Exp Brain Res (2012) 219:293–304
DOI 10.1007/s00221-012-3088-6

RESEARCH ARTICLE

Control of aperture closure initiation during trunk-assisted reach-to-grasp movements

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Received: 20 January 2012 / Accepted: 24 March 2012 / Published online: 17 April 2012
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Abstract The present study investigated how the involvement and direction of trunk movement during reach-to-grasp movements affect the coordination between the transport and grasping components. Seated young adults made prehensile movements in which the involvement of the trunk was varied; the trunk was not involved, moved forward (flexion), or moved backward (extension) in the sagittal plane during the reach to the object. Each of the trunk movements was combined with an extension or flexion motion of the arm during the reach. Regarding the relationship between the trunk and arm motion for arm transport, the onset of wrist motion relative to that of the trunk was delayed to a greater extent for the trunk extension than for the trunk flexion. The variability of the time period from the peak of wrist velocity to the peak of trunk velocity was also significantly greater for trunk extension compared to trunk flexion. These findings indicate that trunk flexion was better integrated into the control of wrist transport than trunk extension. In terms of the temporal relationship between wrist transport and grip aperture, the relationship between the time of peak wrist velocity and the time of peak grip aperture did not change or become less steady across conditions. Therefore, the stability of temporal coordination between wrist transport and grip aperture was maintained despite the variation of the pattern of intersegmental coordination between the arm and the trunk during arm transport. The transport–aperture coordination was further assessed in terms of the control law according to which the initiation of aperture closure during the reach occurs when the hand crosses a hand-to-target distance threshold for grasp initiation, which is a function of peak aperture, wrist velocity and acceleration, trunk velocity and acceleration, and trunk-to-target distance at the time of aperture closure initiation. The participants increased the hand-to-target distance threshold for grasp initiation in the conditions where the trunk was involved compared to the conditions where the trunk was not involved. An increase also occurred when the trunk was extended compared to when it was flexed. The increased distance threshold implies an increase in the hand-to-target distance-related safety margin for grasping when the trunk is involved, especially when it is extended. These results suggest that the CNS significantly utilizes the parameters of trunk movement together with movement parameters related to the arm and the hand for controlling grasp initiation.

Keywords Prehension · Kinematics · Coordination · Control law · Finger · Trunk

Introduction

When an object is located within the arm's reach, the reach-to-grasp movement is often performed by extending

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the arm toward the object while the trunk serves to stabilize the body posture (Kaminski et al. 1995). However, when an object is located beyond the arm's reach, the trunk is involved to extend the reach distance for grasping the object. The involvement of the trunk in the arm transport increases as the object locates further away from the body (Kaminski et al. 1995; Wang and Stelmach 2001). It is well documented that, during trunk-assisted reaching and reach-to-grasp movements, the trunk is well coordinated with the arm so that the endpoint trajectory of the arm reaching toward a target (Kaminski et al. 1995; Poizner et al. 2000) or an object to be grasped becomes smooth (Marteniuk and Bertram 2001; Seidler and Stelmach 2000; Wang and Stelmach 2001). This is also true for reaching action during which a rigorous forward, backward, or rotation motion of the trunk is involved (Ma and Feldman 1995; Pigeon and Feldman 1998; Pigeon et al. 2000; Pigeon et al. 2003).

It is still a matter of debate whether the trunk motion is controlled as an integral component of prehensile action during trunk-assisted reach-to-grasp movements. The trunk motion is thought to be regulated separately from the arm, as evidenced by the fact that the trunk is still moving at the completion of reach-to-grasp movements (Saling et al. 1996; Seidler and Stelmach 2000; Wang and Stelmach 2001). Furthermore, Saling et al. (1996) found that the trunk motion was not temporally coordinated with the grip aperture formation when different grasping accuracies were required. These findings lead to a conclusion that the trunk is independently controlled from the grip component. However, more recent studies demonstrated that when the grasp required high precision, the trunk motion was integrated into the control of grip component (Bertram et al. 2005; Marteniuk and Bertram 2001; Wang and Stelmach 2001). Furthermore, when a reach-to-grasp movement was performed under a suboptimal condition (i.e., in the absence of vision), trunk involvement during reaching to an object resulted in an increase in grip aperture (Rand et al. 2010a). Thus, the degree to which the trunk motion is coordinated with the grasp component depends on the complexity of the prehension task (Marteniuk and Bertram 2001). Moreover, a recent study, in which an external perturbation was applied to the trunk during a reach-to-grasp movement, reported a phase-dependent change in the trunk influence on the grip aperture formation (Yang and Feldman 2010). Namely, the trunk motion influenced the grip formation only after the arm velocity reached its peak.

To explore further how trunk motion is integrated into the transport–aperture coordination, the present study systematically tested various combinations of trunk backward or forward motion with arm-extension or arm-flexion movements during reach-to-grasp movements and applied our recently developed control law model for aperture closure initiation (Rand et al. 2006a, b, 2007). According to this law,[1] aperture closure during the reach is initiated when the hand crosses a certain hand-to-target distance threshold defined as a function of hand velocity, hand acceleration, and grip aperture. Indeed, the initiation of aperture closure during the reach is a functionally important event in coordinating various body segments to achieve the intended goal of the reach-to-grasp movement. We have shown previously that a highly precise relationship between these movement parameters is established at the initiation of aperture closure during the reach and maintained throughout the aperture closure phase until the target object is grasped (Rand et al. 2008, 2010b). In our most recent study, we incorporated trunk dynamics into the aforementioned relationship between the hand-to-target distance and the other movement parameters of the transport and aperture components for grasping initiation (Rand et al. 2010a). It is not known, however, how the control law for aperture closure initiation changes when the trunk motion is rigorously manipulated during prehensile movements to targets located within the arm's reach. When the trunk is actively moved during such movements, the trunk cannot be used as a stabilizer for the arm motion. Instead, the trunk motion will add more complexity to the control system, thereby possibly altering the transport–aperture coordination significantly.

In the present study, we investigated whether the control law for aperture closure initiation changes when the directions of the trunk and arm motions are systematically manipulated. If the control law is changed due to the involvement of trunk and/or a specific direction of trunk motion, it would manifest itself either as reduced transport–grasp coordination (i.e., weak correlation) among the movement parameters important for initiating aperture closure (hand-to-target distance at grasp initiation, peak aperture, wrist velocity and acceleration, trunk-to-target distance, and trunk velocity and acceleration) or as a specific consistent change in the relationship among those parameters.

