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Coordination between hand and trunk movements in a Fitts' Law task

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COORDINATION BETWEEN HAND AND TRUNK MOVEMENTS IN A FITTS'

LAW TASK

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To my wife, my daughter, my son, and my parents

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LIST OF ABBREVIATIONS

COP: Center of pressure

HD: Hand movement direction

HW: Hand target width

ID: Index of difficulty

RMS: Root mean square

RMS_e: Root mean square error

SD: Standard deviation

TD: Trunk movement direction

TW: Trunk target width

ABSTRACT

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It has been shown that limb movements are coupled in space and time in a bimanual Fitts' task. The present study was designed to examine whether coordination of hand and trunk share some sets of coordinative principles with bimanual coordination. Participants (n = 28) were required to perform a Fitts' task with the dominant hand and a Fitts' task with the trunk. These tasks were performed separately or together. The task required moving the trunk, the dominant hand or both, such that the cursor/cursors on a computer screen was/were moved from the starting position/positions to the designated target/targets as fast and as accurately as possible. When the hand and the trunk moved in the same direction, hand movement and trunk movement were initiated and executed in a synchronized fashion, and the velocity was coupled. In contrast, when the hand and the trunk moved in the opposite directions, hand movement and trunk movement were not synchronized and the velocity was not coupled, as though they moved independently. The distinctions were further confirmed when the results were compared across different combinations of movement directions. Hand movement and trunk movement were more synchronized and the velocity was more coupled when they moved in the same direction than when they moved in the opposite directions. In addition, hand movement and trunk

movement were initiated sooner and executed faster when they moved in the same direction than when they moved in the opposite directions. Therefore, the coordination between hand and trunk when they moved in the same direction showed the same coordinative patterns as the bimanual coordination, but not when they moved in the opposite directions. It is argued that the interaction between biomechanical and task constraints played an important role in determining optimal coordinative patterns. In conclusion, the coordinative patterns are not determined solely by the muscular skeletal structure involved in the coordination, but are determined by the interaction of biomechanical constraints and task constraints imposed on the action of the effectors. The central nervous system controls the formation of synergies to optimize the coordinative patterns also depending on the constraints. These findings support the idea that coordination is the result of the constraints imposed on the action of the effectors.

CHAPTER 1. INTRODUCTION

1.1 <u>Review of the Literature</u>

Most human activities in daily life require coordination between different

effectors. For example, holding large objects requires upper limbs; walking requires

coordination between lower and upper limbs; reaching beyond arm length requires trunk

movement; and even speaking is usually accompanied by manual and facial gestures.

This multieffector coordination has been extensively studied, and fruitful coordinative

principles have been discovered and proposed. Some coordinative principles are

suggested to be common across coordination between different effectors. For example the

coordination between fingers on different limbs, between fingers on the same limbs, and

between hands and feet exhibit common principles. However, to what extent these

coordinative principles are shared between tasks requiring coordination between different

limbs and non-limbs body parts has not been studied.

Different types of multieffector coordination usually require different muscle

groups. These muscle groups sometimes are originated from the same motor tract groups.

Specifically, distal limb muscles (for example, muscles controlling movements of hand

and finger) are primarily controlled by the lateral descending motor tract group

(corticospinal tract and rubrospinal tract). Axial muscles (for example, muscles

controlling movements of head and trunk) and proximal muscles (for example, muscles

controlling movements of upper arm) are controlled by the medial descending motor tract group (vestibulospinal tract, reticulospinal tract, tectospinal tract, etc.) (Shinoda, Kakei, & Sugiuchi, 1994). Moreover, the motor cortical areas of each hemisphere fully control the motility of the contralateral extremities. Ipsilateral motor control appears to be most effective for the guidance of axial and proximal limb musculature and least effective in governing distal limb musculature particularly that related to individual movements of the hand and fingers (Brinkman & Kuypers, 1973; Geschwind, 1970; Sperry, Gazzaniga, & Bogen, 1969).

For example, Brinkman and Kuypers (1973) required split-brain monkeys to retrieve food pellets from a special test board. The test board was designed to minimize the tactile information to the reaching hand. The optic chiasm, anterior commissure, hippocampal commissure, corpus callosum, massa intermedia and the dorsal mesencephalic commissures of the monkey's brain were transected. The visual input was restricted to one half of the brain (the seeing half of the brain) by covering the eye of the animal ipsilateral to the half of the brain. When the food reaching task was performed by the arm contralateral to the seeing half of the brain, hand and fingers were brought accurately to the food with the precision grip posture. After the hand reached the board, the food morsel was dislodged by the combined movement of the index finger and thumb. In contrast, when performed by the arm ipsilateral to the seeing half of the brain (the arm and the half of the brain are on the same side.), hand and fingers were brought to the proper place less accurately than that of the contralateral arm, and the precision grip posture was never observed before they contacted with the board. The precision grip posture appeared after the contact, but the hand and finger began to explore the board

surface tactually and never led to retrieval of the food morsel. Thus, the seeing half of the brain controls the whole contralateral arm, hand and finger movements. Meanwhile, the seeing half of the brain also controls the whole ipsilateral arm movements, but not the hand or finger movements.

The motor systems subserving control of the axial musculature and of the proximal limb musculature are organized on a bilateral basis, in which each half of the brain controls both ipsilateral and contralateral musculature (Aglioti, Berlucchi, Pallini, Rossi, & Tassinari, 1993; Di Stefano, Morelli, Marzi, & Berlucchi, 1980; Wiesendanger, Kaluzny, Kazennikov, Palmeri, & Perrig, 1994). Di Stefano et al. (1980) required right-handed participants to perform visuomotor reaction time tasks. Participants pressed one or two keys (flexion of the thumb), or pulled one or two levers (flexion of the elbow and an abduction of the shoulder) as soon as possible, in reaction to the light flash of one of the two bulbs which were placed on the left and right side of the perimeter of visual field. In the unilateral condition, participants responded to the light with either left or right hand. In the bilateral condition, participants responded to the light with both hands. Unilateral reactions were faster than bilateral reactions. In the unilateral condition, ipsilateral responses were faster than contralateral responses for both key-pressing and lever-pulling. In the bilateral responding condition, the ipsilateral-contralateral time difference was reduced for the key-pressing condition, but was totally eliminated for the lever-pulling condition. Furthermore, the temporal correlation between the two effectors was very strong for lever-pulling responses, but not as strong for key-pressing responses. The authors inferred that bilateral responses are controlled by a bilateral distributed motor

system which ensures yoked movements of both limbs, and the bilateral motor system is more preferentially directed to control the proximal musculature.

Similarly, Aglioti et al. (1993) required subjects to respond to one of the two lights using three different setups. Specifically, the thumb key-pressing responses involved distal muscles, the lever-pulling responses involved distal muscles, and the shoulder key-pressing involved mostly axial muscles. In the unilateral condition, uncrossed responses were faster than crossed responses. The responses involving distal muscles were the fastest, and those involving axial muscles were the slowest. Bimanual distal responses produced by the acallosal subjects resulted in greater than normal crossed-uncrossed differences in reaction time. However, bimanual responses produced by proximal and axial muscles showed no crossed-uncrossed differences. Thus, responses involving proximal and axial muscles were governed by a bilateral distributed motor system.

1.1.1   Coordinative Principles from a Dynamical System Approach

Advocates of a dynamical system approach to interlimb coordination argue that coordination is a consequence of evolving processes of self-organization or pattern formation in complex systems (Haken, 1983; Haken, 1988; Kelso, 1981; Kelso, 1984). The behavior of the complex system can be successfully modeled by means of a few macroscopic quantities, called "order parameters" (Haken, 1983). The order parameter governs the macroscopic behavior of a complex system. It has been shown that relative phase, which refers to the angular deviation between the two oscillating limbs, is an order parameter for many interlimb coordination tasks (Baldissera, Cavallari, & Civaschi, 1982;

Kelso, 1981; Kelso, 1984; Kelso, Buchanan, & Wallace, 1991; Kelso & Jeka, 1992; Swinnen, Walter, Lee, & Serrien, 1993).

Kelso (1981) required subjects to produce simultaneous oscillatory movements with the left and right index fingers in the coronal plane. The subjects started a trial in in-phase or anti-phase coordination. In the in-phase pattern, the homologous muscle groups of each finger contracted at the same time, such that the two fingers moved in the opposite direction simultaneously (in together, out together). In the anti-phase pattern, homologous muscle groups of the two fingers contracted in an alternating order, such that the fingers moved together to the left or right in a parallel fashion. The subjects attempted to oscillate at a frequency specified by an auditory metronome. Frequency increased monotonically during a trial. Participants were instructed not to intervene if they felt the pattern change. Participants who initially performed the in-phase finger movements could stay in the pattern as the rate was systematically increased. However, subjects who initially performed the anti-phase finger movements had little difficulty in maintaining the pattern at low cycling frequencies, but suddenly switched to the in-phase pattern at a certain frequency (critical frequency) as the frequency increased. When the oscillatory period increased (rate decreased) after the pattern changed from anti-phase to in-phase, subjects did not switch back to the anti-phase movement pattern. Thus, Kelso showed that in-phase coordination was more stable than anti-phase coordination in bimanual coordination.

