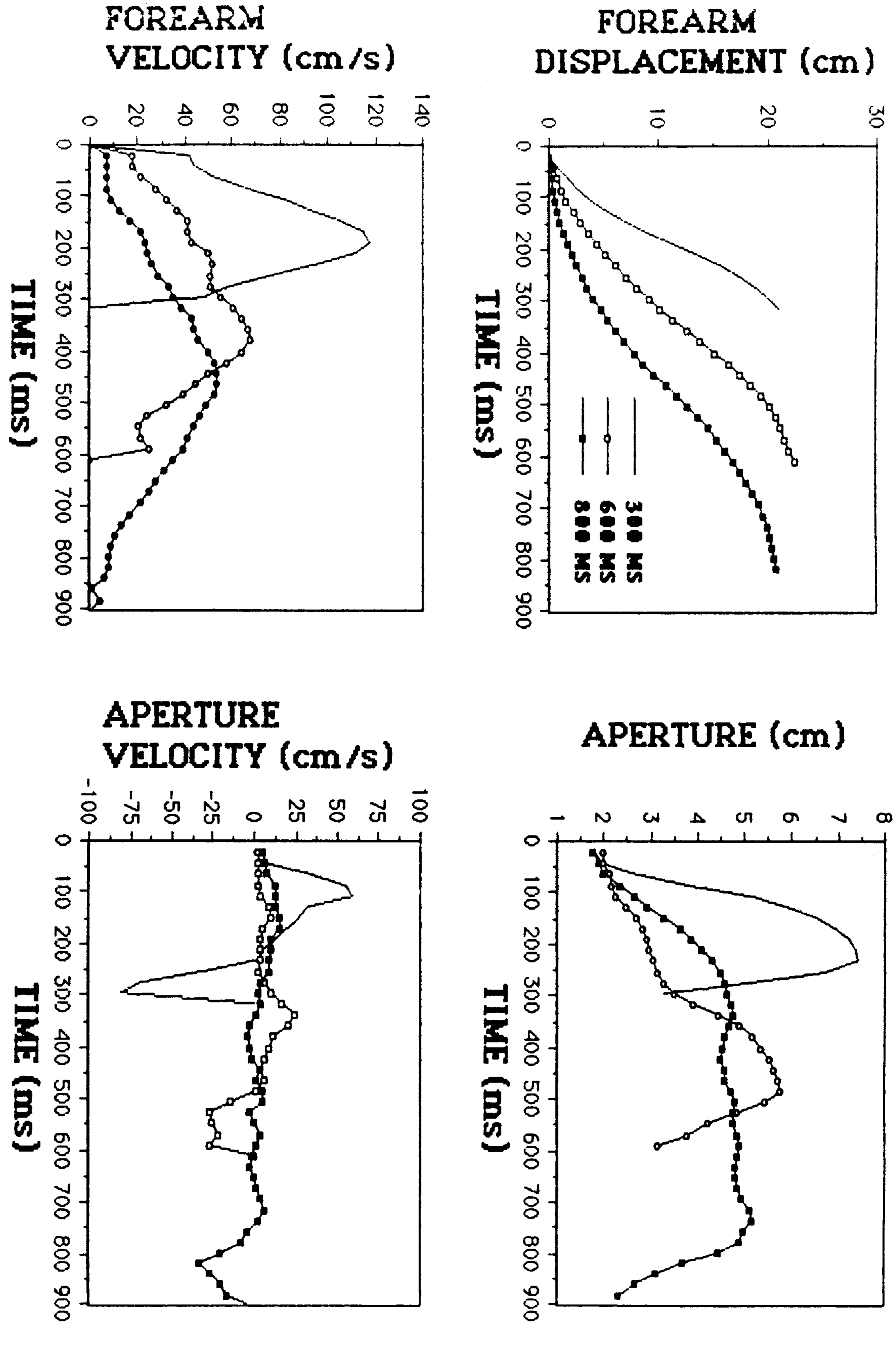
Figure 10. Open grip within-trial correlations between forearm velocity and aperture size across both transport durations from subjects D, E and F in Experiment 2.