Materials and methods

Participants

A total of seventeen young adults participated in this study (11 men, 6 women; Mean (SD) age = 23.5 (2.9) years;

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[1] The term "control law" is standard and central in the mathematical theory of control (e.g., Naslin 1969). It describes the dependence of control action (expressed, e.g., in joint torques or muscle activity) on the parameters of the motor plant, which in our experimental paradigm includes the dynamics of the arm and its relationship with the reach target. If the existence of such a control law is supported by experimental data, it suggests that the initiation of aperture closure is based on the neural computation of such a function.

range = 21–31 years). All participants reported to be right-hand dominant. This study was approved by Arizona State University's Institutional Review Board overseeing the use of human participants in research. All participants signed consent forms prior to participation.

Procedure

Participants were comfortably seated at a table. The distance from the participant's midline in the front to the edge of the table was adjusted for each participant so that participants could move the trunk comfortably back and forth in the sagittal plane and still were able to easily grasp an object for all conditions. The average value of the distance across participants was 12.9 ± 2.2 cm (mean ± SD). The maximum reach distance without bending the trunk forward was measured between the tip of the index finger and the edge of the table. The average maximum reach distance across participants was 50.4 ± 3.1 cm. There were two target locations, one at 5 cm (T1) and one at 25 cm (T2) from the edge of the table. Depending on the condition, one location was used as the start position, while the other was used as the target position (Fig. 1). T1 served as the start position and T2 served as the target location for conditions related to arm-extension movement. Conversely, T2 served as the start position and T1 served as the target location for conditions related to arm-flexion movement. A cylindrical target object (height, 2.5 cm; diameter, 3 cm) was placed on the target location for prehensile movements.

At the beginning of each trial, participants sat with their trunk in an upright position without using the back of the seat. Participants kept their thumb and index finger together, placed the ulnar side of the hand on the table, and rested their index finger and thumb at the start position. Subsequently, the examiner said "ready". Then, after a random delay (between 1 and 2 s), an auditory "go" signal was delivered. In response to the "go" signal, the participants reached for the object, grasped it with the thumb and index finger, and lifted it a few centimeters off the table. The completion of the lift was the end of a trial. The participants then put the object down on the table, brought their trunk back to an upright position, and placed their hand at the starting position for the next trial. The participants were instructed to move at a fast but comfortable speed. If trunk involvement was required to reach and grasp the cylinder, participants were instructed not to rotate their trunk, but to move their whole trunk forward or backward while reaching for the object. If trunk involvement was not necessary, participants were instructed not to move the trunk.

To examine the effects of the arm and trunk motions on the control of reach-to-grasp movements, four conditions with different arm and trunk combinations were tested: (1) trunk-extension, arm-extension; (2) trunk-extension,

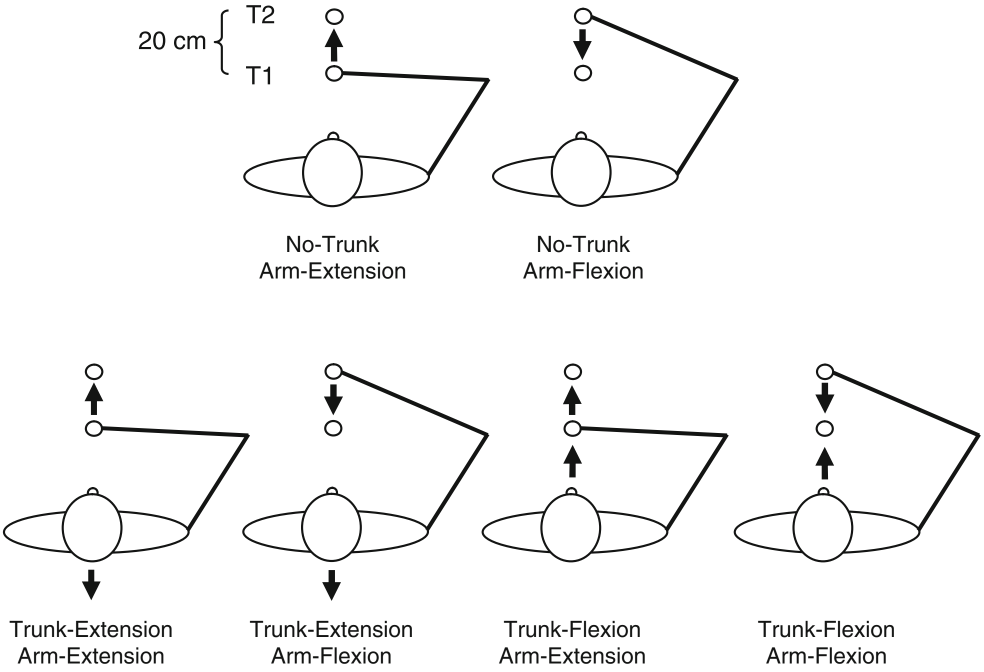

Fig. 1 Six experimental conditions that prescribed different trunk and arm movements. Participants reached for and grasped a target object by extending or flexing the arm while trunk-extension, trunk-flexion, or no-trunk motion was executed. The distance from the T1 target location to T2 target location was 20 cm. The drawings show the initial hand locations. The directions of the arm and trunk motions are indicated by the *arrows*

arm-flexion; (3) trunk-flexion, arm-extension; and (4) trunk-flexion, arm-flexion (Fig. 1). Additionally, there were two conditions in which the reach-to-grasp movements did not require trunk movement (no-trunk), each of which was combined with the two different arm motions (arm-extension and arm-flexion). All four trunk-involved conditions and the two no-trunk conditions were randomized and counterbalanced across participants to reduce practice and fatigue effects. Prior to the recording of each condition, participants practiced a few trials to familiarize themselves with the required movements. A block of twelve trials were performed for each condition, in which the last ten trials were used for data analysis. Thus, a total of sixty movements were analyzed for each participant.

