RESEARCH NOTE

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Coordination among the body segments during reach-to-grasp action involving the trunk

Abstract To understand the internal representations used by the nervous system to coordinate multijoint movements, we examined the coordination among the body segments during reach-to-grasp movements which involve grasping by the hand and reaching by the arm and trunk. Subjects were asked to reach and grasp an object using the arm only, the trunk only, and some combinations of both arm and trunk. Results showed that kinematic parameters related to the transport component of the arm and the trunk, such as peak velocity and time to peak velocity, varied across conditions and that the coordination pattern between the arm and trunk was different across conditions. However, parameters related to the grasp component, such as peak aperture, time to peak aperture, and closing distance, were invariant, regardless of whether the hand was delivered to the target by the arm only, the trunk only, or both. We hypothesize that a hierarchy of motor control processes exists, in which the reach and grasp components are governed by independent neuromotor synergies, which in turn are coordinated temporally and spatially by a higher-level synergy.

Key words Prehension · Trunk · Spatial coordination · Human · Motor control

Introduction

When one intends to grasp an object, a number of ways to reach for and grasp the object exists, depending on the characteristics of the object, such as the size, shape and location of the object. Considering the number of body segments involved (e.g., fingers, hand, arm), the reach-to-grasp movement is a very skillful, complex action controlled by the nervous system (Jeannerod 1981; Stelmach et al. 1994). In an attempt to understand how the nervous

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system coordinates such complex movements, many researchers have investigated the relationship between the transport and grasp components and have proposed several mechanisms underlying the coordination between the two components. Although it has been originally suggested that the grasp and transport components are governed by independent visuomotor channels, which are synchronized by a loose temporal coupling (Jeannerod 1981), some researchers argued that the two components are not independent of each other and that they are coordinated by a certain temporal mechanism (Gentilucci et al. 1992; Hoff and Arbib 1993), while others argued that the relation between the two components involves more than a temporal coupling and that a higher-order control system is responsible for their integration (Jakobson and Goodale 1991).

Neuroanatomical evidence, however, provides some support for the idea of independent control between the transport and grasp components, although it does not necessarily mean that they are not coordinated together. Decending motor-control pathways innervating the distal and the proximal musculature are different in that the proximal musculature receives projections from the ventral corticospinal tract, whereas the more distal musculature receives projections from the lateral corticospinal tract and the rubrosinal tract (Martin 1989). Although these separate pathways descend in parallel, they have been suggested to be arranged in a hierarchical fashion, which also provides a possible connection between the proximal and distal musculature for their coordination (Armand and Aurenty 1977; Armand and Kuypers 1980; Martin 1989). With regard to the reach-to-grasp movement, therefore, it is possible that the transport component, which involves the proximal musculature, and the grasp component, which involves the distal musculature, are controlled by separate motor pathways, which are connected to preserve the coordination between the two components.

Most previous studies employed a typical reach-to-grasp task, which involved reaching by the arm and grasping by the hand. Investigating more complex tasks may broaden our understanding of the strategies used by the nervous system to guide action. We thus examined the re-

lationship among the hand, arm, and trunk because, in many occasions, the transport of the hand to the object involves not only the arm, but also the trunk, which expands the reaching distance. Reach-to-grasp movement involving trunk motion, then, consists of reaching by the arm, trunk, or a combination of both, and grasping by the hand. Previously, Saling et al. (1996) examined the temporal relationship among the body segments involved in trunk-assisted prehension and found that the arm and trunk motions appear to be controlled independently by the nervous system. In that study, the relationship among the body segments were examined under only one condition, in which the subjects were asked simply to move their arm and trunk naturally when reaching for an object. Further, they examined the resultant arm motion only, which reflects the combined action of both the arm and the trunk (i.e., endpoint motion), rather than the endpoint motion and the arm motion relative to the trunk separately. It is important to examine these motions separately, since it has been suggested that the endpoint motion is not affected by changing coordination between the arm and the trunk (Ma and Feldman 1995). To extend these findings, we investigated coordination between the transport and grasp components, as well as coordination among the endpoint, arm (relative to the trunk), and trunk motions by examining changes in the grasp formation caused by various arm and trunk combinations involved in the transport component, with the hypothesis that, despite variations in coordination between the trunk and arm movements, kinematic properties related to the grasp component would be invariant.

