

# Two Functionally Different Synergies During Arm Reaching Movements Involving the Trunk

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## SUMMARY AND CONCLUSIONS

1. To address the problem of the coordination of a redundant number of degrees of freedom in motor control, we analyzed the influence of voluntary trunk movements on the arm endpoint trajectory during reaching.

2. Subjects made fast noncorrected planar movements of the right arm from a near to a far target located in the ipsilateral work space at a 45° angle to the sagittal midline of the trunk. These reaching movements were combined with a forward or a backward sagittal motion of the trunk.

3. The direction, positional error, curvature, and velocity profile of the endpoint trajectory remained invariant regardless of trunk movements. Trunk motion preceded endpoint motion by ~175 ms, continued during endpoint movement to the target, and outlasted it by 200 ms. This sequence of trunk and arm movements was observed regardless of the direction of the endpoint trajectory (to or from the far target) or trunk movements (forward or backward).

4. Our data imply that reaching movements result from two control synergies: one coordinates trunk and arm movements leaving the position of the endpoint unchanged, and the other produces interjoint coordination shifting the arm endpoint to the target. The use of functionally different synergies may underlie a solution of the redundancy problem.

## INTRODUCTION

Because of the redundancy in the number of the degrees of freedom of the body, the nervous system has the capacity to select a desired trajectory and interjoint coordination from many possible strategies to reach the goal (Bernstein 1967; Kelso et al. 1991; Mussa-Ivaldi et al. 1988). Planar arm reaching movements to a target may be produced by alterations in the elbow and shoulder angles leaving the trunk position and the wrist angle unchanged (e.g., Flanagan et al. 1993). Thus, in this motor task, the nervous system reduces the number of degrees of freedom to produce a unique arm configuration for each target position. Subjects are able to change this strategy by voluntarily producing variations in the wrist position during reaching (Koshland and Hasan 1994). They may also be forced to move the trunk when the target is placed far from the body in such a way that it cannot be reached by an arm movement alone. In this case, the hand moves along the same path regardless of the segments involved, although the coordination between the joints is altered (Kaminski et al. 1992). In the present study the same target located at a 45° angle to the sagittal midline could be reached by the hand with or without a sagittal trunk movement depending on the instruction to the

subject. We tested the hypothesis that reaching movements involving the trunk are a combination of two functionally independent synergies. One synergy involves only arm joints to produce a hand trajectory to the target, and the other one coordinates movements of the trunk and arm joints leaving the position of the arm endpoint unchanged. Alternatively, trunk and arm joints are controlled in the framework of a single synergy modified according to the geometry of the changing system (Lacquaniti 1992).

## METHODS

Normal subjects ( $n = 3$ ) sat on a stool with their right arm on a table. The subject held the tip of his index finger (the arm endpoint) above an illuminated target [light-emitting diode (LED); the near target] inlaid in the surface of the table at a distance of 20 cm from the midline of the chest. When a far target was illuminated at the distance of 40 cm on the right side at a 45° angle to the sagittal midline of the trunk, the subject shifted the arm endpoint to the far target as fast as possible (Fig. 1A, *top*). Subjects were asked not to make corrections if an error in the final position occurred. Wrist, elbow, and shoulder positions as well as the coordinates of the arm endpoint were recorded with the Optotrak motion analysis system by infrared light-emitting diodes (IREDs).

In the 1st set of 10 trials (Fig. 1A, *top*), subjects produced arm movements from the near to the far target, and, after a holding period of 200–500 ms, they moved the arm back while the trunk was motionless. In the second set (10 trials), they combined the arm movement to the far target with a forward sagittal motion of the trunk (Fig. 1A, *middle*) produced by means of a hip flexion (“in-phase movements”). When, in the same trial, the arm returned to the near target, they produced a backward trunk motion. In the third set (10 trials), the arm motions to the far and the near target were combined with a backward and forward sagittal motions of the trunk, respectively (“out-of-phase movements”). Note there was an angle of 45° between the directions of the arm endpoint and trunk movements (Fig. 1A, *middle*). We computed tangential velocities of movement along the endpoint trajectories, as well as the curvature, length, and direction of the trajectory. The latter was computed for each discrete movement as the angle between a linear regression line of the trajectory and a frontal horizontal line of the trunk, separately for movements to the far and the near target.