Trunk, wrist and finger positions during reach-to-grasp movements were recorded using an Optotrak 3D system (Northern Digital). Infrared light emitting diodes (IREDs) were placed on the tips of the thumb and index finger, the wrist, the elbow, the shoulder, and the middle of sternum. An additional IRED was placed on the cylinder in order to record its position and movement. Positions of the IREDs were sampled at a rate of 100 Hz.

Data analysis

Kinematic characteristics related to the grip and the transport components were analyzed. The transport component was assessed based on the position of the wrist IRED. Furthermore, the movement of the trunk was assessed based on the position of the trunk IRED placed on the sternum. Wrist (trunk) velocity during the reach was tangential velocity calculated as the first derivative of wrist (trunk) position. Derivatives were calculated using the sliding window technique, where the data points within the window (the window width was 7 points) were approximated with a quadratic polynomial. The polynomial was then used for calculating the analytic derivative at the window's center (or at other points when the window overlapped the beginning or end of the data array representing the curve). Thus, calculating derivatives using this method also provided data filtering. The grasp component was assessed based on the positions of the IREDs on the index and thumb fingertips. Grip aperture was defined as the resultant distance between these two IREDs. The end of grasp was identified as the time when both fingers came in contact with the object. The end of the transport was defined as simultaneous to the end of grasp. Calculating the onset of transport and aperture was performed by an automated movement parsing algorithm (Teasdale et al. 1993; algorithm B).

Basic kinematic parameters related to the transport component included transport time (from wrist onset to the end of grasp), the time to peak wrist velocity, peak wrist velocity, peak trunk velocity, the duration from trunk onset to wrist onset, the duration from peak wrist velocity to peak trunk velocity. Parameters related to the grip aperture component included peak grip aperture, the time to grip aperture onset (from wrist onset to grip aperture onset), the time to peak grip aperture (from wrist onset to peak grip aperture), the time from peak wrist velocity to the time of peak grip aperture, and the hand-to-target distance at grasp initiation (i.e., the distance that the hand travelled from peak aperture to the end of grasp). The hand-to-target distance was calculated as a vector length between two positions of the wrist IRED. The time to peak wrist velocity, the duration from trunk onset to wrist onset, the duration from peak wrist velocity to peak trunk velocity, the time to grip aperture onset, the time to peak grip aperture, and the time from peak wrist velocity to the time of peak grip aperture were expressed as percentages of transport time.

A mean value across all trials for each participant was calculated for each condition. These mean values were used for statistical comparisons using a 3 (trunk motion: no-trunk, extension, flexion) × 2 (arm motion: extension, flexion) ANOVA with repeated measures. When appropriate, post hoc comparisons were performed using Bonferroni corrected t-tests ($\alpha = 0.05$) in order to identify significant differences between individual cell means.

Modeling aperture closure initiation based on a control law

To examine transport–aperture coordination for grasp initiation, a model of the control law governing aperture closure initiation (see Introduction) was examined for all conditions. Similarly to our previous study of trunk-assisted reach-to-grasp movements (Rand et al. 2010a), trunk-related movement parameters (trunk-to-target distance, trunk velocity, and trunk acceleration) at the time of finger closure initiation were added to our previous control law model, which consisted of only the finger- and arm-related movement parameters (Rand et al. 2006a, b, 2007). We hypothesized that the aperture closure is initiated when the hand crosses a hand-to-target distance threshold, which is a function of the aperture magnitude, wrist velocity and wrist acceleration, trunk-to-target distance, as well as trunk velocity and trunk acceleration, which were measured at the time of finger closure initiation. According to this model (Model 1), the condition for the onset of aperture closure can be presented formally as

$$D_w = D_{\mathrm{thr}}(G, V_w, A_w, D_t, V_t, A_t), \qquad (1)$$

where D_w is distance between the hand and the target object, G is grip aperture, V_w is wrist velocity, A_w is wrist acceleration, D_t is distance between the trunk and the target object, V_t is trunk velocity, A_t is trunk acceleration, and D_{thr} is a distance-to-target threshold. It is assumed that aperture closure is not initiated while $D_w > D_{\mathrm{thr}}$.

To test the validity of the control law model, movement parameters corresponding to the above seven model variables were measured at the time of peak aperture (and hence the initiation of the aperture closure). This approach has been successfully used in our previous study that tested the transport–aperture coordination of reach-to-grasp movement where the trunk never moved (Rand et al. 2006a, b, 2007) and where the trunk did move (Rand et al. 2010a). A linear approximation of the above model was used to fit the data. Specifically, the function D_{thr} (G, V_w, A_w, D_t, V_t, A_t) was presented as

$$D_{\mathrm{thr}}\left(G, V_w, A_w, D_t, V_t, A_t\right) = D_0 + k_G \cdot G + k_{Vw} \cdot V_w + k_{Aw} \cdot A_w + k_{Dt} \cdot D_t + k_{Vt} \cdot V_t + k_{At} \cdot A_t,$$

where D_0, k_G, k_{Vw}, k_{Aw}, k_{Dt}, k_{Vt}, and k_{At} are constant coefficients (unknown parameters that require identification). The unknown coefficients of the model of the control law for aperture closure initiation were identified based on the standard method, namely by minimizing the least square deviation of the model's prediction from the actual, experimentally measured values of the prediction target (hand-to-target distance at grasp initiation). Then, for each condition separately, the R-square (R^2) value[2] and the residual error magnitude (absolute residual error) of the model fitting were calculated based on all trials and all participants for that condition. The residual error (E) was calculated for each trial by using the equation $E = D_0 + k_G \cdot G + k_{Vw} \cdot V_w + k_{Aw} \cdot A_w + k_{Dt} \cdot D_t + k_{Vt} \cdot V_t + k_{At} \cdot A_t - D_w$. For this analysis, data that were outside the range of ±3 standard deviation of residual error based on the above model fitting for each condition were eliminated as outliers. As a result, seventeen trials (1.67 %) in total were removed.

Modulation of the control law for aperture closure initiation

To verify whether the relationship between D_{w}, G, V_{w}, A_{w} D_{t}, V_{t}, and A_{t} estimated in trials from the no-trunk, arm-extension condition was significantly different from the relationships in other conditions of arm- and trunk-motion manipulations, the following residual error analysis was performed for each condition.

Step 1. Based on values from all trials across all participants in the no-trunk, arm-extension condition, a linear approximation of Model 1 was applied in the same way as described above.