Similar mutual directional principles have been found when subjects performed bimanual wrist movements (Kelso, 1984), hand and foot movements in the sagittal plane (Baldissera et al., 1982; Carson, Goodman, Kelso, & Elliott, 1995; Salesse & Temprado,

2005; Salesse, Temprado, & Swinnen, 2005), and movements of two joints of the same limb (Kelso et al., 1991). Baldissera et al. (1982) required participants to perform cyclical flexion and extension of hand and ipsilateral foot movements in the sagittal plane. When the forearm was placed in a supine position, the in-phase condition was defined as flexion (extension) of the wrist with dorsi flexion (plantar flexion) of the foot, and the anti-phase condition was defined as flexion (extension) of the wrist with plantar flexion (dorsi flexion) of the foot. When the forearm was placed in a prone position, the in-phase condition was defined as flexion (extension) of the wrist with plantar flexion (dorsi flexion) of the foot, and the anti-phase condition involved flexion (extension) of the wrist with dorsi flexion (plantar flexion) of the foot. Similar results were found regardless of the arm position (supine or prone). Specifically, hand and foot movements in the same direction (in-phase) were stable and maintained the phase relations when the rate of oscillation was increased. Hand and foot movements in the opposite direction (anti-phase) were less stable and reversed to the original in-phase pattern when the rate of oscillation was increased. Abrupt phase transitions from the anti-phase pattern to the in-phase pattern were noted when the hand was placed in a prone position, but less abrupt when hand was placed in a supine position.

Carson et al. (1995) required participants to perform rhythmic movements of the ankle and the wrist entrained to an auditory metronome. The modes of coordination between hand and foot were the same as those described in the study of Baldissera et al. (1982). Movements made when limb segments were moving in the same direction (in-phase) were more stable than those made in the opposite direction (anti-phase). In contrast to the results of Baldissera et al. (1982), the number of phase transitions and the

time of transition occurrence were identical in each hand preparation (prone vs. supine).
The authors suggested the stability of the movement patterns was determined by the
spatial constraints (e.g. combination of movement directions) rather than anatomical
constraints (e.g. coupling of specific muscle groups).

Using the same paradigm, Salesse et al. (2005) required participants to perform
hand-foot coordination with either normal vision or no vision of the limbs. In the normal
vision condition, participants wore transparent goggles and were instructed to look at the
moving limbs and coordinate hand and foot as accurately as possible. In the no vision
condition, the goggles which participants wore were opaque. The authors predicted that
vision could stabilize the in-phase coordination patterns which were intrinsically
perceived as stable and destabilize the anti-phase coordination patterns compared to the
no vision condition. The number of phase transitions when participants initially
performed the anti-phase pattern was greater than that for the in-phase pattern (157 vs. 6).
Relative phase variability for the anti-phase pattern was greater than that for the in-phase
pattern. Therefore, the anti-phase pattern was more difficult to maintain than the in-phase
pattern. In the normal vision condition, relative phase variability of the anti-phase pattern
when isofunctional muscles were activated was smaller than that when non-isofunctional
muscles were activated. When non-isofunctional muscles were activated, seeing the limbs
stabilized the in-phase pattern and destabilized the anti-phase pattern. However, when
isofunctional muscles were activated, vision did not play any role in affecting the stability
and the number of phase transitions during either in-phase or anti-phase coordination.
The authors concluded directional constraints play a principal role in the stability of
hand-foot coordination. In addition, if the functionality of neuro-muscular coupling is

considered, the muscle grouping principle (homologous vs. non-homologous) observed in the coordination of upper limbs can be expanded to coordination between upper and lower limbs (isofunctional vs. non-isofunctional). Moreover, the intrinsically stable patterns of hand-foot muscular coupling were shown to be more impervious to the manipulation of visual information.

For coordination between hands and also between hand and foot, there are no direct mechanical-anatomical influences between the two segments. Moving the two joints of the same upper limb, in which the influence of mechanical linkage between the joints was substantial, shared the same coordinative principle with the coordination between hands and that between hand and foot (Kots, Krinshiy, Naydin, & Shik, 1971; Kelso et al., 1991). Kelso et al. (1991) required participants to perform coordination between the elbow and wrist joint of the right arm. Participants attempted to synchronize elbow extension to an auditory beat. The first pattern of coordination involved isofunctional muscle groups, wrist flexion (extension) synchronized with elbow flexion (extension). The other pattern involved non-isofunctional muscle groups, wrist extension (flexion) synchronized with elbow flexion (extension). When the metronome rate increased, the observed phase transition depended on forearm position, not simply on the muscle group. Specifically, with the forearm supine, transitions were observed only from the non-isofunctional muscle groups to the isofunctional muscle groups, but not in the reverse direction. With the forearm prone, transitions were observed only from the isofunctional muscle groups to the non-isofunctional muscle groups, but not in the reverse direction. Thus, coordination constraints on the nervous system were direction-dependent, and did not simply result from fixed muscle pairing across the joints (Kelso et

al., 1991). However, shifts in relative phase could occur simply because participants performing the anti-phase pattern relaxed the wrist when frequency increased. If this was the case, the authors reasoned that relative phase and other dependent measures in conditions in which participants were instructed to "relax" the wrist when frequency increased should be similar to conditions in which participants were not instructed to do so.

In the second experiment, Kelso et al. (1991) required participants to perform only the supine and prone in-phase wrist and elbow movements as those in the first experiment. Participants first actively performed each of the in-phase patterns on one set of trials (the active condition). Then on another set of trials, in order to emphasize the role of mechanical coupling between the two joints, participants attempted to actively flex and extend the elbow but to relax the wrist as much as possible (the passive condition). The mean relative phase was greater for the passive condition (11.8 degrees) than the active condition (5.5 degrees). Wrist angle exhibited a large difference between the passive condition (77.7 degrees) and the active condition (90.3 degrees). The relative phase and other dependent measures of the two set of trials were not the same. Therefore, the relative phase changes were not caused by mechanical effects. The authors thus suggested that the mechanical effects, mainly inertial coupling, did not contribute greatly to the observed phase transitions.

1.1.2   Temporal and Spatial Coupling

There is strong evidence that both symmetrical and asymmetrical movements of the limbs share a common timing process to produce synchronous movements (Hering 1868; Kelso & Schoner, 1988; Kelso, Southard, & Goodman, 1979 a, b; Steenbergen,

Hulstijn, Vries, & Berger, 1996). The strong tendency toward synchronous movements is evidence of temporal coupling between limbs. There is also strong evidence of spatial coupling between limbs. The upper limbs tend to produce assimilated spatial patterns when they actually are required to perform two different spatial patterns (Franz, 1997; Franz, Zelaznik, & McCabe, 1991; Kelso, Putnam, & Goodman, 1983).

Spatial coupling and temporal coupling co-exist in a bimanual task. Franz et al. (1991) required participants to produce continuous circle drawing movements with one hand and continuous line-drawing movements with the other hand at the same time. The trajectory of lines became elliptical (more circle alike) as did the circles (more line alike). Quantitative spatial analyses indicated that the index of circularity (the ratio of trajectory projection to the two dimensions) of "lines" produced in the line-drawing task increased and the index of circularity of the "circles" produced in the circle-drawing task decreased. The effect was referred as "the spatial magnet effect". All tasks were produced at the same average speed indicating that the hands remained tightly synchronized. Therefore, the spatial magnet effect occurred despite that there was a tight temporal coupling between the two hands.

It has been shown that temporal coupling and spatial coupling rely on different neural structures, and thus can be dissociated (Franz, Eliassen, Ivry, & Gazzaniga, 1996). Franz et al. (1996) examined performance of normal participants and callosotomy patients on bimanual drawing tasks. In the first experiment, participants continuously drew long or short lines for 10 seconds in a back-and-forth or left-and-right manner at a self-determined pace, in response to the visually lateralized stimuli. The two hands reversed direction within 10 ms of each other for more than 90% of the movements.

There was consistent tendency for one hand to lead the other. The hands were temporally coupled for both normal participants and the callosotomy patient. When the stimuli were orthogonal, the normal participants produced greater angular deviations in the two trajectories than when the stimuli were in the same orientation. In contrast, the callosotomy patient produced smaller angular deviations in the two trajectories in the orthogonal conditions compared with the same-orientation conditions. In the second experiment, instead of drawing continuous straight lines, participants drew two three-sided rectangles which increased the complexity of the spatial trajectories. Participants were instructed to start and complete drawing the three-sided rectangles as rapidly as possible. For the normal participants, reaction time was longer when the two stimuli required movements along orthogonal axes than the same axis. Reaction time was longer when the two stimuli were unequal in size than when they were equal in size. In contrast, reaction time for the callosotomy patient did not change across conditions. A similar pattern was obtained for total movement duration. Furthermore, the callosotomy patients bimanually drew required geometric figures with more spatial accuracy than the normal participants. Taken together, temporal coupling occurred despite the primary pathways between the cerebral hemispheres (corpus callosum) were severed, whereas spatial coupling resulted from the direct interactions between the cerebral hemispheres. Thus, Franz et al. demonstrated a dissociation in spatial and temporal coupling.