A

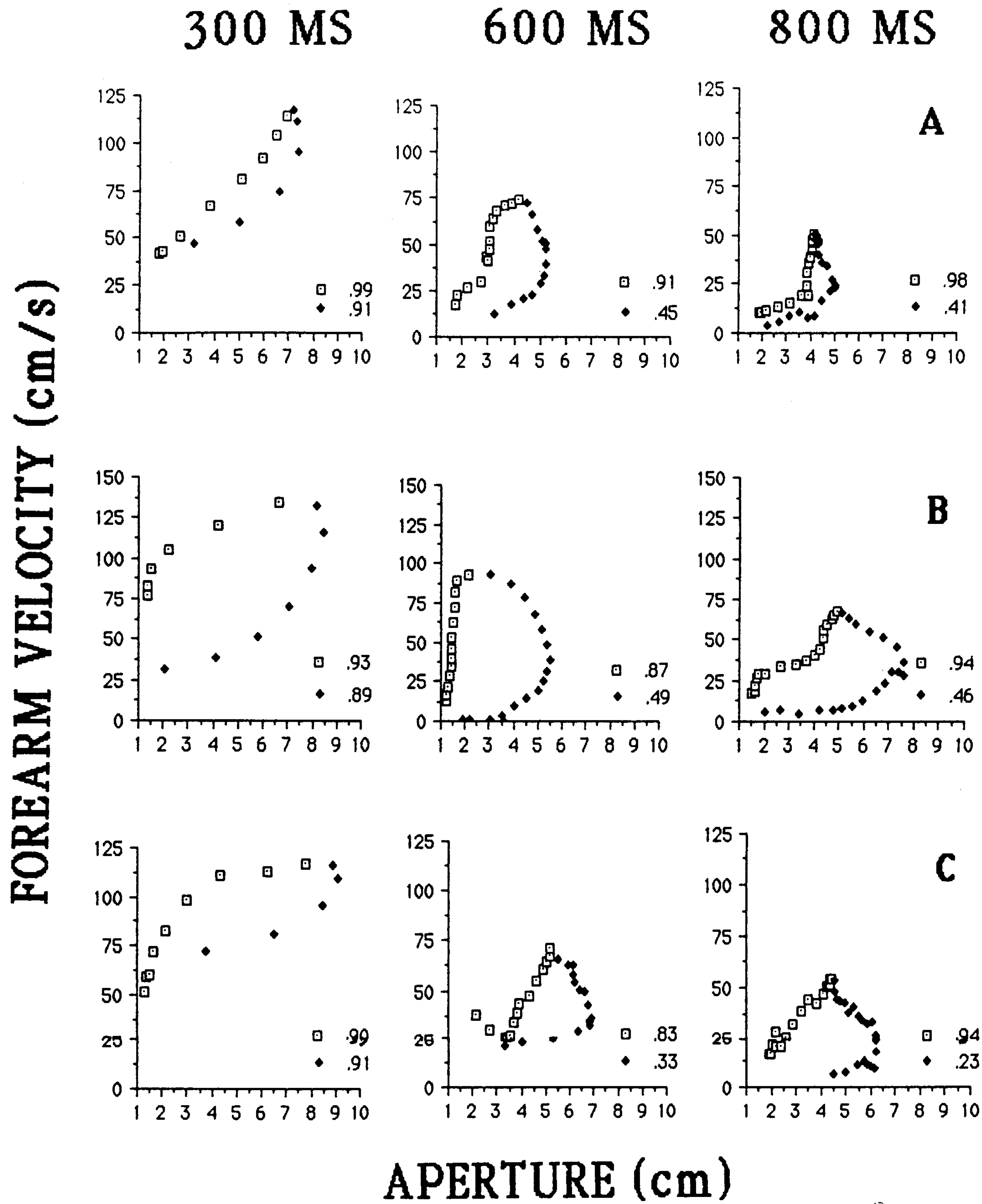
B



C



FOREARM DISPLACEMENT (cm)
300 MS
600 MS
800 MS
TIME (ms)
APERTURE (cm)
TIME (ms)
FOREARM VELOCITY (cm/s)
TIME (ms)
APERTURE VELOCITY (cm/s)
TIME (ms)


300 MS
600 MS
800 MS
A
B
C
FOREARM VELOCITY (cm/s)