Step 2. The coefficients of the above linear approximation (D_0, k_G, k_{Vw}, k_{Aw}, k_{Dt}, k_{Vt}, and k_{At}) of the model were identified.

Step 3. Using the coefficients obtained in Step 2, the residual error (E) was calculated in the same way as described above *under the same condition* (i.e., no-trunk, arm-extension condition). Note that the mean residual error is always zero.

Step 4. The same coefficients were used to calculate residual errors for all trials across all participants performed under the other five conditions. A significant mean residual error for any of the other five conditions indicated that the relationship between the hand-to-target distance (D_{w}) and the other six variables (G, V_w, A_w, D_t, V_t, and A_t) defined in Model 1 changed in a manner such that the hand-to-target distance at which aperture closure was initiated was consistently lengthened (or shortened) relative to that distance under the reference condition (i.e., the no-trunk, arm-extension condition for which the model coefficients were calculated at Step 2). As Model 1 assumes that aperture closure is not initiated while $D_w > D_{\mathrm{thr}}$, such lengthening (or shortening) of the hand-to-target distance relative to the other six variables implies that the distance-to-target threshold for the initiation of aperture closure (D_{thr} for Model 1) was shifted to increase (or decrease) the safety margin for grasping. To compare the residual errors across conditions, a 3 (trunk motion: no-trunk, extension, flexion) × 2 (arm motion: extension, flexion) ANOVA was applied.

Results

General characteristics of transport component

The effects of manipulations of arm and trunk motions on the kinematic characteristics of the transport component are summarized in Table 1-I. The wrist transport time was significantly increased when movement of the trunk contributed to the reach compared to when it did not contribute ($F(2, 32) = 22.06$, $p < 0.001$). This lengthening was observed for both trunk extension and flexion (post hoc, $p < 0.001$ for each direction). Peak wrist velocity also became slower when movement of the trunk contributed (trunk-motion effect: $F(2, 32) = 6.01, p < 0.01$). Although this measurement did not exhibit any significant arm-motion effect, the interaction between trunk and arm on wrist velocity proved to be significant $F(2, 32) = 4.4$,

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[2] Standard statistics showing to what extent the model "explains" the variance of the variable used as the prediction target. R-square value is equal to the square of the coefficient of correlation between the model's prediction and the actual value of the prediction target.

Table 1 Effect of trunk- and arm-motion conditions on the kinematic parameters of reach-to-grasp movements

	Trunk motion			Arm motion	
	No-trunk	Extension	Flexion	Extension	Flexion
(I) Transport component					
Transport time (ms)[a,c]	715 (36)[f,h]	811 (48)	817 (48)	769 (42)	794 (46)
Peak wrist velocity (mm/s)[a,d]	539 (25)[g,h]	489 (20)	484 (26)	494 (22)	515 (24)
Time to peak wrist velocity (%)[a,b]	42.3 (1.3)[f,i]	45.5 (1.2)	44.9 (1.3)	46.0 (1.2)	42.5 (1.1)
Peak trunk velocity (mm/s)[d]	–	236 (9)	225 (7)	236 (7)	225 (8)
Duration from trunk onset to wrist onset (%)[a,d]	–	3.9 (0.7)	0.6 (0.8)	2.1 (0.6)	2.4 (0.9)
Duration from peak wrist velocity to peak trunk velocity (%)	–	15.3 (2.8)	14.2 (1.4)	14.3 (1.5)	15.2 (2.3)
(II) Grip aperture component					
Peak grip aperture (mm)	46 (2)	47 (2)	46 (1)	46 (2)	47 (2)
Time to grip aperture onset (%)[b]	12.6 (0.8)	11.9 (1.0)	12.9 (1.1)	14.2 (1.1)	10.8 (0.9)
Time to peak grip aperture (%)[a,e]	69.9 (1.0)[f,h]	72.2 (0.9)	72.5 (0.7)	71.8 (1.0)	71.4 (0.7)
Duration from peak wrist velocity to peak grip aperture (%)[c]	27.6 (1.0)	26.8 (1.0)	27.7 (1.1)	25.8 (1.0)	28.9 (1.0)
Hand-to-target distance at grasp initiation (mm)[a,d]	19 (2)[j]	21 (2)	18 (1)	20 (2)	19 (1)

Mean (SE)

% values are expressed as a percentage of transport time

[a] Trunk-motion effect significant: ($p < 0.05$)

[b] Arm-motion effect significant: ($p < 0.05$); [c] ($0.05 < p < 0.1$)

[d] Trunk-motion and arm-motion interaction significant: ($p < 0.05$); [e] ($0.05 < p < 0.1$)

[f] Difference between No-trunk and Trunk extension significant: (post hoc test, $p < 0.05$); [g] ($0.05 < p < 0.1$)

[h] Difference between No-trunk and Trunk flexion significant: (post hoc test, $p < 0.05$); [i] ($0.05 < p < 0.1$)

[j] Difference between Trunk extension and Trunk flexion significant: (post hoc test, $0.05 < p < 0.1$)