A well-known experimental paradigm used to investigate bimanual synchrony is the bimanual version of Fitts' paradigm (Amazeen, Ringenbach, & Amazeen, 2005; Kelso et al., 1979 a, b; Kelso et al., 1983; Riek, Tresilian, Williams, Coppard, & Carson, 2003). Fitts (1954) required participants to perform a reciprocal stylus tapping task

between two targets as quickly and as accurately as possible. The target width and the
distance between the two targets were manipulated to provide different task difficulties.
Movement time increased linearly as the index of difficulty increased. This relation is
known as Fitts' Law. The duration of a movement (T) is determined by the ratio of
movement distance (D) to target width (W): $T = a + b \log_2(2D/W)$, where a and b are
empirically determined constants. $\log_2(2D/W)$ is called the index of difficulty (ID). Fitts'
Law has received a great deal of experimental support in a wide variety of tasks using
various effectors, such as the arm, hand, fingers, and foot (Drury, 1975; Fitts & Peterson,
1964; Kim, Parnianpour, & Marras, 1996; Langolf, Chaffin, & Foulke, 1976; for a review,
see Plamondon & Alimi, 1997). Langolf et al. (1976) required subjects to perform both
the microscopic peg transfer task and the Fitts' reciprocal tapping task. The method of
moving the stylus subtly changed with movement amplitude. Specifically, when
movement amplitude was extremely small, subjects carried out the movement primarily
with finger flexion and extension under the microscope. When movement amplitude
increased, subjects began to flex or extend both wrist and fingers, and then use both the
forearm and upper arm. Fitts' Law was observed regardless that different anatomical
segments (finger, wrist or arm) were used to carry out the movement. Drury (1975)
instructed seated subjects to tap reciprocally with the foot between two wooden blocks.
Consistent with Fitts' Law, movement time of foot increased linearly as the ID increased.
Kim et al. (1996) found when subjects performed a rhythmic trunk-bending task, Fitts'
Law held for the angular movement of the hip.

Using a bimanual discrete Fitts' task, Kelso et al. (1979 a, b) studied the
coordination of bimanual movements. Subjects moved each hand from a starting point to

a target as quickly and as accurately as possible after the presence of an auditory stimulus. When the hands performed tasks with the same difficulty, movement time of each hand was not different from that of the single hand movement. When the hands performed tasks with unequal difficulties, the movement time difference between the two hands was considerably reduced when compared to the difference of the single hand movement conditions. The difficult task determined movement time. Specifically, when compared with the single hand movement, movement time of the hand performing the easy task increased significantly, whereas movement time of the hand performing the difficult task stayed about same. There were no significant hand differences in reaction time, time to peak velocity and acceleration although the hands moved through different distances (long vs. short) to different targets (large vs. small). The authors suggested that the central nervous system tended to place temporal constraints upon the limbs, so that the limbs acted as "a single unit".

Kelso et al., (1983) confirmed the earlier findings (Kelso et al., 1979 a, b) on tasks when homologous muscle groups were involved (hands moved laterally to the opposite direction, the first experiment) and even tasks when non-homologous muscle groups were involved (hands moved laterally to the same direction, the third experiment). In the second experiment, participants moved the two limbs to the two targets respectively as quickly and as accurately as possible. Participants moved one limb to clear a barrier in the middle of its path, while the other limb had a clear path. The initiation of the limb which had to clear the obstacle was slightly faster than the other limb. Movement time of the limb with the obstacle was greater than that of the other limb. Movement time of the limb without an obstacle increased when compared with the single limb movement, such

that the movement time difference between the two limbs was reduced. Although not consistent for all participants, the displacement, velocity and acceleration of the limb without an obstacle were similar to those of the limb with the obstacle. Therefore, despite the fact that there was no physical barrier, the limb that had a clear path to the target moved as though it also cleared an obstacle. In other words, two limbs reached their respective targets in a spatially and temporally coupled manner.

Although there is a tendency for two hands to produce temporally synchronized movements, bimanual aiming and prehension tasks have also been found to not be perfectly synchronized. The interlimb asynchrony is relatively small, but distinct. It has been suggested that temporal synchrony and asynchrony between the two hands are context dependent (Balakrishnan & Hinckley, 2002). Asynchrony between bimanual movements increased when the asymmetry in task difficulties for the two limbs increased (Fowler, Duck, Mosher, Mathieson, & Mathieson, 1991; Marteniuk, Mackenzie, & Baba, 1984; Mason & Bruyn, 2009; Steenbergen et al, 1996). Fowler et al. (1991) required participants to move the hands from home keys to targets as quickly and accurately as possible in the sagittal plane. Reaction time for the hands was not different. Movement time differences between hands increased significantly as the ID difference between the targets increased. Similar results were found by Steenbergen et al. (1996) in which participants with spastic hemiparesis were instructed to transfer small balls into holes. There was a tendency for the impaired hand to reach the target later than the other hand. The tendency of asynchrony became greater when the asymmetry in task difficulty for the two limbs became greater. Along with the task difficulty, inertia of the two hands also affected the asynchrony between them. Marteniuk et al. (1984) required participants to

perform bimanual hand movements to targets as quickly and as accurately as possible. The reaction time difference and movement time difference between left and right hand were significant when the two hands covered different distances or when the stylus weights were unequal. Specifically, when the two tasks differed only in stylus weight (50 grams vs. 350 grams), there was a prominent asynchrony between hands.

It has also been hypothesized that asymmetries in allocating attentional resources underlie interlimb performance asynchrony (Peter, 1994). The combined effects of handedness and attention on limb asynchrony have been broadly studied using bimanual Fitts' paradigms (Amazeen et al., 2005; Riek, et al, 2003; Srinivasan & Martin, 2010). Amazeen et al. (2005) assumed that the easier task required less attention than the more difficult task. In two experiments, both right-handed and left-handed participants performed bimanual rhythmic Fitts' Law task. Specifically, participants tapped their index fingers between two pairs of square targets as fast and as accurately as possible. The authors predicted that the hand performing the more difficult task would tend to lead. Increasing the relative difficulty between hands increased the attention devoted to the difficult task and further increased the tendency to lead. In Experiment 1, both target distance and width were manipulated to adjust the relative difficulty between tasks of the two hands. In Experiment 2, target distance was manipulated in one session and target width was manipulated in another session. In each experiment, participants showed a tendency to the lead with their dominant hand. In Experiment 1, there was a greater dominant hand lead when the hand performed the easier task. In Experiment 2, the same results were found in the session when only target distance was manipulated. Therefore, left-handers showed a greater left-hand lead when the targets for the left hand became

smaller and right-handers showed greater right-hand lead when the targets for the right hand became smaller.

Riek et al. (2003) assumed that eye movements were an important determinant of the overt attention in the bimanual Fitts' task. Eye movements were also measured when participants performed a rhythmic bimanual Fitts' Law task in the coronal plane. There was a "hover" phase before the hands acquired the targets, where one hand hovered above the target waiting for the other hand to be spatially positioned. Meanwhile, the eyes were found to fixate on one target to adjust the spatial end-point error of one hand, and then switch to the other target to do the same thing for the other hand. Once the second hand was spatially aligned with the target, the two hands moved down simultaneously to contact the targets without changing eye fixation from the final target. The authors suggested the "hover" strategy is caused by the limitations of the human visual system. Specifically, it was difficult to correct end-point errors of the two hands simultaneously using visual feedback when they were a certain distance (6 cm) apart. Therefore, they suggested that visual acquisition of spatial information in bimanual aiming tasks played an important role in the synchronization of hand movements. The eye-hand coordination of symmetric bimanual tasks was further investigated in Srinivasan and Martin (2010). Right-handed participants moved an object with each hand from an initial position to specified target location. When competing visual demands were present, left hand movements required more foveal visual information of the target as guidance, while right hand movements were controlled until the terminal phase with the target in the peripheral view field. Thus, the feedback requirements for each hand were asymmetrical when accuracy demand was critical.

To the best of my knowledge, there is no work examining the temporal and spatial coupling between two effectors other than the limbs using the bimanual version of Fitts' paradigm introduced by Kelso et al. (1979 a, b). Therefore, whether these coordinative principles can be directly observed in hand-foot coordination or hand-trunk coordination is not known. However, the coordination between hands and feet were investigated in a very similar paradigm (Sherwood, 1990).

Sherwood (1990) required the seated participants to move the hands and the feet forward simultaneously a specified distance to targets in one continuous rapid movement without corrections. The participants were prevented from viewing their limbs, and no visual feedback was presented during movement. In the first experiment, the participants either moved all four limbs to the same distance of 9 cm, or moved the left side limbs a shorter distance of 5 cm and the right side limbs a distance of 9 cm. The participants were instructed that they could move whenever ready following the command to move but not a "reaction time" task, and the movement time was not controlled. The initiation times of all four limbs were within 50 ms of each other. Averaged movement time was the same for two groups. The greatest movement time difference between limbs was 25 ms in the group with same distances. However, when compared with the respective limbs in the group with same distances, the left limbs (shorter distance) moved about 140 ms faster and the right limbs (same distance) moved about 120 ms slower in the group with different distances. Moreover, the upper limbs reached peak velocity sooner than the lower limbs.