APERTURE (cm)
.99
.91
.91
.45
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.93
.89
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.94
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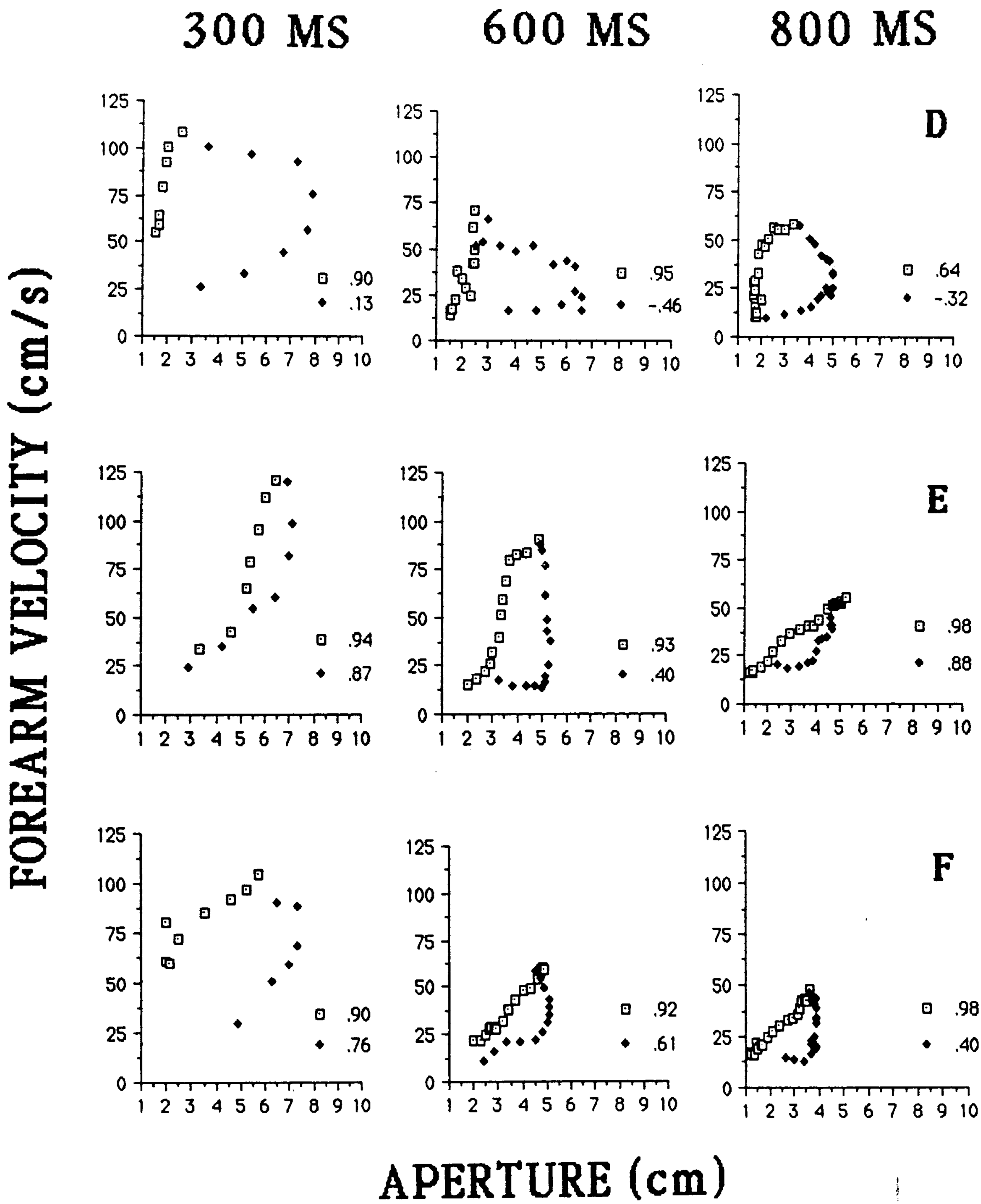