Materials and methods

Ten healthy college students (four males and six females) participated in this experiment. They gave their informed consent prior to the experiment. Subjects sat on a chair and reached to grasp a Plexiglas dowel (2 cm in diameter and 12 cm in height) placed on a table in front of them, under five different conditions: (1) reaching by the arm (Arm-Only), (2) reaching by the trunk (Trunk-Only), with the arm constrained to the trunk (the upper and lower arms strapped to the trunk, thus the shoulder and elbow angles kept constant), (3) reaching naturally by both arm and trunk (Arm-Trunk), (4) reaching initiated by the trunk and followed by the arm (Trunk-First), and (5) reaching initiated by the arm and followed by the trunk (Arm-First). To make sure that subjects performed the Trunk-First and Arm-First conditions as intended, performance of the subjects was carefully monitored during the data collection. Any trial in which the delay between the onsets of the trunk and arm motions was not clearly observed was deleted. After the data collection, every trial was checked again by viewing the kinetmatic data profiles. The distance between the positions of the resting hand and the target before each movement trial (approximately 40 cm) was kept constant across conditions, while the position of the chair was moved closer to the table when the subjects had to reach by the arm only. It allowed the subjects to reach for the object without using their trunk. The height of the chair also was adjusted for each subject, so that the forearm was maintained near a horizontal level in a resting condition. Subjects were instructed to move at a comfortable speed and were encouraged to move the trunk and/or the arm directly towards the target without any rotation or lateral motion. Twenty trials were recorded per each condition and average values for each kinematic parameter were used for statistical analyses (i.e., ANOVAs).

Using an Optotrak 3-D system, movements were recorded from four body parts, to which infra-red-emitting diode markers were attached: index-finger nail, thumb nail, metacarpal of the index finger, and the middle of the sternum. These data were used to obtain a number of temporal kinematic measures for the grasp component (i.e., aperture duration, peak aperture, and absolute and relative time to peak aperture) and for the transport component (i.e., absolute and relative time to peak velocity of both the wrist and trunk). Since the movement of the wrist marker reflects the combined action of the arm and trunk, transport component related to the arm was further divided: resultant velocity of the arm and trunk (termed *endpoint motion*) and velocity of the arm independent of the trunk motion (termed *arm motion*). To obtain the arm velocity, the distance between the hand and trunk markers at every sample point was calculated and its distance-time function was differentiated. In addition to these temporal measures, we considered spatial kinematic measures, since a spatial pattern of coordination between the grasp and transport components has been suggested (Haggard and Wing 1995, 1998). Using the data of the thumb travelling along an axis joining the home and target positions, we calculated the hand-transport distance, in both absolute and relative terms, between the two points in time when the onset of the grip aperture occurred and when the peak aperture occurred (i.e., opening distance) and also between the times when the peak aperture occurred and when the thumb and the index finger contacted the object (i.e., closing distance).

Results and discussion

Coordination between arm and trunk

Generally, the coordination pattern between the arm and the trunk, caused by various arm and trunk combinations, was different across conditions (Fig. 1A). For the Trunk-Only condition, velocity profiles on the endpoint and trunk motions were very similar, indicating that the hand was delivered to the target primarily by the trunk. This finding was confirmed by the velocity profile of the arm motion, which was close to zero throughout the movement. For the conditions in which both the arm and trunk were used, we found that the onset of reaching movement was always initiated by the trunk in the Trunk-First condition and by the arm in the Arm-First condition for every subject, whereas no fixed pattern was observed in the Arm-Trunk condition. For the arm component, peak velocity, movement duration, and absolute time to peak velocity of both endpoint and arm motions was significantly different across conditions ($P<0.01$ for all parameters). Relative time to peak velocity was significant for the arm ($P<0.01$), but not for the endpoint motion. For the trunk component, peak trunk velocity and the relative time to peak trunk velocity was significantly different across conditions ($P<0.01$ for both parameters). That the coordination between the arm and trunk was different across conditions is confirmed by the graphs of the endpoint and arm velocity plotted against the trunk velocity (Fig. 1B), in which the shape of the loops, representing the coordination pattern between the arm and trunk, and the direction in which the loop began appeared different across conditions.