In the second experiment, the participants either moved all four limbs the same distance of 9 cm, or moved the upper limbs a longer distance of 15 cm and the lower

limbs a distance of 9 cm. The movement time of the upper limbs and the lower limbs were similar in the group with the same distances, whereas the upper limbs exhibited about 180 ms longer movement time than the lower limbs in the group with different distances. Movement time of the lower limbs in the group with different distances increased only about 50 ms compared to the group with the same distances, suggesting that the lower limbs did not significantly slow down to accommodate the slower movement of upper limbs. Again, the upper limbs in the group with different distances reached peak velocity faster than the upper limbs of the group with same distances. Taken together, there was no tendency for all limbs to show temporally coupled movements when the tasks were different. The author argued that the results were caused by the different tasks used, and the movements had twice the duration of the aiming movements compared to previous studies (Kelso et al., 1979 a, b; Kelso et al., 1983; Marteniuk et al., 1984).

1.1.3   Coordination between Hand and Trunk

In most studies, the coordination between hand and trunk is studied in conditions when only the hand performed a goal-directed movement. Extensive evidence has shown that muscle activity in the prime movers of voluntary movements is preceded by activity of postural muscles to compensate for the resulting perturbation of balance caused by the voluntary arm movements (Belenkii, Gurfinkel, & Paltsev, 1967; Bouisset & Zattara, 1981; Clement, Gurfinkel, Lestienne, Lipshits, & Popov, 1984; Cordo & Nashner, 1982; Slijper, Latash, & Mordkoff, 2002), trunk movements (Crenna, Frigo, Massion, & Pedotti, 1987), and leg movements (Mouchnino, Aurenty, Massion, & Pedotti, 1992). These anticipatory postural adjustments are viewed as part of the planned voluntary response

(Vernazza, Alexandrov, Massion, 1996; Weeks & Wallace, 1992). Therefore, any voluntary goal directed movement of a limb involves coordination activity in the supportive postural muscles (Marteniuk, Ivens, & Bertram, 2000). In other words, performing a voluntary goal-directed movement by the limbs could in itself introduce the coordination between hand and other body segments, such as the trunk.

Coordination is defined as a problem of constraining many degrees of freedom into a smaller number degrees of freedom solution (Bernstein, 1967; Turvey, 1990). The central nervous system is capable of selecting a desired trajectory and interjoint coordination from many possible strategies to achieve the goal when the body had redundant degrees of freedom (Kelso et al, 1991; Ma & Feldman, 1995; Mussa-Ivaldi, McIntyre, & Bizzi, 1988). Anticipatory postural adjustments are evidence that trunk (whole body) adjustments compensate for the potential perturbations caused by the goal-directed movement. When redundant degrees of freedom are involved to produce a goal-directed movement, some other segments are also capable of compensating unexpected perturbations in order to successfully accomplish the movement, such as force production with multiple fingers (Li, Latash, & Zatsiorsky, 1996; Scholz, Danion, Latash, & Schoner, 2002), hand reaching with multiple joints (Lacquaniti & Soechting, 1982), and speech production (Abbs & Gracco, 1984; Abbs, Gracco, & Cole, 1984; Kelso, Tuller, Vatikiotis-Bateson, & Fowler, 1984). For example, Abbs and Gracco (1984) required participants to produce test utterances while an unanticipated mechanical perturbation (downward pulling) was applied to the lower lip. The upper lip showed a compensatory movement by moving down more than normal. As a result, the required speech production was achieved without being disrupted by the perturbation. Similarly, in the

coordination between hand and trunk, trunk movement is compensatory to the goal-directed hand movement.

Both involuntary and voluntary trunk movements were incorporated smoothly into the goal of hand movement when participants were seated (Archambault, Pigeon, Feldman, & Levin, 1999; Kaminski, Bock, & Gentile, 1995; Ma et al., 1995; Wang & Stelmach, 1998). Kaminski et al. (1995) required seated participants to reach for targets as quickly as possible either within arm length or beyond arm length in the sagittal plane. When the targets were beyond arm length, the trunk started to move simultaneously with the arm and persisted until target contact, although there was no tight coupling between trunk and hand velocity. The involvement of trunk motion had no effect on the end point variability and the configuration of joints and segments in attaining the target. The addition of trunk flexion, rotation and scapular motion did not alter the coupling between the elbow and shoulder joints, and had no effect on the path of the hand or the smoothness of its velocity profile. Furthermore, trunk motion was smoothly integrated into the transport phase of the hand, and trunk flexion either stopped simultaneously with other joints or was the last to complete. Thus, the authors suggested that the trunk not only acted as a postural stabilizer, but also was a prime mover of the hand close to the target when it was beyond the arm length.

Ma et al. (1995) required seated participants to move their right arm in anterior-posterior direction to a target as fast as possible without correction. Participants performed three different sets of trials. In the first set, participants reached for the target without trunk movement. In the second set, participants reached for the target while the trunk voluntarily moved in the same direction ("in-phase movements"). In the third set,

participants reached for the target while the trunk voluntarily moved in the opposite

direction ("out-phase movements"). Arm tangential velocity decreased when voluntary

trunk movements were utilized. In addition, the trunk started to move before the arm and

kept moving for a short period of time (about 200 ms to 400 ms) after the arm reached the

target in both in-phase and out-phase movements. However, trajectory direction,

trajectory length, position error, curvature, and velocity profile of the arm remained

invariant regardless of the trunk movement direction. The potential contribution of trunk

movement to the end point motion to the target was compensated by the movements of

the shoulder and elbow. The authors proposed that reaching movements resulted from

two independent control synergies. The first synergy coordinated trunk and arm

movements so that the endpoint position remained unchanged. The second synergy

produced interjoint coordination to shift the endpoint to the target.

The invariance in hand trajectory was also observed in the tasks when the

voluntary forward bending of trunk was unexpectedly blocked, or in the tasks when

pointing to a target that was moving with the trunk (Adamovich et al., 2001). Seated

participants moved the dominant hand fast (peak hand velocity ranged from 80 cm/s to

260 cm/s) from initial position to a target within the reach of the arm. Participants were

also required to combine arm movement with a sagittal trunk motion. Vision was

removed when the movement started. The trunk motion was randomly blocked on 30% of

the trials. Participants attempted not to react to the perturbation or to make corrections of

the final hand position (Experiment 1). The endpoint trajectory followed identical paths

and the spatial distribution of final positions of the hand remained invariant, regardless

whether the trunk motion was blocked or not. The endpoint velocity profiles were

different only near the offset of the movement of the endpoint. Specifically, the velocity

of the hand decreased near the offset of the movement of the endpoint when the trunk

motion was blocked. In contrast, the patterns of the elbow-shoulder coordination changed

in response to the trunk arrest. Specifically, when the trunk motion was blocked,

participants produced more elbow extension and shoulder abduction in a latency that did

not exceed 100 ms.

In Experiment 2, Adamovich et al. (2001) required participants to voluntarily

initiate a change in direction of the hand motion from frontal to sagittal as soon as the

trunk arrest was felt. The participants were unable to initiate changes in direction before

about three-quarters of the movement distance had been covered by the hand. The mean

latency of the direction-changing responses took place at about 320 ms after the onset of

the hand motion. The endpoint trajectory did not change until the onset of the voluntary

direction-changing response, indicating that a compensation of the trunk influence on the

endpoint trajectory started before the onset of the voluntary response.

In Experiment 3, Adamovich et al. (2001) examined how the amount of the

compensatory arm movement varied depending on task demands. Participants held the

left forearm and hand still horizontally with a light 50-cm rod attached along the dorsal

surface of the arm. The tip of the left thumb touched the sternum, such that the left arm

and the trunk moved as a rigid body. The initial marker was placed on the end of the rod

proximal to the hand, and the target was on the distal end. The participants moved the

right index finger without vision along the rod without touching it, while making a hip

flexion. The participants were instructed not to correct when the trunk motion was

blocked. When endpoint trajectory was measured in an absolute, motionless frame of

reference, the endpoint trajectories were different between when the trunk motion was not blocked and when it was blocked. In response to the trunk arrest, peak velocity decreased. However, in a coordinate system relative to the trunk, trajectories were identical regardless whether the trunk was block or not. Taken together, the authors concluded that hand trajectory invariance can be produced in an external spatial frame of reference, or in an internal frame of reference (trunk-centered).