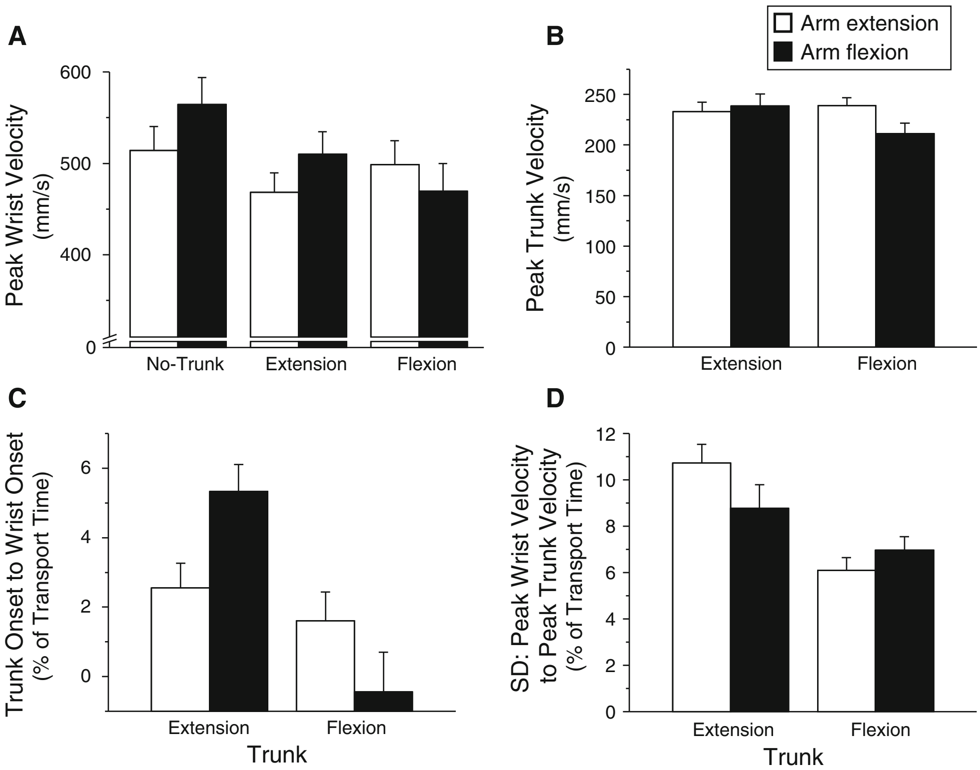
$p < 0.05$). As can be seen in Fig. 2a, the arm-flexion movement was slower compared to arm-extension movement when the trunk was flexed. In contrast, this pattern was reversed for the no-trunk and trunk-extension conditions. As seen in Table 1-I, the participants had a longer wrist acceleration period (time from onset to peak wrist velocity as percentage of the total reach duration) when the trunk was involved ($F(2, 32) = 4.6$, $p < 0.05$) or when the arm was extended ($F(1, 16) = 21.5$, $p < 0.001$) during the reach.

Regarding trunk movement, the peak trunk velocity (Fig. 2b) was much slower than the peak wrist velocity (Fig. 2a). The speed of trunk movement was relatively stable across experimental conditions with trunk involvement. The only condition that showed a deviation of trunk speed from the other trunk movement conditions required the participants to combine a trunk flexion with arm flexion, which resulted in a lower trunk velocity peak. As a result of this deviation, the trunk-by-arm interaction became significant ($F(1,16) = 5.8$, $p < 0.05$). In the trunk-flexion, arm-flexion condition both the arm (Fig. 2a) and trunk (Fig. 2B) motions became slower as compared to the other trunk movement conditions.

In terms of the temporal coordination between the wrist and trunk movements at the onset of the transport component, the trunk motion generally started earlier than that of the wrist motion (Fig. 2c, Table 1-I), being in agreement with a previous study (Saling et al. 1996; Wang and Stelmach 2001). To determine whether the participants initiated the wrist movement at a consistent time after the onset of trunk movement, the time required from the trunk onset to wrist onset was measured and expressed as the percentage of reach duration. It was shown that this time was flexibly altered depending on the combination of movement directions among the segments. It significantly increased when the trunk was extended as compared to when it was flexed ($F(1,16) = 35.6$, $p < 0.001$). While arm motion did not show a main effect for this measurement ($p > 0.05$), there was a significant trunk-by-arm interaction ($F(1,16) = 13.1$, $p < 0.01$). The interaction was due to an additional delay in the wrist onset when the arm was flexed as compared to the delay of wrist onset when the arm was extended in the trunk-extension condition, whereas it was reversed in the trunk-flexion condition (Fig. 2c).

During the wrist transport toward the object, the trunk velocity reached its peak later than that for the wrist velocity, again being in agreement with previous studies (Saling et al. 1996; Wang and Stelmach 2001). The time from peak wrist velocity to the time of peak trunk velocity was also expressed as a percentage of reach duration (Table 1-I). This time measurement did not show any

Fig. 2 Effects of changing the trunk- and arm-movement directions on the peak wrist velocity (**a**), peak trunk velocity (**b**), the time from trunk movement onset to wrist movement onset (**c**), and the variability (SD) of the time from peak wrist velocity to peak trunk velocity (**d**). Trunk-motion manipulations include the trunk-extension condition (Extension) and the trunk-flexion (Flexion) condition (in **a**–**d**). In (**a**), the no-trunk condition (No-trunk) is also included. The *white columns* refer to the arm-extension condition and the *black columns* refer to the arm-flexion condition. *Error bars* refer to the standard errors. In (**c**) and (**d**), the values are expressed as a percentage of transport time



significant changes across different trunk- and arm-motion directions ($p > 0.05$), thus indicating that the temporal relationship between two velocity peaks did not depend on the combination of trunk- and arm-motion directions.

In order to further determine whether this temporal relationship between the two velocity peaks of the trunk and arm motion was consistent across trials within each condition, the standard deviation (SD) of this duration across trials was calculated as a variability measure of temporal coordination (Fig. 2d). This parameter was expressed as the percentage of reach duration. The variability was increased when the trunk was extended compared to the condition where it was flexed ($F(1,16) = 19.5$, $p < 0.001$). While there was no significant arm-motion effect on the variability ($P > 0.05$), a significant trunk-by-arm interaction was found ($F(1,16) = 6.3$, $p < 0.05$). This was due to a decrease in variability when the arm was flexed compared to arm extension in the trunk-extension conditions, whereas this arm effect was reversed when the trunk was flexed (Fig. 2d). The variability was the smallest when arm extension was combined with trunk flexion across all trunk-involved conditions.

Additionally, the variability across trials was also measured for the time from the onset of the trunk to that of wrist motion and expressed as the percentage of reach duration. The average SD value across all participants was 6.0 % (trunk-extension, arm-extension), 4.7 % (trunk-extension, arm-flexion), 4.3 % (trunk-flexion, arm-extension), and 5.1 % (trunk-flexion, arm-flexion). The pattern of change in the variability due to the experimental trunk-movement conditions tended to follow a similar pattern as the variability of the time from the peak wrist velocity to the peak trunk velocity (Fig. 2d). As a result, the trunk-by-arm interaction just failed to reach significance ($F(1,16) = 4.1, p = 0.059$). These results of the two variability parameters together indicate that the extent of the temporal variability between the trunk and arm movements during the reach is different depending on the specific combination of movement directions between the trunk and arm.