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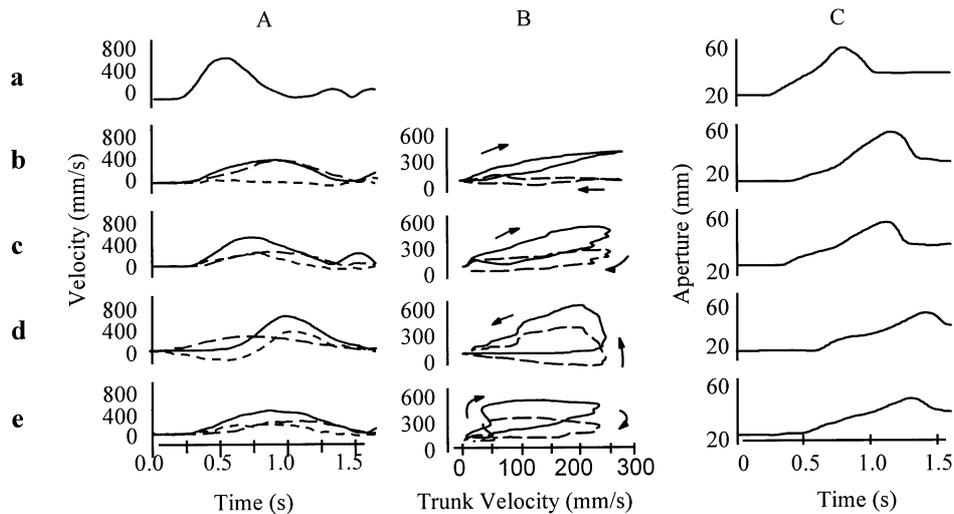
Fig. 1a–e Coordination between arm and trunk. **a** Reaching by the arm. **b** Reaching by the trunk. **c** Reaching naturally by the arm and trunk. **d** Reaching initiated by the trunk. **e** Reaching initiated by the arm. (Each *line* represents an individual trial from the same subject.) A *Solid line* represents endpoint velocity, *broken line* trunk velocity, *dotted line* arm velocity-differential. Arm velocity differential, when initiated by the trunk, shows negative values for the first 0.8 s, indicating that the trunk was not moving or moving slower than the arm. *B* Coordination patterns between the arm and trunk motions. *Y axis* represents endpoint (*solid line*) and arm (*broken line*) velocity. *C* Aperture formation plotted as a function of time

Aperture formation

Despite the differences in the coordination patterns between the arm and trunk across conditions, the striking feature of these data is that both temporal and spatial kinematic properties related to the grasp component were invariant across conditions (Fig. 1C). Statistical analysis found no significant difference across conditions in any of the aperture-related measures (i.e., aperture duration, peak aperture, time to peak aperture in both absolute and relative terms, opening and closing distance in both absolute and relative terms). Aperture duration and absolute time to peak aperture tended to be shorter in the Arm-First condition than in other conditions, although they were not significant. It may be due to the fact that Arm-Only was the most familiar condition to the subjects.

Spatial coordination between grasp and transport components

It has been frequently suggested that the transport and grasp components are temporally coordinated together to preserve the optimal performance (Gentilucci et al. 1992; Hoff and Arbib 1993). Since the temporal aspect of the coordination between the grasp and transport components has been studied extensively by previous studies, we focussed rather on the spatial aspect of the coordination between the two components. Analysis of the aperture formation shows that the occurrence of the peak ap-

erture was precisely controlled in a spatial manner across conditions (Fig. 2). The peak aperture occurred at approximately the same point in distance between the home and object positions, across conditions when it was plotted against normalized hand-transport distance. The important feature of these data is that the reach-to-grasp tasks were achieved with very different coordination patterns, yet the closure of grip aperture was remarkably invariant. Regression analyses were conducted to further analyze the invariance of opening/closing distance, since it is important to know whether the spatial feature of the aperture formation remains invariant under different conditions within each individual subject. Thus, standardized regression coefficients (B), which can measure the amount to change in opening/closing distances resulting from a one-standard-deviation change in the total hand-transport distance, were calculated for individual conditions within each subject (i.e., five Bs per subject; 50 Bs total for each variable). Results showed that, for the opening distance (ranged from 0.55 to 0.99), 47 Bs among the 50 were significantly greater than zero ($P<0.05$), whereas, for the closing distance (ranged from 0.01 to 0.58), only one B was greater than zero. These coefficients were subjected to an ANOVA as a standard dependent variable (the assumptions for an ANOVA were met for this variable), which showed that both opening and closing distances were not significantly different across conditions ($\omega^2=0.02$ and 0.03 for opening and closing distance, respectively). These data indicate that the opening distance systemically increases as the total hand-transport distance increases, although the closing distance did not and that the patterns of changes in opening/closing distances did not differ across conditions, thus suggesting that the closing distance remains invariant under different conditions in which the temporal and spatial features of the transport vary. In other words, the closing distance was invariant regardless of whether the hand was delivered by the arm, the trunk, or the combination of both. This suggests that, during the transport of the hand to the object, the distance between the moving hand and the object is one of the important variables controlled by the nervous system
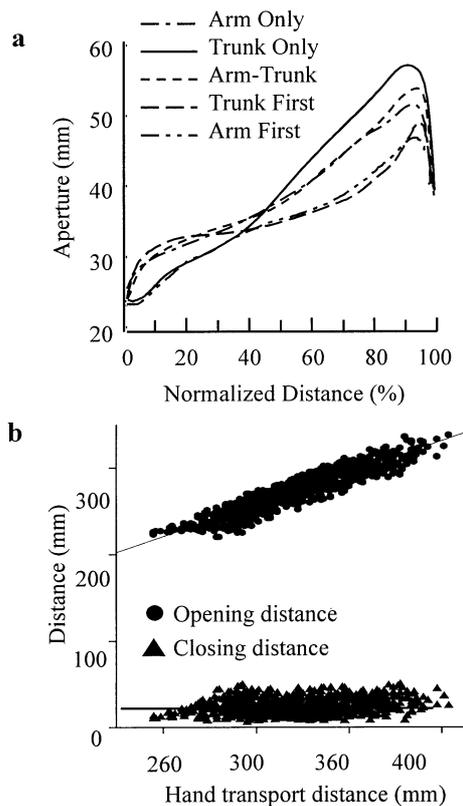
Fig. 2a, b Relation between grasp aperture and hand-transport distance. **a** Aperture plotted against normalized transport distance across conditions (*lines* represent individual trials from each condition from the same subject). **b** Scatter plot showing relations between opening/closing distance and total transport distance (data are from all subjects; each subject shows a similar pattern)