The principles of coordination between hand and trunk appeared to be shared across the pointing tasks when the target was beyond arm length from a seated position. Alternatively, pointing to a target beyond arm length from a standing position undoubtedly required more effort on maintaining body balance than from a seated position, because of the greater perturbation caused by trunk movement. Therefore, the patterns of coordination between hand and trunk should be different when requiring a high degree of equilibrium control. Marteniuk, Ivens, and Bertram (2000) required participants to tap an initial large target then quickly tap a second target varying both in size and distance. In one condition, participants pointed while standing still. In the other condition, participants pointed while walking alongside the table supporting the targets. Endpoint variability, movement time and the trajectory of the end effectors were essentially the same between the two conditions, although trunk movements were distinct in the two conditions. The authors suggested that the movements involved in the tasks were planned and controlled by considering the whole body as a single unit. These results were in agreement with the findings from the experiments in which participants were seated (Kaminski et al., 1995; Ma et al., 1995), which showed the hand moved along a similar path despite multiple segments involved.

Meanwhile, it has also been shown that the coordination between hand and trunk changes with task complexity and equilibrium constraints (Berrigan, Simoneau, Martin, & Teasdale, 2005; Pozzo, Stapley, & Papaxanthis, 2002). Pozzo et al. (2002) required standing participants to point with the index figure of each hand simultaneously to the end of a wooden dowel placed on the ground in front of them. The height of the dowel was set at either 5% of participant height or 30% of the height resulting in two distances between the finger and the end of dowel, and participants pointed at a normal speed or as fast as possible. The required pointing movements involved coordination of shoulder, hip, knee and ankle joints. The center of mass exhibited a large displacement (mean of 6.3 cm) and was not stabilized as expected, but was accelerated towards the target. The finger trajectory was curved and the shape of finger path varied according to movement speed and target distance. Specifically, the finger path at the normal speed exhibited more pronounced curvature than that at the fast speed. Although at the fast speed the finger path tended to be straight, the path for the near distance was not as straight as that for the farther distance. Furthermore, variability between finger paths increased with increased pointing distance. The authors suggested that an equilibrium constraint played a role in the generation of hand trajectory for complex, whole-body pointing movements in addition to the constraints placed on the goal directed movements.

How task complexity and equilibrium constraints of an aiming movement influence the contribution of the trunk to the goal-directed hand movement was also examined (Berrigan et al., 2005). Subjects pointed as fast and as accurately as possible in the sagittal plane to a target varying only in width. Movements were executed in a seated or a standing position. Movement time was different between the seated position and the

standing position only for the most difficult task (the ID was 6.9). An apparently greater

hip flexion was associated with the hand movement when standing and smaller hip

flexion was associated with greater elbow extension when seated. When seated, the

amplitude of the center of pressure was not affected by the index of difficulty of the task.

The speed of the center of pressure at target impact decreased as the index of difficulty

increased. Meanwhile, the maximum speed of the center of pressure was strongly

correlated with the maximum hand speed. In contrast, when standing, the displacement of

center of pressure increased as the index of difficulty increased. The speed of the center

of pressure at target impact did not change with the index of difficulty. The maximum

speed was also kept unchanged. The authors thus suggested that to coordinate the hand

and the trunk, the subjects regulate their center of pressure to provide a controlled

referential for the hand movement.

1.2   Rationale for the Study

Common coordinative principles are shared across tasks involving multiple limbs,

including moving fingers, the two arms, two hands, and moving hand and foot and so on.

However, to what extent do common principles exist for hand-trunk coordination is not

well studied. The posture stabilizing role and hand transporting role of trunk when a hand

is performing a goal-directed movement has been well studied and demonstrated.

Meanwhile, the hand in most cases plays a manipulative role in a goal-directed

movement, in which the performance of the hand is the ultimate concern in terms of the

task success. In contrast, the trunk is viewed as providing a supportive role in a goal-

directed movement, in which its movement or adjustment is incorporated into the

endpoint movement to facilitate the task success. Thus, it is conceivable that the

coordination of limb and trunk do not behave in a similar fashion as bimanual coordination.

Bernstein (1967) stated movements were not chains of details but structures that were differentiated into details. Bernstein also stated that movements are structurally whole, simultaneously exhibiting a high degree of differentiation of elements and differing in the particular forms of the relations between elements. If this is the case, regardless of the role an effector usually plays (manipulative role vs. supportive role), there should be evidence to support the idea that the movement of hand and the movement of trunk are one and the same type of Bernsteinian structure.

One hand plays a supportive role to the other hand in performing a goal-directed movement (Dufosse, Hugon, & Massion, 1985; Hugon, Massion, & Wiesendanger, 1982; Paulignan, Dufosse, Hugon, & Massion, 1989). Dufosse et al. (1982) required seated and blindfolded subjects to position the right forearm at a right angle with the upper-arm, and maintain the forearm horizontal during the experiment. In one condition, subjects lift a load with the left hand from a platform supported by the right forearm in response to a tone. The right forearm was able to hold a stable position, and the elbow position was constant. The biceps activity of the right arm decreased, and preceded the force produced by the left arm by about 25 ms. Therefore, the right arm (the "postural" forearm) showed an anticipatory inhibition of the forearm flexors which was time locked with the onset of biceps contraction in the voluntary forearm resembling the anticipatory postural adjustment.

Goal-directed movements of the supportive trunk or whole body have also been shown to share common movement control principles that mainly govern movements of

manipulative effectors (Kim et al., 1996; Cai, Ryu, Haddad, Smith, & Zelaznik, in preparation; Ryu, Cai, Haddad, & Zelaznik, in preparation). Cai et al. (in preparation) required participants to shift their center of pressure, or a marker on the trunk (above the navel) to move a cursor on a computer screen between two targets varying in distance and width as quickly and as accurately as possible. The alignment of the targets was adjusted to the movement direction of the marker or the center of pressure accordingly. The participants moved the whole body with hands along the body and without bending the knees and the hip. In one experiment, the participants shift the whole body in the medial-lateral direction. The nine indices of difficulty ranged from 2.0 to 4.0. The mean error rate for the marker group was 7.8%, and the mean rate for the center of pressure group was 8.1%. The movement of each participant in the marker group obeyed Fitts' Law. Movement time, averaged across participants, was a linear function of index of difficulty. In the center of pressure group, the center of pressure movement was not as consistent as the body-marker movement. Furthermore, the greater the body movement (displacement increased from 0.9 cm to 4.0 cm), the better the linear relationship appeared (r-squared value increased from 0.05 to 0.94). The relationship between movement time averaged across participants and the index of difficulty was also clearly consistent with Fitts' Law. No difference in the slopes of T and ID was found for the two groups.

In another experiment, participants performed similar tasks as those of previous experiment, but in the anterior-posterior direction. The mean error rate for the marker group was 6.0%, and the mean rate for the center of pressure group was 11.4%. The authors observed Fitts' Law regardless whether the marker on the trunk or the center of

pressure was controlled. Specifically, Fitts' Law was consistently observed for individual participants and across participants in both groups. We suggested that voluntary trunk movement obeyed Fitts' Law.

Ryu et al. (in preparation) examined whether whole-body and hand movements could switch their roles accordingly when the portion of contribution of each effector to the movement goal was changed. Standing participants held the forearm of the dominant arm horizontal in the sagittal plane and the elbow angle was about 90 degrees. The other arm was kept along the torso. The participant controlled a cursor on a computer screen. The displacement of the cursor was the result of a combination of finger and/or the COP movement. For example, the displacement of the cursor could be the sum of 40% of the displacement of the marker plus 60% of the displacement of the center of pressure. The participants were unaware of the divided contribution to the combined displacement of the cursor. The participants attempted to keep the cursor within a 1 cm circle as close to the center as possible. There was a clear trend that the standard deviation of the index finger displacement decreased when its contribution to the goal variability increased. Unexpectedly, the standard deviation of the center of pressure did not tend to change with its contribution to the goal variability. The authors suggested that the task was not difficult enough to elicit changes in the variability of the center of pressure. Interestingly, the mean power frequency analyses on the displacement of the index finger and the displacement of the center of pressure revealed a tradeoff between the index finger stiffness and the whole body stiffness. Specifically, when the index finger contributed more to the goal variability, the stiffness of the index finger increased and the stiffness of

the whole body decreased. When the whole body contributed more to the goal variability, the stiffness of the whole body increased and the stiffness of the index finger decreased.

Taken together, I posit that movement control principles do not differ between manipulative effectors and supportive effectors. It would provide additional evidence concerning the similar nature of manipulative effectors and supportive effectors when these two types of effectors are explicitly required to be coordinated. In the present study, I investigated the coordination between hand and trunk when each performed a goal-directed task. To answer the question whether common coordinative principles are shared in the coordination between a manipulative effector and an effector mainly considered as a supportive role should provide us more insight into how coordination of two effectors is controlled by the central nervous system.

It is also worth noting that there are other major concerns on examining coordinative principles in hand-trunk coordination. First of all, similar to the coordination between wrist joint and elbow joint, there are also direct mechanical influences between hand movement and trunk movement. Especially when standing, hand movement alone could cause activations of muscles involved in trunk movement. Trunk movement also unavoidably affects hand movement. Therefore, the interaction between hand movement and trunk movement should be considered. Second, even if the trunk is executing a goal-direction movement, the trunk still plays an important role in maintaining the equilibrium. In other words, unlike the hand, any voluntary trunk movement always introduces great perturbation to the body balance especially when people are standing. Lastly, the difference between segment inertias is much more evident than that between wrist joint

and elbow joint or between hand and foot. All these facts should significantly influence how the central nervous system controls the coordination between hand and trunk.