General characteristics of grip aperture component

The effects of changing arm and trunk movement directions on the grasp component are summarized in Table 1-II. Peak grip aperture was not affected either by the trunk movement conditions or by the arm movement conditions ($p > 0.05$). To examine whether the time required for initiating the movement of the fingers during reaching was altered by the trunk and arm directions, the percentage of reach time before the onset of a change in grip aperture (time to grip aperture onset) was measured. As seen in Table 1-II, the participants had an earlier grip onset during the arm flexion than during the arm extension for reaching ($F(1, 16) = 12.7$, $p < 0.01$). There was neither a significant trunk effect nor a significant interaction between trunk and arm directions.

To determine whether the participants produced reach-to-grasp movements with a consistent temporal relationship between the wrist transport and grip aperture components, the time from the reaching onset to peak grip aperture was also measured and expressed as the percentage of reach duration (time to peak grip aperture). This time measurement was increased when the trunk was involved compared to the conditions with no trunk involvement (trunk main effect, $F(2,32) = 5.7$; $p < 0.01$, see Table 1-II for the post hoc results). However, there was no significant arm-motion effect. The time from peak wrist velocity to the time of peak grip aperture also was expressed as a percentage of reach duration (Table 1-II). This duration was not significantly altered by the trunk or arm movement direction ($p > 0.05$).

To further assess the variability of the above temporal relationship between the transport and aperture components in terms of the onset timing and the peak timing of the finger movements during the reach, the standard deviation across trials was calculated for each of the above temporal parameters. The average SD value across all participants ranged from 4.7 to 5.3 % across all conditions for the time to grip aperture onset, from 4.7 to 5.1 % for the time to peak grip aperture, and from 4.7 to 6.4 % for the duration from peak wrist velocity to the peak grip aperture. However, the variability of all the parameters was not significantly changed by experimental conditions. Thus, the temporal coordination between the wrist transport and grip aperture components was stable across trials regardless of the combination of trunk and arm motions. This finding contrasts with the results (Fig. 2d) of the temporal variability between the trunk and arm motions within the transport component.

Modeling aperture closure initiation based on a control law

In relation to the spatial coordination between the transport and aperture coordination associated with the initiation of aperture closure, the hand-to-target distance at grasp initiation was measured (Table 1-II, Fig. 3). This parameter showed a significant trunk main effect ($F(2,32) = 3.8$, $p < 0.05$). Post hoc tests revealed that the fingers tended to start to close at much closer distance to the target when the trunk moved forward (trunk-flexion) compared to when the trunk moved back (trunk-extension) ($0.05 < p < 0.1$). There was also a significant trunk-by-arm interaction ($F(2,32) = 8.83$, $p < 0.01$). As seen in Fig. 3, this effect was due to the fact that in the trunk-flexion condition, the hand-to-target distance at grasp initiation showed a substantial shortening when the arm was flexed compared to when the arm was extended. Conversely, the influence of the arm motion was none when no-trunk motion was used and reversed when the trunk was extended.

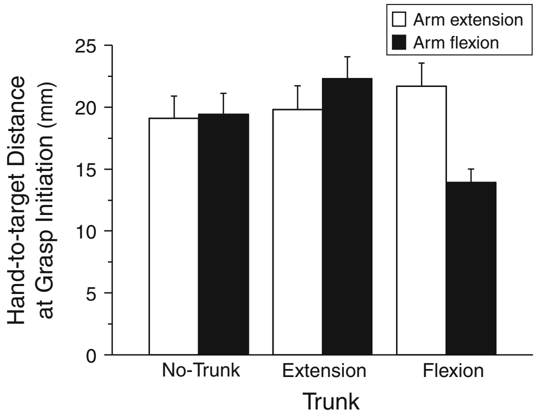


Fig. 3 Effects of changing the trunk- and arm-movement directions on the hand-to-target distance at grasp initiation. Trunk-motion manipulations include the no-trunk condition (No-trunk), trunk-extension condition (Extension), and trunk-flexion condition (Flexion). The *white columns* refer to the arm-extension condition and the *black columns* refer to the arm-flexion condition. *Error bars* refer to the standard errors

Despite the above changes of the hand-to-target distance at grasp initiation depending on experimental conditions, our previous studies utilizing a model of the control law for aperture closure initiation showed that this parameter was modulated in relation to other parameters of arm transport and finger aperture (Rand et al. 2006a, b, 2007) as well as the trunk movement as a part of the transport movement (Rand et al. 2010a). To account for the latter modulation, the relationship between the hand-to-target distance and other parameters representing the state of trunk, arm and finger movements at the time of aperture closure initiation was analyzed by using the model (Model 1) of the control law for aperture closure initiation.

The validity of the control law described as Model 1 was tested by fitting the model to the experimental data collected across all trials and across all participants for each condition separately. The R^2 values and residual error magnitude (i.e., absolute residual error) as model-fitting error are presented in Table 2. The results of model fitting showed that the dependence of hand-to-target distance on aperture amplitude, wrist velocity and acceleration, trunk velocity and acceleration, and trunk-to-target distance at the time of aperture closure initiation described by the model was statistically highly significant ($p < 0.001$) with high R^2 values for each experimental condition. These results support the hypothesis that the initiation of aperture closure is governed by a specific control law, which is in agreement with our previous studies that have examined reach-to-grasp movements performed without trunk

Table 2 R^2 values and mean absolute residual errors across all trials for each condition by using Model 1

Condition	R^2	Residual error (mm) (SE)
Arm extension without trunk	0.845*	2.71 (0.18)
Arm flexion without trunk	0.787*	3.25 (0.18)
Arm extension, trunk extension	0.762*	3.21 (0.19)
Arm flexion, trunk extension	0.817*	3.00 (0.17)
Arm extension, trunk flexion	0.756*	3.44 (0.21)
Arm flexion, trunk flexion	0.603*	2.92 (0.17)

* $p < 0.001$

involvement (Rand et al. 2006a, b, 2007) and with trunk involvement (Rand et al. 2010a).

Among all trunk-related conditions tested, the no-trunk condition scored the highest R^2 value when it was combined with arm-extension motion. Compared to that condition, the R^2 values decreased when the arm flexion was used or trunk motion was involved. Such decrease indicates the increased variability of the relationship among movement parameters. Especially, when the arm flexion was combined with trunk flexion, R^2 value became the lowest (Table 2). However, it seems possible that the low R^2 value was to some extent due to smaller ranges of hand-to-target distance data in the arm-flexion, trunk-flexion condition compared to the rest of conditions (Fig. 3).