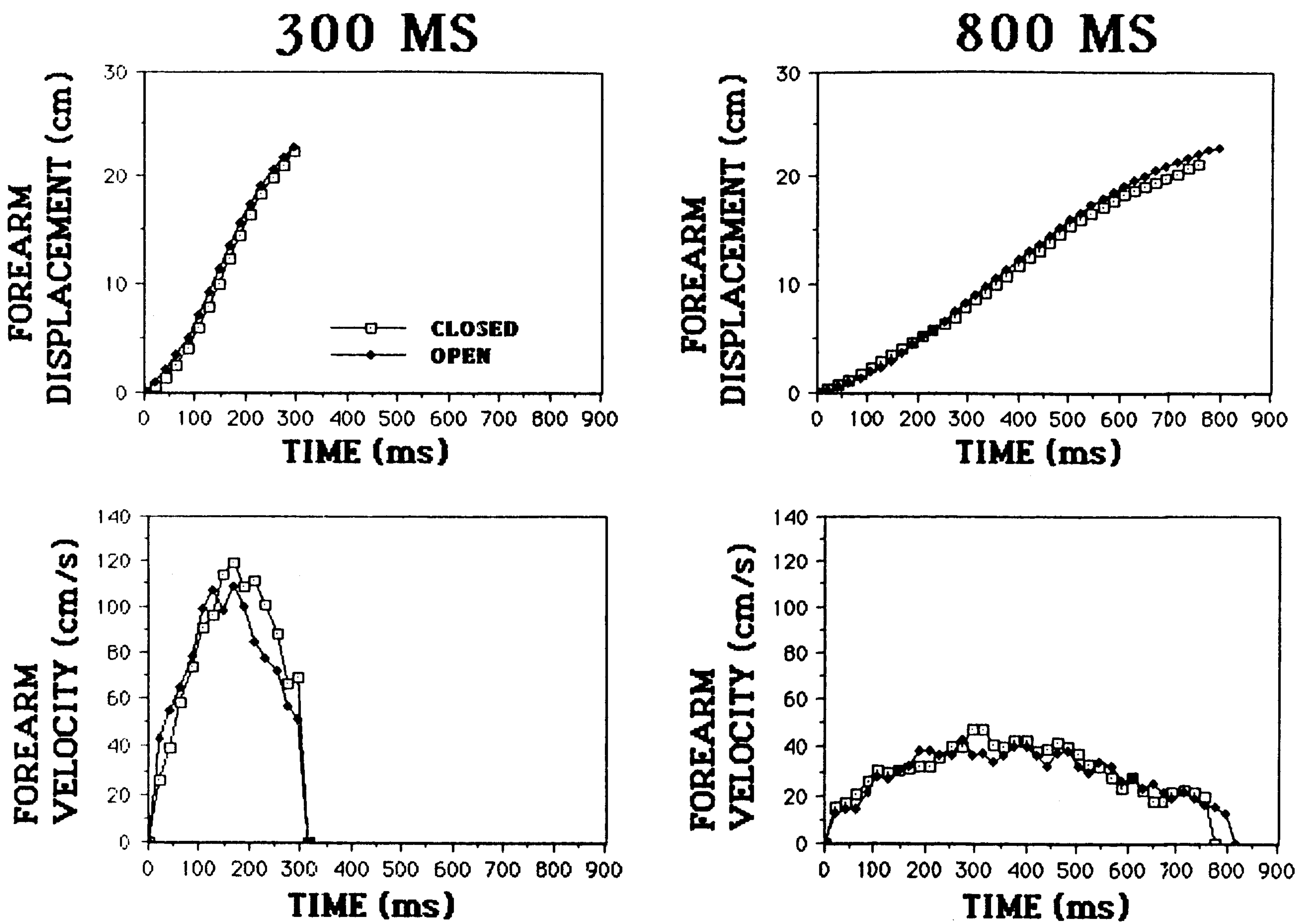
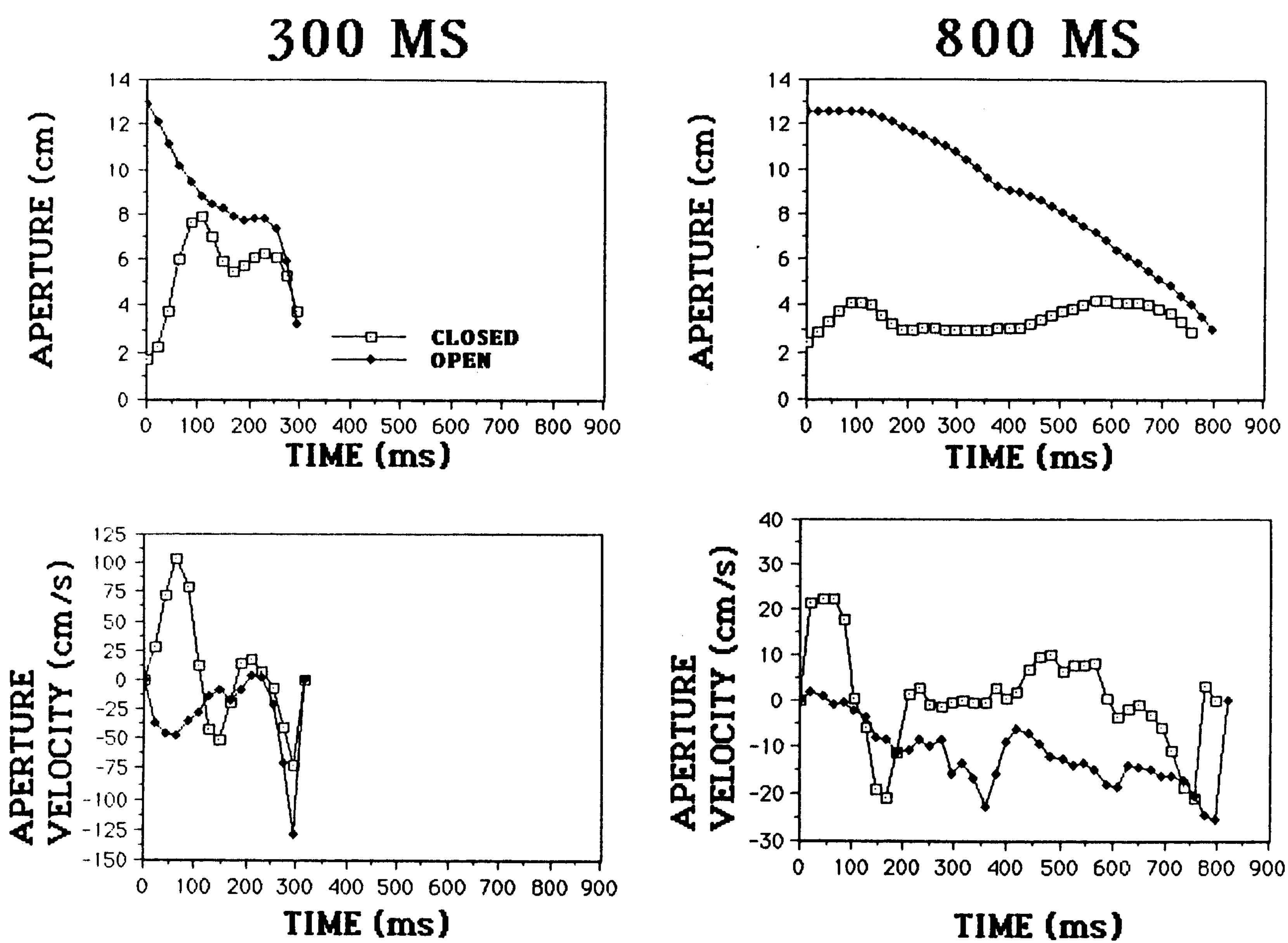
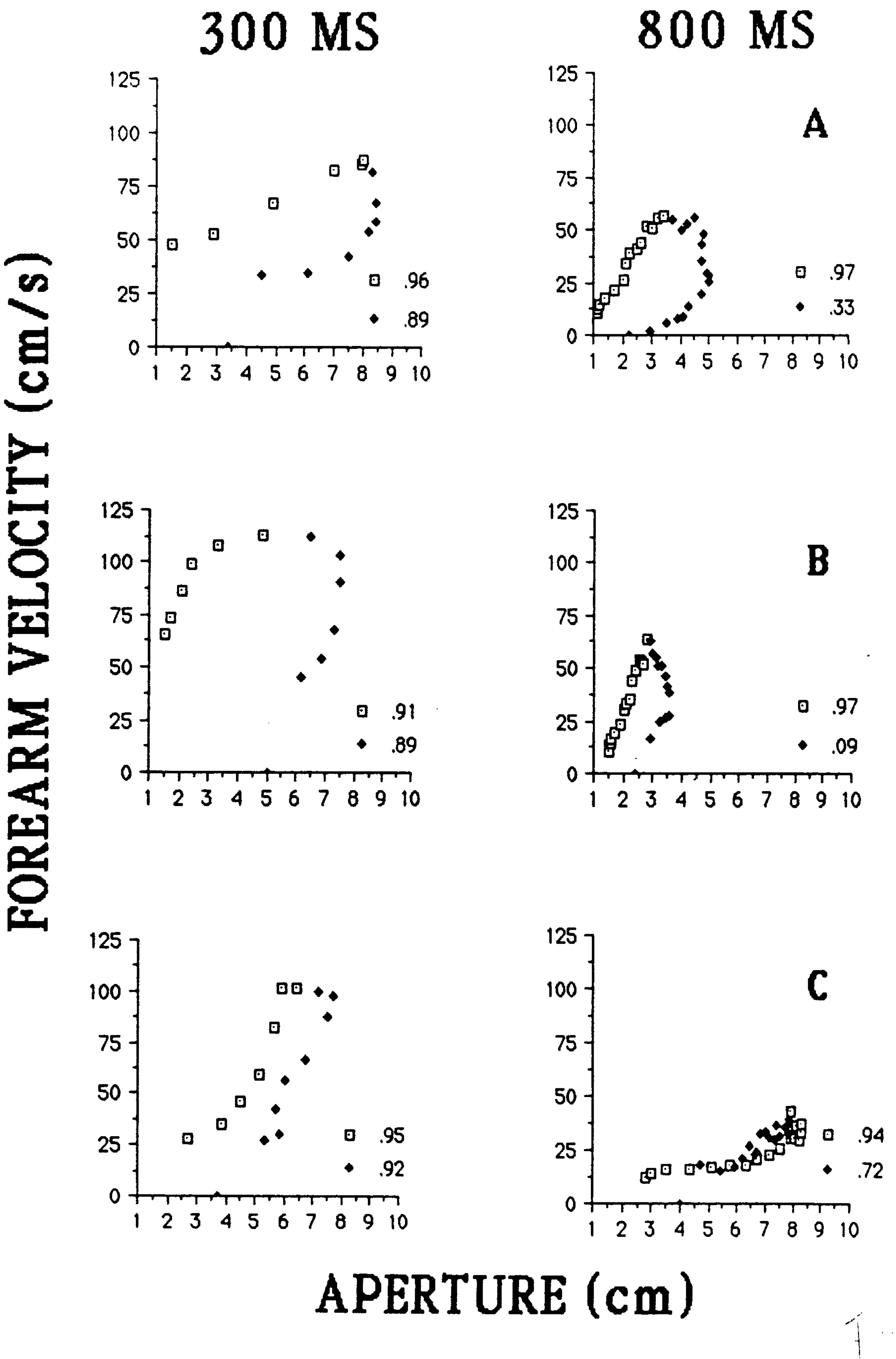
.91
.83
.33
.94
.23


300 MS
600 MS
800 MS
D
E
F
.90
.13
.95
-.46
.64
-.32
.94
.87
.93
.40
.98
.88
.90
.76
.92
.61
.98