The bimanual Fitts' paradigm was adopted in the present study to examine the coordination between hand and trunk. In daily life, it appears that the tasks more commonly require us to coordinate hand and trunk in the anterior-posterior direction than in the medial-lateral direction. I posit that people are less experienced in the coordination between hand and trunk in the medial-lateral direction. Moreover, the movement in the medial-lateral direction is more symmetrical than that in the anterior-posterior direction (Cai et al., in preparation; Duarte & Freitas, 2005). Therefore, I examined whether common coordinative principles were shared in the coordination between hand and trunk in the medial-lateral direction.

CHAPTER 2. METHODS

2.1   Participants

Thirty-one college students (23 females and 8 males) participated in the experiment. All participants were right-handed based on self-report. Three participants (2 females and 1 male) did not finish the experiment due to self-reported fatigue (1 female and 1 male) or not being able to finish the whole session within the designated testing period (1 female). The mean (standard deviation, SD) age, height and weight of the 28 included participants were: 25 (4) years, 165 (9) cm, and 64 (11) kg, respectively. All participants were free of any self-reported neurological dysfunction that can influence voluntary movements and postural control. The Purdue University Institutional Review Board approved all procedures.

2.2   Apparatus

A booth (1.5 m by 1.0 m by 2.3 m), made of black curtains and black poster board, was used to reduce the ambient feedback so that the participant was not distracted by other surrounding visual information. A 15-inch computer LED screen was placed in the booth and mounted about 1.0 m from the participant and 1.4 m above the floor. The position of the computer screen was manually adjusted, so that the center of it was level with the participant's eye level (approximately 1.5 m to 1.8 m above the floor). The computer LED screen was adjusted to be parallel to the coronal plane, and used to

provide visual feedback. The approximate place where the participant was asked to stand was marked using blue tape on the floor. Two stripes of black tape were placed 25 cm apart on the floor and parallel to the sagittal plane of the participant, as the indications of foot position.

A Pohlemus Liberty-8 motion capture system was used to capture the motion of the hand and the motion of the trunk. The motion capture system was capable of capturing motion of up to eight wired markers at a sampling frequency of 240 Hz. In present study, only two markers were used. A marker was used to attach to the participant's trunk by using the elastic strap, slightly above the navel. Another marker was taped on the nail of the participant's index finger of the dominant hand.

A computer installed with the Windows XP system ran a custom written LabVIEW program (LabVIEW 8.6, National Instruments Corp., Austin, TX). The computer was placed behind the booth and was not visible to the participant. The computer was interfaced with the Liberty motion capture system and the computer screen in the booth. Two speakers provided acoustic feedback.

In Figure 2.1, the experimental setup is presented. The location of each marker was acquired at 200 Hz. The trajectory of the hand / trunk in the medial-lateral direction was shown as a small green / red dot moving left-and-right on the black background computer screen in the booth. The displacement of the dots was calibrated, such that they reflected the actual displacement of the markers. The on-screen update rate of the dot positions was set as 50 Hz. The starting position of the hand/trunk was shown as a white circle with a radius of 0.25 cm, and the designated target of the hand/trunk was shown as a white rectangle. The target center was 2.5 cm away from the middle of the screen, and

perpendicular to the movement direction. A green disk (1-centimeter diameter) appearing

2.5 cm above the center of screen served as the warning signal, and a short sound (15-

millisecond duration) produced by the speakers provided the stimulus to move.

Figure 2.1 Illustration of the experimental setup.

2.3   Tasks

The task required moving the trunk, the dominant hand or both, such that the

cursor/cursors on the screen was/were moved from the starting position/positions to the

designated target/targets as fast and as accurately as possible. The participants were

instructed to move the trunk in the medial-lateral direction with the non-dominant hand

along the side of their body and without bending the knees or rotating the torso, while

keeping both feet on the ground at all times. They were also instructed to move the hand in the medial-lateral direction while keeping the elbow angle at about 90 degrees.

The distance between the starting position and the center of the target was 6 cm and kept constant for the whole experiment. There were two prescribed target widths: the small target width was 1 cm and the large target width was 2 cm. The movement direction was either to the left or to the right. Therefore, there were a total of 24 conditions (Figure 2.2): four hand-only task conditions, four trunk-only task conditions, and 16 hand-trunk task conditions. In Figure 2.2, the 16 hand-trunk conditions are presented according to the four different combinations of movement directions: four conditions in which the hand and the trunk moved to the left (hand-left trunk-left), four conditions in which the hand and the trunk moved to the right (hand-right trunk-right), four conditions in which the hand moved to the right and the trunk moved to left (hand-right trunk-left), and four conditions in which the hand moved to the left and the trunk moved to the right (hand-left trunk-right).

The display on the computer screen was designed to ensure that the target/targets was/were always close to the middle of the screen. When either effector moved alone, there were one starting position and one target displayed on one side (left or right) of the screen according to its movement direction (right or left). The target was placed close to the center of the screen while the starting position was far, so that the cursor movement direction was the same as the movement direction of the effector. When the hand and the trunk moved together, there were two starting positions and two targets displayed on the screen according. Each combination of starting position and target was displayed in the same way as if the effector moved alone. Because the two combinations of starting

position and target were presented on the same side of the screen when the hand and the trunk moved in the same direction, the combination of starting position and target for the hand was placed above that for the trunk vertically. In Figure 2.3, the combined hand and trunk movement and the designated display on the computer screen for four hand-trunk conditions in which target widths are equal are presented.

2.4 Procedures

Upon arriving to the lab, participants took off their shoes but kept the socks on. They were instructed to align the second toe of each foot to the two black tapes on the floor such that the feet were approximately 25 cm apart. The center of the computer screen was then adjusted to the eye-height of the participant. Before a trial began, the participant reached the dominant hand out in the sagittal plane, so that the marker on the finger and the marker on the trunk were approximately in the same horizontal plane.

A trial consisted of two phases: calibration and data collection. During calibration, the participant stood still on the floor and held the hand still for 5 seconds. No feedback was provided on the screen. The neutral positions of the two markers were calculated as the mean within the 5-second period, and mapped to the centers of designated starting positions respectively (the centers of two small circles). The participant was instructed to keep the required posture until feedback was provided, so that the dots (the locations of the two markers) were close to the centers of the two starting circles respectively. The participant was required to adjust the two dots, if necessary, such that they were inside the two starting circles respectively.

After the participant was ready, data collection commenced. First, the warning signal appeared in the center of the screen. After a one- to three-second period

Figure 2.2 Depictions of movement direction and target width combinations for the 24 conditions in the experiment. The target distance is fixed at 6 cm. The target width is either large (2 cm) or small (1 cm). The letter "H" stands for hand, the letter "T" stands for trunk, the arrow direction indicates movement direction, and the relative size of rectangle indicates the relative target size.

Figure 2.3 Depictions of hand (H) and trunk (T) movement directions and the designated feedback provided on the computer screen for the 16 hand-trunk conditions: (a) the hand and the trunk move to the left, (b) the hand and the trunk move to the right, (c) the hand move to the right and the trunk move to the left, (d) the hand move to the left and the trunk move to the right. The arrow direction indicates movement direction. The small circles indicate starting positions and the rectangles indicate targets. The dotted line indicates the middle of the screen.

(randomized), the auditory stimulus was presented and data collection began. Depending on the condition, the participant voluntarily moved the hand, the trunk or both in the medial-lateral direction, such that the dots were moved into their designated targets as quickly and accurately as possible respectively. The participant attempted to keep each dot inside the targets until the end of the trial, but not to undershoot or overshoot the targets. An auditory beep five seconds later signaled the end of a trial.

The 24 conditions were presented in a random order. Prior to each new condition, the participant practiced the task without the acoustic stimulus until s/he told the experimenter that s/he was ready. Each condition consisted of six trials: the first trial served as familiarization, and the last five trials were used in the data analysis. During the last five trials, any trial with an apparent under-shoot (either the hand movement or the trunk movement ended before reaching the target) or over-shooting problem (either the hand movement or the trunk movement passed the target) was repeated. However, the participant performed no more than 10 trials in each condition. The participant could rest for up to 15 seconds after each trial when requested, and was required to sit down on a chair for 30 seconds after every four conditions. Each participant performed all 24 experimental conditions. The duration of the entire session was about 75 minutes.

2.5   Data Reduction

All calculations, operations and normalizations involved in the data reduction were implemented using custom written Matlab programs (Matlab, MathWorks, TX).

Displacement in the medial-lateral direction was analyzed. By convention, the movement toward a target produced greater positive displacement. The displacement data were filtered using a low-pass, fourth-order, zero-lag Butterworth filter with a cut-off

frequency of 8 Hz. The maximum displacement of the trajectory was calculated and located. If the maximum displacement was greater than the sum of the target distance and half of the target width (over-shoot) or smaller than the difference between the target distance and half of the target width (under-shoot), the trial was excluded from further data analyses. Velocity was calculated using a three-point central difference technique.