## RESULTS

The direction of the arm trajectory remained the same regardless of the direction of trunk movement (Fig. 1B; maximal slope difference <4%), even though the arm tangential velocities in trials that included trunk movements

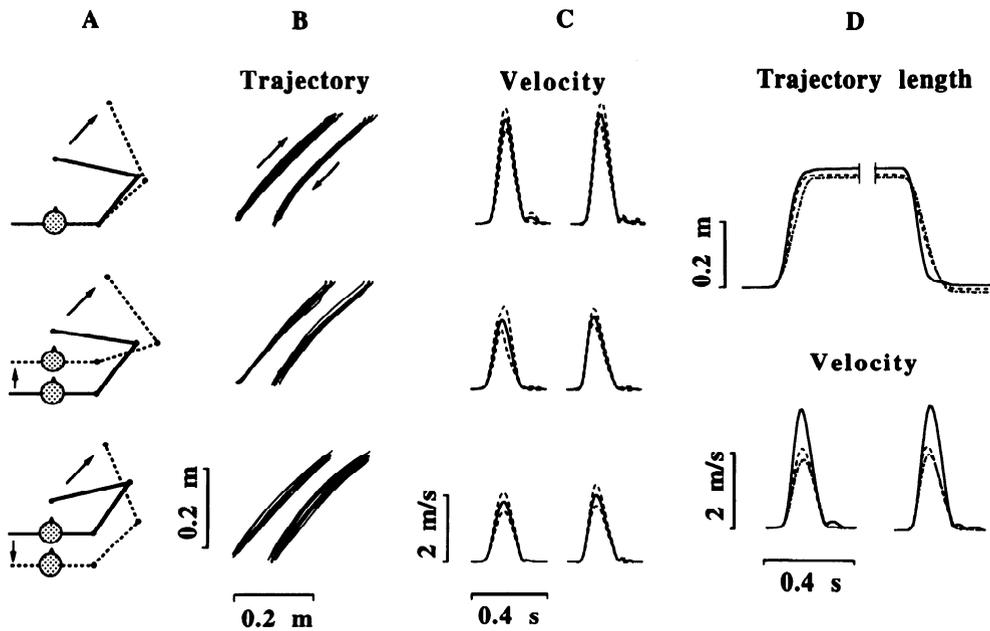


FIG. 1. Arm endpoint trajectory and velocity of arm and trunk movements. *A*: experimental paradigm. *Top*: arm movement ( $\nearrow$ ) when the trunk is motionless. *Middle*: sagittal trunk movement ( $\uparrow$ ) combined with arm movement ( $\nearrow$ ; in-phase coordination). *Bottom*: out-of-phase coordination of trunk and arm movements. *B*: endpoint trajectories (10 trials). For a better visual discrimination, trajectories of movements to ( $\nearrow$ ) and from ( $\nwarrow$ ) the far target are separated. *C*: mean tangential velocities (—) and  $\pm$ SD (---) for reaching movements from the near target to the far target (*left graphs*) and back (*right graphs*). *D*: time-scaled and averaged trajectory lengths (*top*) and tangential velocities (*bottom*) for trials without (—), with in-phase (---), or out-of-phase (-·-·-) trunk movements.

were substantially decreased (Fig. 1C). The mean peak velocities were  $3.28 \pm 0.30$ ,  $2.19 \pm 0.32$ , and  $1.86 \pm 0.27$  (SD) m/s for movement without trunk motion, motion in-phase, and out-of-phase, respectively. The mean values of the curvature of arm trajectories (mean  $\pm$  SD:  $-1.41 \pm 0.14$ ,  $-1.17 \pm 0.24$ , and  $-1.37 \pm 0.26 \text{ m}^{-1}$  for movement without trunk motion, motion in-phase, and out-of-phase, respectively) as well as the final coordinates of the arm endpoint were also not affected by trunk movements. The higher speed of arm movements without trunk movements was associated with the presence of decaying terminal oscillations in the arm position and velocity (Fig. 1C, *top*). Except for this difference, a bell-shaped velocity profile was observed in all types of experiments. These profiles could be made identical by scaling the amplitude. Trajectory lengths (the integral of the tangential velocity over the movement time) were greater when the trunk was motionless (Fig. 1D). This may be explained by the increase in the peak velocity of the arm endpoint as well as by the increase in the number of terminal oscillations of the arm movement that prolonged the movement time. In contrast, the length of the trajectories differed insignificantly for in-phase and out-of-phase coordinations of trunk and arm movements (Fig. 1D, *top*). Thus the direction, length of the trajectory, position error, curvature, and velocity profile remained invariant regardless of the direction of the trunk movement.