.40
FOREARM VELOCITY (cm/s)
APERTURE (cm)


300 MS
800 MS
FOREARM DISPLACEMENT (cm)
FOREARM VELOCITY (cm/s)
TIME (ms)
CLOSED
OPEN
0
10
20
30
40
60
80
100
120
140
200
300
400
500
600
700
800
900


300 MS
800 MS
APERTURE (cm)
APERTURE VELOCITY (cm/s)
TIME (ms)
CLOSED
OPEN


300 MS
800 MS
FOREARM VELOCITY (cm/s)
APERTURE (cm)
A
B
C
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.89
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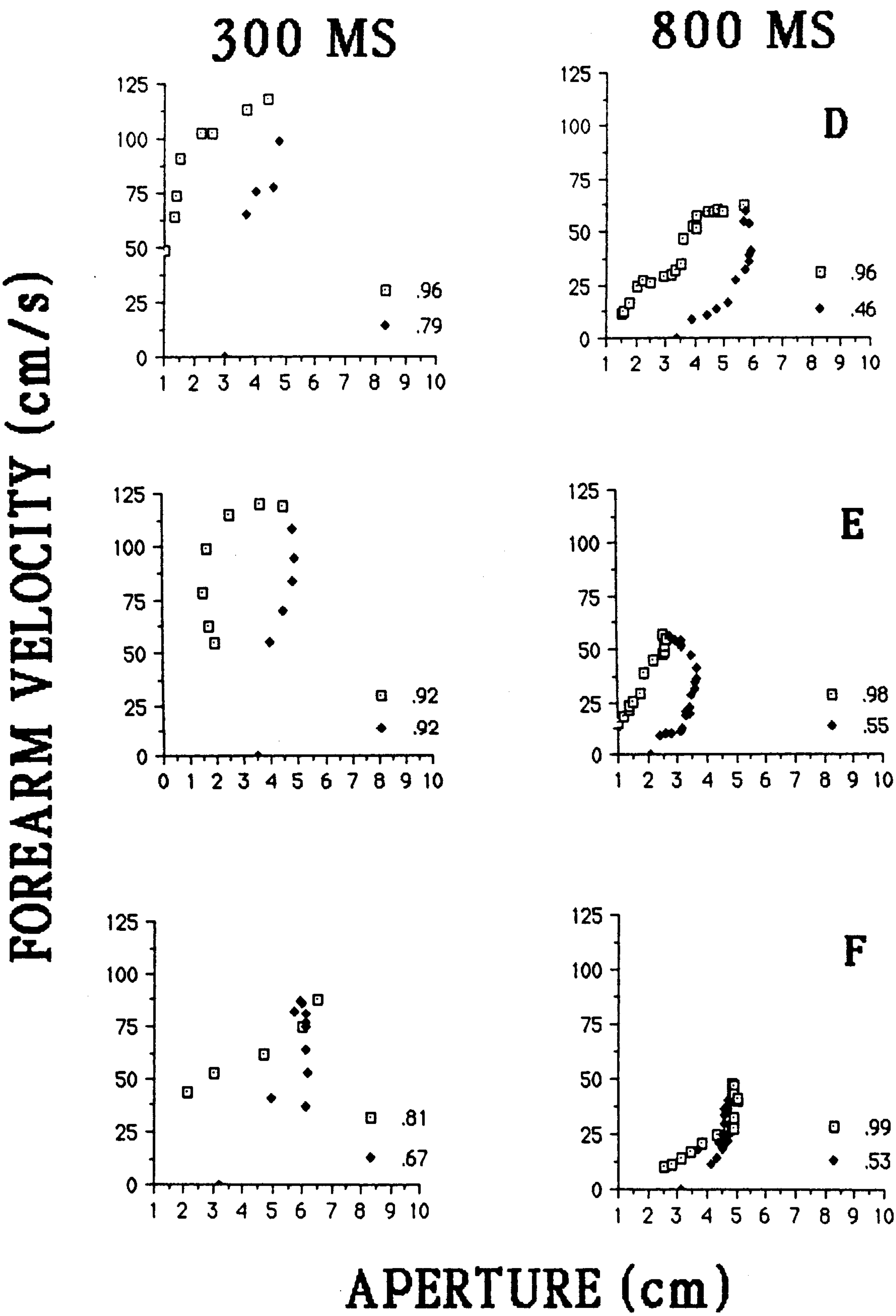
.09
.95
.92