The velocity data were trimmed to obtain the actual movement based on the velocity profile (Figure 2.4). Because both the trunk and hand could show small spontaneous oscillations even though the participants were required to stay stable, a typical velocity profile had fluctuations at both the beginning and the end. Therefore, the starting point and the end point of the movement were determined using a criteria based on the percentage of velocity (see also Riek et al., 2003). First, the peak velocity was determined. Then, the starting point was determined from the peak velocity backward to the sample in which the velocity decreased to be equal to or less than 5% of the peak velocity. The end point was determined from the peak velocity forward to the sample in which the velocity decreased to be equal to or less than 5% of the peak velocity.

If the starting point was more than 0.5 cm away from the center of initial circle or the end point was not in the target, the trial was considered an error and excluded from further data analysis. The data trimming processes were implemented by a data trimming program, and visually inspected and manually adjusted if needed.

Reaction time was determined as the time from stimulus onset to movement onset. If reaction time was less than 80 ms, the trial was considered as a false start and excluded from further data analyses. Total response time was determined as the time from stimulus

onset to movement endpoint. Movement time was then calculated as the time from when the movement started to when the movement ended.

Figure 2.4 Illustration of data trimming based on velocity criteria. The starting point is determined as the sample in which the velocity decreased from the peak velocity backward to 5% of the peak velocity. The end point is determined as the sample in which the velocity decreases from the peak velocity forward to 5% of the peak velocity.

The trimmed velocity was also decomposed to a low-frequency velocity component and a high-frequency velocity component using a 3rd order Savitzky-Golay (polynomial) smoothing filter with a frame length of 41 data points. Savitzky-Golay smoothing filters are based on polynomial fitting (Savitzky & Golay, 1964). The

Savitzky-Golay smoothing filters are considered to be better at maintaining signal widths and peak heights without losing important information when obtaining the trend of the signal (Pintens et al., 2011). The smoothed velocity (the trend of signal) was considered as the low-frequency velocity component containing the global changing trend of velocity. The residual velocity was calculated as the difference between the original velocity and the smoothed velocity, and considered as the high-frequency velocity component containing noises and possible small adjustments of the velocity.

The amplitude of the trimmed velocity and the two velocity components were normalized to standardized z scores, and the length was normalized to 1001 points using a cubic spline interpolation technique. Finally, the normalized 1001-point velocity was down-sampled to 101 points. In Figure 2.5, examples of the normalized velocity are presented. Velocity coupling analyses were performed on the normalized velocities.

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2.6   <u>Data Analyses</u>

</div>

The absolute reaction time difference for the hand-trunk conditions was calculated to assess the absolute movement onset synchrony between the hand and the trunk, and the absolute movement time difference was calculated to assess the absolute movement execution synchrony. For each condition for each participant, absolute reaction time difference was first calculated as the absolute difference between hand reaction time and trunk reaction time on a trial-by-trial basis. Then absolute reaction time differences were averaged across trials. Absolute movement time difference was calculated and averaged in the same fashion.

The RMS velocity difference measures the difference between the velocity of hand and the velocity of trunk. The RMS velocity difference was also calculated with a

(a)

(b)

Figure 2.5 Typical examples of normalized 101-point hand and trunk velocity for the 16 hand-trunk conditions: (a) the hand and the trunk moved in the same direction, and (b) the hand and the trunk moved in the opposite directions.

lag from -20 points to 20 points. If the velocity of hand and the velocity of trunk had the same shape but were out of phase, the lagged RMS velocity difference will show the minimum value at some point other than zero. Specifically, if the trunk led the hand in the actual movement, the lag point at which the minimum occurred will be positive. If the hand led the trunk in the actual movement, the lag point at which the minimum occurred will be negative.

Pearson's correlation coefficient was calculated between the hand velocity and the trunk velocity to examine the degree of movement dependence between the hand and the trunk. The larger the correlation coefficient, the more dependent the two segments were. Pearson's correlation was also performed with a lag ranged from -20 points to 20 points. If the velocity of hand and the velocity of trunk were dependent on each other but out of phase, the lagged correlation of velocity will show the maximum at some point other than zero. If the trunk led the hand in the actual movement, the lag point will be positive. If the hand led the trunk, the lag point at which the maximum occurred will be negative. Fisher's r to Z transformations (Fisher, 1921) were used to obtain an average correlation coefficient over trials of each condition for each participant and an average value across participants for each condition.

To estimate the extent to which coordination occurred in hand-trunk conditions, synthetic hand-trunk conditions were constructed from the hand-only conditions and the trunk-only conditions. In other words, the results of the 16 synthetic hand-trunk conditions were calculated based on the results of the four hand-only conditions and the results of the four trunk-only conditions. For example, a synthetic hand-trunk condition in which the hand moved to the left to the small target and the trunk moved to the right to

the large target was constructed from the hand-only condition in which the hand moved to the left to the small target and the trunk-only condition in which trunk moved to the right to the large target. The hand-only condition and the trunk-only condition were chosen on trial-by-trial basis to construct a synthetic condition. If there was an error in either the chosen hand-only condition or the chosen trunk-only condition, the resulted synthetic condition was discarded from further analyses. All synthetic hand-trunk conditions were analyzed in the same fashion as the actual hand-trunk conditions. The synthetic hand-trunk conditions served as a baseline for comparisons with the actual hand-trunk conditions. If the dual-effector tasks exhibited independence, the results of actual hand-trunk conditions should be the same as the results of synthetic hand-trunk conditions.

2.7   Statistical Analyses

For each of the dependent measures (reaction time and movement time) for each combination of hand movement direction and trunk movement direction, there were four single-effector and four two-effector conditions, making a total of 12 separate means for each participant. Kelso and colleagues carried out preplanned contrasts using Dunn's procedure on the means of interest (Kelso et al., 1979 a, b; Kelso et al., 1983). The procedure splits up the alpha level among a set of planned comparisons and does not require a significant prior significant overall F-ratio (Kirk, 2013). To compare directly to Kelso and colleagues' results (Kelso et al., 1979 a, b; Kelso et al., 1983), the effects of target width were analyzed in the same fashion using Dunn's procedure in the present study. Specifically, the mean square error was computed for reaction time and movement time respectively, then depending on the number of means (12), the number of planned

comparisons (16) and the degrees of freedom for experimental error (324) a critical difference d is calculated. A given difference between means must exceed a critical difference d to be significant at the 0.05 or 0.01 alpha level.

Another analysis examined effects of movement direction. For the 16 hand-trunk conditions, four-way repeated measures ANOVAs with hand movement direction (HD), trunk movement direction (TD), hand target width (HW), and trunk target width (TW) as factors were used to examine hand/trunk reaction time, hand/trunk movement time, absolute reaction time difference, and absolute movement time difference. Four-way ANOVAs were also adopted to analyze the RMS velocity difference and the correlation coefficient of velocity. The Scheffé's test was used for post hoc comparisons as necessary. All statistical analyses were performed using the IBM SPSS Statistics software (Version 21).

CHAPTER 3. RESULTS

Each participant successfully performed a minimum of three trials in each condition. The error rates for the 24 conditions ranged from 1% to 16%, with a median of 6%. The mean error rate for eight hand-only and trunk-only conditions was 5% (SD = 4%). Specifically, the mean error rate for four hand-only conditions was 4% (SD = 4%), and it was 7% (SD = 3%) for four trunk-only conditions. All errors in hand-only conditions or trunk-only conditions were due to hand or trunk overshooting the target. The mean error rate for the 16 hand-trunk conditions was 9% (SD = 5%).

The error rates in different combinations of movement directions were also examined. The mean error rate for eight conditions in which the hand and the trunk moved in the same direction was 8% (SD = 5%). Specifically, the mean error rate for conditions in which the hand and the trunk moved to the left was 4% (SD = 2%), and it was 11% (SD = 6%) for conditions in which the hand and the trunk moved to the right. The mean error rate for eight conditions in which the hand and trunk moved in the opposite direction was 10% (SD = 4%). Specifically, the mean error rate for conditions in which the hand moved to the right and the trunk moved to the left was 8% (SD = 3%), and it was 12% (SD = 4%) for conditions in which the hand moved to the left and trunk moved to the right. For the 16 hand-trunk conditions, participants missed the target on 8% of the trials. The trunk was about as much as twice likely to miss the target than the hand

(the trunk missed the target in a total of 128 trials, while the hand missed the target in a total of 68 trials), similar to conditions in which the hand and the trunk moved alone.

3.1   Effects of Target Width

The effects of target width were examined on reaction time and movement time in the same fashion for each combination of movement directions in order to determine whether the coordinative patterns of bimanual coordination are observed in the coordination between the hand and the trunk (Kelso et al., 1979 a, b; Kelso et al., 1983). If the coordinative principles are shared, it is expected that similar coordinative patterns will be observed in all conditions despite movement direction.