Figure 2 compares the averaged arm endpoint trajectory of movements (—) to the averaged trunk movements made in-phase and out-of-phase with arm movements. The trunk begins to move first (starting at *point a*). Despite the trunk motion, the position of the arm endpoint remains unchanged for  $\sim 150$ – $200$  ms (between *points a* and *b*).

The trunk continues to move during the endpoint motion (between *b* and *c*) and keeps moving for  $\sim 200$ – $400$  ms after the endpoint of the arm has reached the target (between *c* and *d*). This sequence of trunk and arm movements was

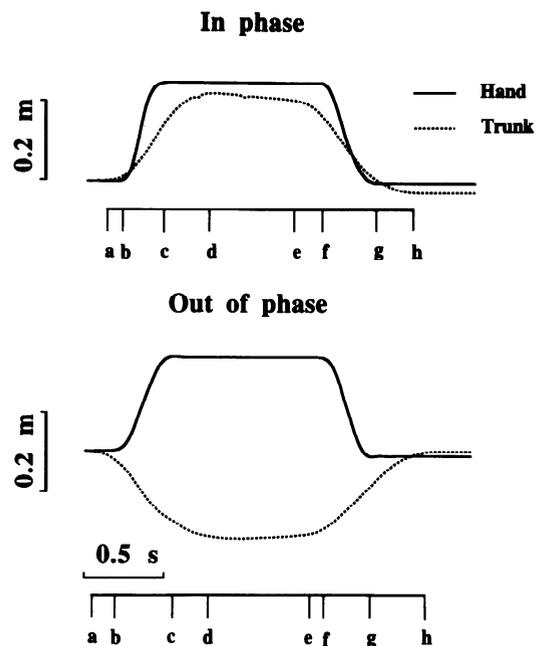


FIG. 2. Averaged movements of the arm endpoint (—) and the trunk (-·-·-) produced in-phase (*top*) or out-of-phase (*bottom*). Symbols *a*–*d* show, sequentially, the trunk movement onset (*a*), the arm endpoint movement onset (*b*), the endpoint movement offset (*c*), and the trunk movement offset (*d*) for movements to the far target; symbols *e*–*h* show the same sequence for movement to the near target.

observed both for in-phase and out-of-phase movements as well as in movements to and from the far target.

## DISCUSSION

Our data show that, before and after the hand movements, trunk and arm joint movements were coordinated in such a way that the arm endpoint position remained unchanged (Fig. 2). Regarding the intermediate phase, the finding that the hand trajectory was not affected by the trunk motion implies that a similar combination of trunk and arm movements (a compensatory synergy) that does not influence the position of the arm endpoint was merged with an already existing arm reaching synergy. Our data thus support the hypothesis that two functionally independent synergies were combined in the movement.

The coordination of movements not affecting the accomplishment of the motor task ("compensatory synergies") have been observed in other studies. One classical example of a compensatory synergy is the eye-head coordination provided by the vestibuloocular reflex, which nullifies the gaze shift elicited by head rotations. Another example is our ability to produce coactivation of antagonist muscles of the arm while preserving the original arm configuration. Spinal frogs are not only able to move the hindlimb endpoint to different sites of the body during the wiping reflex but also able to change the hindlimb configuration leaving the endpoint motionless, which suggests the use of a compensatory synergy (Berkinblit et al. 1986). If synergies are functionally independent, they may be generated either sequentially or in parallel without affecting the movement efficiency as was the case in the present study. A similar conclusion can be reached from other studies. Shifts in the equilibrium arm configuration in pointing movements to an initial and a displaced target are likely produced sequentially (Flanagan et al. 1993), even though the kinematic patterns suggest a parallel process, i.e., the movement to the displaced target is the sum of the hand movements to the initial target and from the initial to the displaced target (Flash 1990). In the present experiments the potential contribution of trunk motion to the motion of the endpoint to the target was neutralized by appropriate compensatory movements of the shoulder and elbow. To reach a target located further away may require forward leaning of the trunk and even, if one is seating, raising the body from the chair (Kaminski et al. 1992; Kelso et al. 1993; J. A. S. Kelso, personal communication). In the case of raising from the chair, an additional functional goal (postural stabilization) should be met. Similarly, during forward bending of the trunk in standing, two simultaneous goals (upper trunk displacement and postural stabilization)

are achieved by coordinating hip, knee, and ankle joint motions (Alexandrov et al. 1994; Crenna et al. 1987; Ramos and Stark 1990). One may assume that these coordinations may, like in the present study, be decomposed into functionally independent synergies. In general, the use of functionally independent synergies may underlie a solution of the redundancy problem.

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