.94
.72


300 MS
800 MS
FOREARM VELOCITY (cm/s)
APERTURE (cm)
D
E
F
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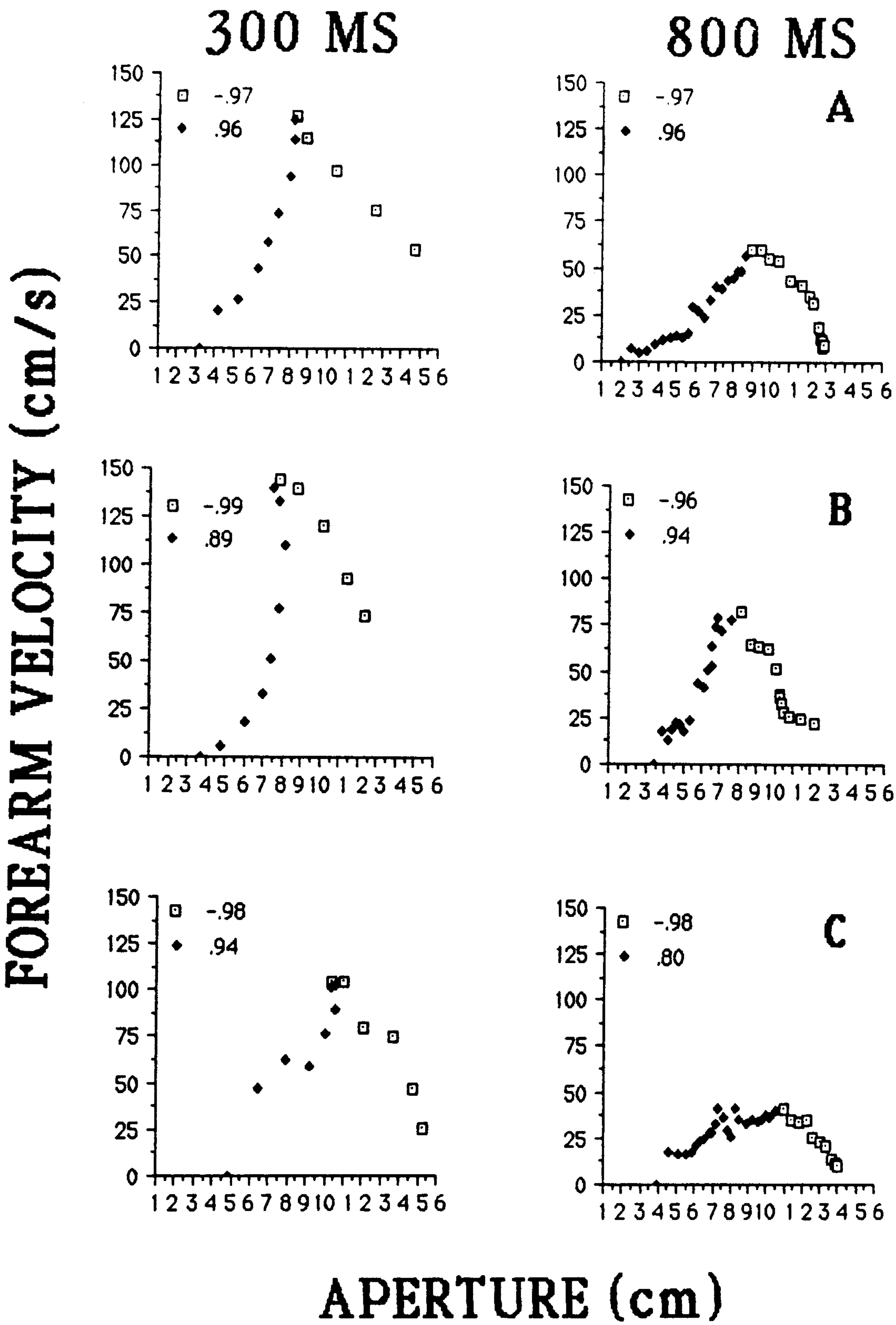
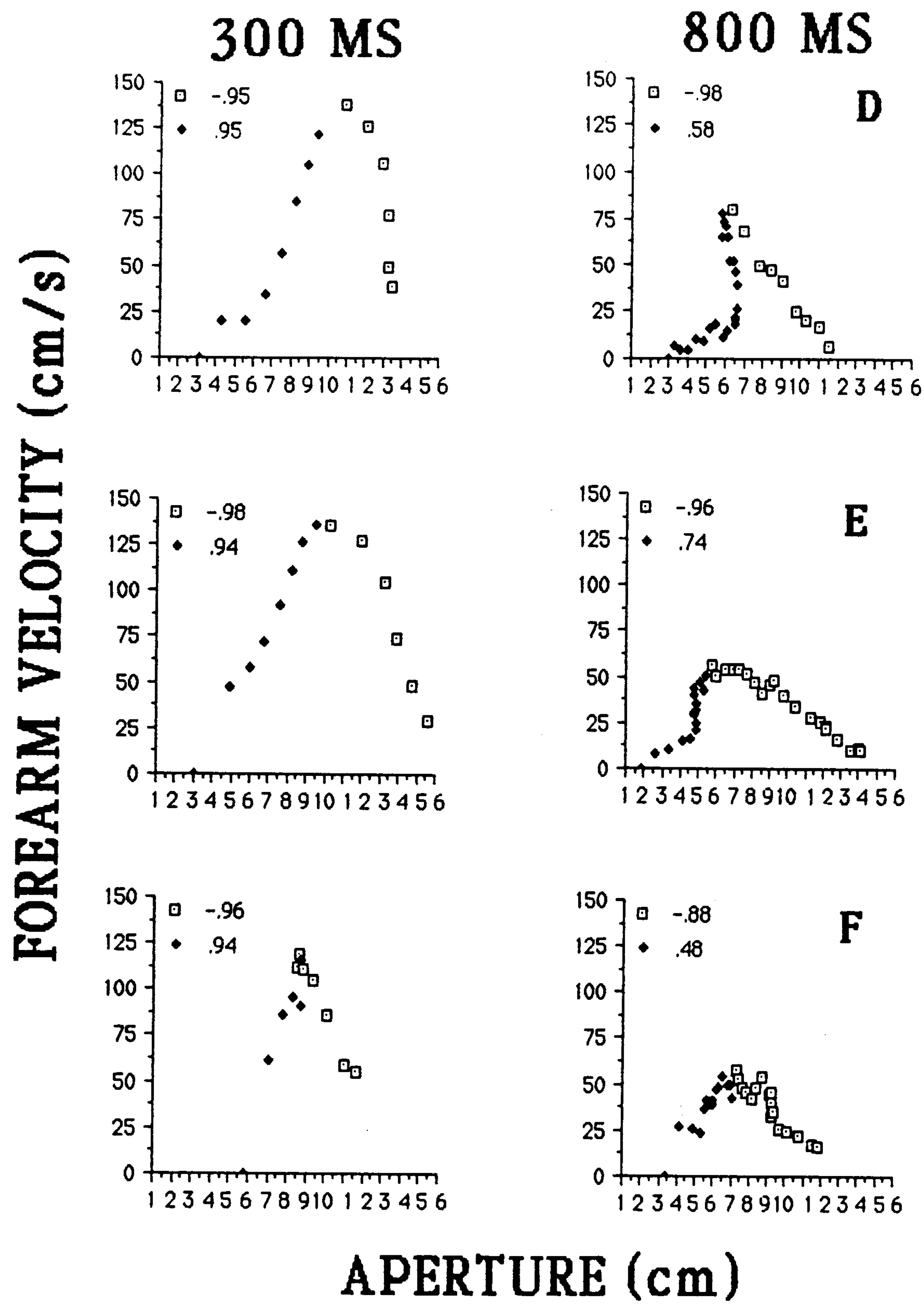
.99
.53


300 MS
800 MS
A
B
C
-.97
.96
-.97
.96
-.99
.89
-.96
.94
-.98
.94
-.98
.80
FOREARM VELOCITY (cm/s)
APERTURE (cm)
0
25
50
75
100
125
150
1 2 3 4 5 6 7 8 9 10 1 2 3 4 5 6


300 MS
800 MS
FOREARM VELOCITY (cm/s)
APERTURE (cm)
-.95
.95
-.98
.58
D
-.98
.94
-.96
.74
E
-.96
.94
-.88
.48
F