to maintain the optimal coordination between the transport and grasp components. Saling et al. (1998) previously showed that the closing distance did not change very much with a change in the total transport distance caused by the presence of an obstacle in the path towards the target object. The present study extends their finding by demonstrating that the closing-aperture distance is invariant, despite the fact that the coordination pattern between the arm and trunk was different across conditions. These data provide further support for the notion that reach-to-grasp movements utilize state-space control (Haggard and Wing 1998; Saling et al. 1998).

It is possible that the spatial invariance of aperture formation simply reflects temporal invariance, since both the absolute and relative time to peak aperture were not statistically different across conditions. If the opening/closing distances increase as a function of movement time, this probably reflects the fact that the spatial features of aperture formation are dependent on temporal features and that the invariance in distance simply reflects the invariance in time. In order to ensure that the spatial control of the aperture formation was rgulated independently from its temporal formation, correlations of the opening and closing distances to the total hand-transport distance as well as to the total aperture duration were calculated

within each subject. Correlations between the opening distance and the total distance were found to be quite high and significant for every subject (mean of 0.86, range between 0.75 and 0.98, $P<0.05$), while those between the opening distance and the total duration were low (mean of 0.17, range between 0.05 and 0.32). The closing distance was relatively lowly correlated with either the total distance (mean of 0.23, range 0.00 and 0.30) or the total duration (mean of 0.24, range 0.00 and 0.50). These correlation data, therefore, suggest that the spatial control of the aperture formation is regulated independently from its temporal formation.

In summary, our data showed that even though the parameters related to the transport component of the arm and trunk were altered and the coordination pattern between them was different across conditions, both temporal and spatial kinematic parameters related to the grasp component remained invariant regardless of whether the hand was delivered by the arm, the trunk, or both. Based on these findings, there seems to exist a hierarchy of motor-control processes involved in reach-to-grasp movement. Our data strongly suggest that the grasp and transport components are governed by two independent neuromotor synergies, which in turn are coordinated by a higher-level synergy that includes both spatial and temporal factors. Since the neuromotor synergy governing the transport component is independent of the synergy governing the grasp component, it can be superimposed without affecting the other synergy. In that way, the motor-control process controling the grasp component can keep the kinematic properties of the grasp formation invariant, regardless of the number of body segments (i.e., the number of degrees of freedom) involved in the transport component. Further, the neuromotor synergy governing the transport component appears to be divided into two subprocesses: one controlling the endpoint motion and the other coordinating the body segments involved in reaching. It has been suggested that reaching movements are governed by two neuromotor synergies: one that controls the endpoint motion and another that coordinates the trunk and arm movements, leaving the endpoint motion unchanged (Ma and Feldman 1995). In our study, despite the fact that differences in the relative time to peak velocity of both the arm and the trunk motions were statistically significant, the relative time to peak velocity of the endpoint motion was not, indicating that the endpoint velocity profiles should closely match across conditions if their amplitudes were scaled. This partially suggests that the arm and trunk motions, which are controlled independently, work together to keep the endpoint motion consistent. The use of such hierarchical motor-control processes may reflect the way in which the nervous system solves the problem of coordination of a redundant number of degrees of freedom in complex, multijoint-movement control.

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