Modulation of the control law for aperture closure initiation

To determine whether the relationship between the hand-to-target distance at grasp initiation and other movement parameters (G, V_w, A_w, V_t, A_t, D_t) was changed due to the manipulation of arm and trunk motions, residual errors were calculated for each condition based on the coefficients of linear approximation computed for a reference condition (i.e., the no-trunk, arm-extension condition, see “Materials and methods” section). The average residual errors across all trials and all participants were plotted for all conditions in Fig. 4. As expected from using the coefficients of the reference condition, the residual errors in all non-reference conditions significantly increased in their *absolute* value. However, the *sign* of those errors was different depending on the condition. Therefore, greater (in magnitude) positive and negative mean error values were obtained for those conditions. A 2 (arm motion: extension and flexion) × 3 (trunk motion: no-trunk, extension, and flexion) ANOVA revealed a significant trunk-motion effect ($F(2, 997) = 1608.9$, $p < 0.001$). Post hoc tests revealed that the residual errors were significantly decreased from the no-trunk condition to the trunk-flexion condition ($p < 0.001$) and from the trunk-flexion condition to the trunk-extension condition ($p < 0.001$). Between the two arm directions, the residual errors in the arm-extension conditions were significantly decreased compared to the arm-flexion conditions ($F(1, 997) = 1639.9$, $p < 0.001$). These decreases in residual errors indicate that the relationship between the hand-to-target distance and the other six parameters changed in such a manner that this distance was lengthened relative to these parameters when the trunk was involved compared to when it was not involved, when the trunk was extended compared to flexed, and when the arm was extended compared to flexed. This decrease in residual error implies that the hand-to-target distance threshold for grasp initiation was shifted to increase the safety margin for grasping (Rand et al. 2007, 2010a). Additionally, there was also an interaction between the trunk-motion and arm-motion ($F(2, 997) = 3.1$, $p < 0.05$). As seen in Fig. 4, the difference of the residual errors between the arm-extension and arm-flexion conditions was greatest for the no-trunk condition and the smallest for the trunk-extension condition, indicating that the degree of the shift to increase the safety margin for grasp initiation was altered depending on the involvement of the trunk motion.

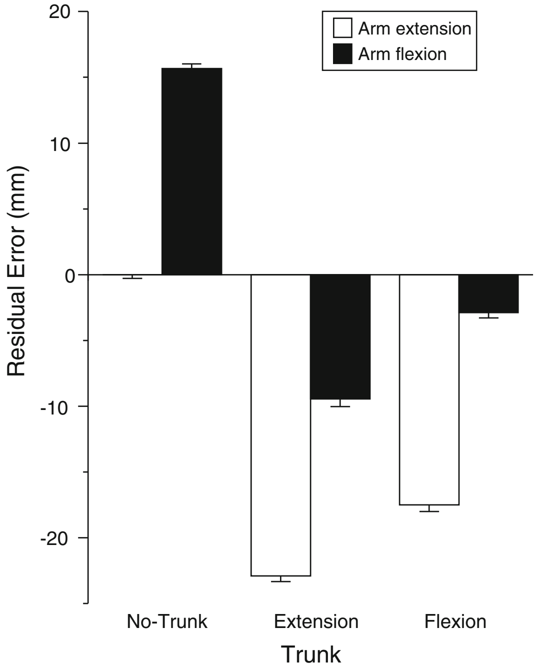


Fig. 4 Mean residual errors for all conditions of the trunk- and arm-motion manipulations. Trunk-motion manipulations include the no-trunk condition (No-trunk), trunk-extension condition (Extension), and trunk-flexion (Flexion) condition. The *white columns* refer to the arm-extension condition and the *black columns* refer to the arm-flexion condition. Mean residual error values are calculated for each condition separately based on the no-trunk, arm-extension condition coefficients. Mean residual errors and SE across all trials and all participants are plotted

Discussion

The current study investigated how the involvement and direction of trunk movement during reach-to-grasp movements affect the coordination between the transport and grasping components. Inclusion of the trunk motion in task performance decreased the speed of arm-reaching movement and lengthened the reaching duration, especially during the acceleration period. Furthermore, the initiation of wrist motion was delayed even more after the initiation of trunk motion when the trunk was extended compared to when it was flexed. Thus, arm-reaching movements were affected depending on the involvement and direction of trunk movement. The observed delay in wrist initiation under the trunk extension means that the trunk and wrist motions are initiated in a sequential manner, one motion at a time. A similarly delayed onset of wrist motion was previously found in trunk-assisted prehension movements performed by patients with Parkinson's disease who are known to have difficulty in controlling multiple segments (Poizner et al. 2000; Wang and Stelmach 2006). In general, the delay signifies a less optimal coordination between the trunk and arm for reaching. This contention is also supported by the increased temporal variability of the time from peak wrist velocity to peak trunk velocity observed in the trunk-extension conditions (Fig. 2d). These features of reach-to-grasp movements assisted by trunk extension likely result from the fact that trunk extension is less common than trunk flexion during reach-to-grasp movements. In other words, the reach-to-grasp movements with trunk extension are considerably less practiced than reach-to-grasp movements assisted by trunk flexion, resulting in the lack of movement control optimality. This reasoning is further supported by the finding that the temporal variability between the trunk and arm movements was the smallest when the trunk flexion was combined with an arm-extension movement (Fig. 2d), as this combination is the most common pattern in the human daily life for trunk-assisted reach-to-grasp movements. Thus, it can be concluded from the basic kinematic analyses that trunk flexion is better integrated into the control of wrist transport than trunk extension.

Regarding the effects of trunk movements on the grasp component, peak aperture was not affected by the manipulation of the trunk movement in the present study (Table 1-II). In our previous study, however, where reach-to-grasp movements were performed under the absence of vision, the inclusion of the trunk increased the magnitude of the peak aperture during reaching (Rand et al. 2010a). Such widening of grip aperture is generally made to increase the safety margin for grasping in order to compensate for an uncertainty of the arm transport (Churchill et al. 2000; Jackson et al. 1995; Rand et al. 2004; Wing et al. 1986). Since the current manipulations of the trunk and wrist motions did not affect this parameter, the movement control system implemented by the CNS likely considers that the control of various movement directions between the trunk and the arm for reaching is secure enough for grasping so that increasing the magnitude of grip aperture is not necessary.

In terms of the effects of trunk motion on temporal coordination between the wrist transport and grasp components, the inclusion of the trunk motion delayed the peak of grip aperture during the reach (Table 1-II). Previously, Saling et al. (1996) also observed the same pattern in a trunk-assisted prehension task. The authors suggested that their finding was not due to the involvement of the trunk, per se, but due to the relatively long reaching distance used in their study because they involved trunk motion. However, our results show that the inclusion of the trunk delayed peak grip aperture despite the fact that the movement distance was the same regardless of trunk involvement.

It should be noted that the involvement of the trunk also delayed the peak of wrist velocity. Thus, both the peak of grip aperture and the peak of wrist velocity were delayed during the reach. As result, the time from the peak wrist velocity to the peak grip aperture was not altered (Table 1-II). These findings suggest that the trunk motion is integrated into the reaching during the earlier phase of reach-to-grasp movements, without affecting the basic temporal relationship between peak wrist velocity and peak grip aperture, which occurs during the later phase of the movement. This early integration of trunk motion into the reach contrasts with previous findings of Feldman and colleagues, showing that the trunk only began to contribute to arm displacement after the velocity of the arm reached its peak (Yang and Feldman 2010; see also Rossi et al. 2002 for trunk-assisted reaching). Thus, at which phase of arm transport the trunk begins to influence the reach seems to be task-specific. The study by Yang and Feldman (2010) placed a target object beyond the arm length, and the trunk naturally extended the arm's reach when grasping the object. Conversely, the present study placed a target object within the arm length, and the trunk motion was prescribed. Since the trunk has to be moved during reaching movements within shorter amplitudes of hand transport in our study, the CNS appears to delay the timing of peak wrist velocity to accommodate the early integration of the trunk into the reach. Despite the above task differences between the two studies, the common aspect is that the trunk motion seems to be well integrated into the reaching component by the time wrist velocity has reached its peak, thereby preparing for subsequent integration with the grasping component.

The current results also showed that the variability of the duration between the peak of grip aperture and the peak of wrist velocity was not altered by the specific combinations of trunk and arm movements. This finding is interesting because the same level of temporal variability was maintained between the transport and grasp components, despite a significant variability of the time interval between the trunk peak velocity and the arm peak velocity within the transport component. Taken together, the above results suggest that the trunk and arm movements are coordinated as one component (i.e., transport), as suggested by previous studies (Kaminski et al. 1995; Ma and Feldman 1995; Pigeon et al. 2000; 2003; Poizner et al. 2000). Based on that coordination, the transport and aperture components are temporally integrated regardless of variation of the prescribed coordination pattern between the arm and trunk.

Control law modeling–based approach to understanding transport–aperture coordination

The main goal of the current study was to determine whether transport–aperture coordination for grasp initiation is altered depending on the prescribed pattern of coordination between the trunk and arm movements during reach-to-grasp movements. The results showed that the hand-to-target distance at the time of grasp initiation was highly predictable based on the control law model that describes the finger/arm/trunk dynamics at the time of grasp initiation (peak grip aperture, wrist velocity and acceleration, trunk-to-target distance, trunk velocity and acceleration; see Table 2), which is consistent with our previous study (Rand et al. 2010a). This finding supports our hypothesis that a specific control law, a function whose input includes those parameters, governs the initiation of aperture closure.

It was revealed that, when the trunk was involved, the participants increased the hand-to-target distance-related safety margin for grasping. Furthermore, the distance-related safety margin is significantly increased under the condition of the trunk extension compared to the condition of trunk flexion (Fig. 4). It should be emphasized that separate comparisons of the averages for each movement parameter between different experimental conditions could not help to produce these important conclusions. For example, the average magnitude of peak grip aperture was not altered by the change of trunk motion. However, these changes of the relationship among movement parameters at grasp initiation (including the peak grip aperture) were detected by using the control law model approach. At the same time, the limited movement control optimality in performing the trunk extension during the reach, as discussed earlier, significantly increased that distance-related safety margin for the control of a grasp initiation. Therefore, the utilization of the model of the control law for aperture closure initiation for data analysis provided an adequate basis for detecting and measuring the effects of trunk-motion involvement in the control of that initiation.

Additionally, the hand-to-target distance-related safety margin also was significantly increased by the arm extension compared to the arm flexion (Fig. 4). Our previous reach-to-grasp study without trunk involvement also revealed that the arm extension in a sagittal plane for grasping performed by the right arm significantly increased the safety margin compared to the arm extension to a leftward direction (Rand et al. 2007). Taken together, the direction of the arm movement is a factor that alters the hand-to-target distance-related safety margins for grasp initiation. It is possible that these different effects across arm movement directions are caused by the different extent of maneuvering the wrist motion in order to grasp the target during the reach. For example, the arm extension in a sagittal plane may require more wrist extension compared with the arm flexion. A future study will be required to test this postulate.

In summary, the present results support the following three conclusions: (1) Trunk flexion is better integrated into the control of wrist transport than trunk extension. (2) Basic temporal coordination between peak transport velocity and peak grip aperture is maintained regardless of trunk and arm movement directions. (3) The hand-to-target distance-related safety margin for grasp initiation is increased when the trunk is extended. The present results obtained by applying a model of the control law for aperture closure initiation to experimental data revealed that the CNS takes into account the dynamics of trunk motion for controlling grasp initiation. In fact, the model describing the relationship between movement parameters at the time of aperture closure initiation is a particular case of a model of optimal transport–aperture coordination that described an optimal relationship among movement parameters related to the hand transport and finger aperture during the entire period of aperture closure (Rand et al. 2008, 2010b). In other words, it has been found that a highly precise pattern of coordination among these movement parameters established at the aperture closure initiation is maintained throughout the aperture closure phase. Therefore, when the trunk is involved, strong coordination among the movement parameters including those related to trunk dynamics is expected not only at the time of aperture closure initiation, but also during the entire period of aperture closure to ensure successful grasping.

Acknowledgments This research was supported by grants from NINDS NS 39352 and 40266.

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