3.1.1   The Hand and the Trunk Moved in the Same Direction

3.1.1.1   The Hand and the Trunk Moved to the Left

Using Dunn's procedure for preplanned contrasts, for reaction time, $MS_e = 6779$, $d = 65$ ms, $p < 0.05$ (a difference should be greater than 65 ms to be significant at the 0.05 alpha level); $d = 76$ ms, $p < 0.01$ (a difference should be greater than 76 ms to be significant at the 0.01 alpha level). As can be seen in Table 3.1, the largest difference between hand and trunk reaction time was 43 ms, which means that none of the differences in reaction time was significant, all ps > 0.05.

For movement time, $MS_e = 105115$, $d = 259$ ms, $p < 0.05$; $d = 300$ ms, $p < 0.01$. As can be seen in Table 3.1, single-effector movement time for the easy task was shorter than its difficult counterpart as Fitts' Law predicts (292 ms shorter for the hand, $p < 0.05$, and 387 ms shorter for the trunk, $p < 0.01$). This effect was also evident for two-effector movements (377 ms shorter for the hand, $p < 0.01$, and 434 ms shorter for the trunk,

p < 0.01). Hand movement time for single-effector movement was significantly shorter than that for two-effector movement of the same difficulty (545 ms shorter when the task was easy, p < 0.01, and 630 ms shorter when the task was difficult, p < 0.01). In contrast, trunk movement time for single-effector movements was not significantly different from that for two-effector movement of the same difficulty (42 ms shorter when the task was easy and 89 ms shorter when the task was difficult, both ps > 0.05). Therefore, the hand always slowed down to accommodate the movement of the trunk. When task demands were varied for each effector, hand movement time for the easy task was significantly longer than movement time for paired easy conditions (311 ms longer for the hand, p < 0.01, and 197 ms longer for the trunk, p > 0.05), and movement time for the difficult task was not significantly different from movement time for paired difficult conditions (91 ms shorter for the hand and 18 ms longer for the trunk, both ps > 0.05). In general, the difficult task determined movement time in the two-effector conditions.

The movement time data in Table 3.1 also indicated that the two-effector movements of equal difficulty were executed simultaneously (the hand led the trunk by 115 ms when the tasks were easy, and the hand led the trunk by 172 ms when the tasks were difficult, both ps > 0.05). Furthermore, paired movements of varying difficulty were also executed simultaneously (the hand led the trunk by 256 ms when the hand task was easy, and the hand led the trunk by 26 ms when the hand task was difficult, both ps > 0.05).

It is suggested that these small differences (insignificant) between the hand and the trunk are because algebraic differences can cancel each other out when the algebraic mean is calculated over trials (Kelso et al., 1983). The mean absolute reaction time

difference and movement time difference for the conditions in which the hand and the trunk moved to the left are presented in Table 3.2. The hand and the trunk were initiated within less than 68 ms of each other in the two-effector conditions. Compared to the hand and the trunk alone condition, the absolute reaction time difference for all conditions decreased when the hand and the trunk moved together (The maximal decrease was 59 ms and the minimal decrease was 36 ms; the maximal percentage of decrease was 50% and the minimal percentage was 37%). Similarly, movement of the hand and the trunk were executed within less than 309 ms of each other in the two-effector conditions. Compared to the hand and the trunk alone condition, the absolute movement time difference for all conditions decreased when the hand and the trunk moved together (The maximal decrease was 700 ms and the minimal decrease was 164 ms; the maximal percentage of decrease was 72% and the minimal percentage was 41%).

3.1.1.2   The Hand and the Trunk Moved to the Right

For reaction time, $MS_e = 6603$, d = 65 ms, $p < 0.05$; d = 75 ms, $p < 0.01$. As can be seen in Table 3.1, the largest difference between hand and trunk reaction time was 44 ms. No significant differences between the hand and the trunk in reaction time were found, all ps > 0.05.

For movement time, $MS_e = 100416$, $d = 252$ ms, $p < 0.05$; $d = 293$ ms, $p < 0.01$. As can be seen in Table 3.1, single-effector movement time for the easy task was shorter than its difficult counterpart as Fitts' Law predicts (152 ms shorter for the hand, $p > 0.05$, and 377 ms shorter for the trunk, $p < 0.01$). This effect was also evident for two-effector movements of the same difficulty (327 ms shorter for the hand, $p < 0.01$, and 380 ms shorter for the trunk, $p < 0.01$). Hand movement time for single-effector movement was

significantly shorter than that for two-effector movement of the same difficulty (489 ms

shorter when the task was easy, $p < 0.01$, and 664 ms shorter when the task was difficult,

$p < 0.01$). In contrast, trunk movement time for single-effector movements was not

significantly different from that for two-effector movement of the same difficulty

(167 ms shorter when the task was easy and 170 ms shorter when the task was difficult,

both $ps > 0.05$). Therefore, the hand always slowed down to accommodate the movement

of the trunk. When the task demands were varied for each effector, trunk movement time

for the easy task was significantly greater than movement time for paired easy conditions

(266 ms greater for the trunk, $p < 0.05$, and 99 ms greater for the hand, $p > 0.05$).

Movement time for the difficult task was not significantly different from movement time

for paired difficult conditions (61 ms shorter for the hand and 171 ms longer for the trunk,

both $ps > 0.05$). In general, the difficult task determined movement time in the two-

effector conditions.

The movement time data in Table 3.1 also indicated that the two-effector

movements of equal difficulty were executed simultaneously (the hand led the trunk by

151 ms when the tasks were easy, and the hand led the trunk by 204 ms when the tasks

were difficult, both $ps > 0.05$). Furthermore, paired movements of varying difficulty were

also executed simultaneously (the hand led the trunk by 261 ms when the hand task was

easy, only 9 ms greater than the critical difference, $p < 0.05$, and the hand led the trunk by

151 ms when the hand task was difficult, $p > 0.05$).

The mean absolute reaction time difference and movement time difference for the

conditions in which the hand and the trunk moved to the right are presented in Table 3.2.

The hand and the trunk were initiated within less than 62 ms of each other in the two-

effector conditions. Compared to the hand and the trunk alone condition, the absolute reaction time difference for all conditions decreased when the hand and the trunk moved together (The maximal decrease was 79 ms and the minimal decrease was 54 ms; the maximal percentage of decrease was 60% and the minimal percentage was 50%). Similarly, movement of the hand and the trunk was executed within less than 310 ms of each other in the two-effector conditions. Compared to the hand and the trunk alone condition, the absolute movement time difference for all conditions decreased when the hand and the trunk moved together (The maximal decrease was 549 ms and the minimal decrease was 172 ms; the maximal percentage of decrease was 65% and the minimal percentage was 39%).

In general, when the hand and the trunk moved in the same direction, no significant difference in reaction time between the two effectors was found. The reaction time results are consistent with those of Kelso and colleagues (Kelso et al., 1979 a, b; Kelso et al., 1983) who showed that the hands initiated simultaneously. For movement time in the present study, in contrast to Kelso and colleagues (Kelso et al., 1979 a, b; Kelso et al., 1983), the hand always slowed down to accommodate trunk movement. The results indicate that the difficult task determined movement time in the two-effector conditions. More importantly, the hand and the trunk moved in a synchronized fashion despite varying task difficulty levels in the paired conditions. A great portion of asynchrony in the single-effector conditions (up to 65%) was removed when the two effectors moved together. Taken together, the coordination between the hand and the trunk when they moved in the same direction was similar to the bimanual coordination observed by Kelso and colleagues (Kelso et al., 1979 a, b; Kelso et al., 1983).

Table 3.1 Mean reaction time (ms) and movement time (ms) for the conditions in which the hand (H) and the trunk (T) moved in the same direction. The arrow direction indicates movement direction, and the relative size of rectangle indicates the relative target size.

Hand		Condition	Trunk	
Movement Time	Reaction Time		Reaction Time	Movement Time
Hand to Left & Trunk to Left				
1081	269	▯ ← H		
		▯ ← T	316	1794
789	314	▯← H		
		▯← T	325	1407
1334	327	▯← H ▯← T	356	1449
1711	308	▯ ← H ▯ ← T	340	1883
1620	301	▯ ← H ▯← T	344	1646
1645	303	▯← H ▯ ← T	341	1901
Hand to Right & Trunk to Right				
954	327	H→ ▯		
		T → ▯	328	1652
802	296	H→ ▯		
		T → ▯	343	1275
1291	315	H→▯ T →▯	339	1442
1618	287	H→ ▯ T → ▯	331	1822
1557	291	H→ ▯ T →▯	321	1708
1390	319	H→ ▯ T → ▯	352	1651

Table 3.2 Mean absolute difference (ms) in reaction time and movement time for the conditions in which the hand (H) and the trunk (T) moved in the same direction. The arrow direction indicates movement direction, and the relative size of rectangle indicates the relative target size.

Actual		Condition	Synthetic	
Movement Time	Reaction Time		Reaction Time	Movement Time
Hand to Left & Trunk to Left				
176	59	▯← H ▯← T	118	620
287	60	▯ ← H ▯ ← T	96	740
235	64	▯ ← H ▯← T	102	399
309	68	▯← H ▯ ← T	117	1009
Hand to Right & Trunk to Right				
199	52	H→▯ T →▯	113	496
249	62	H→▯ T →▯	130	715
268	52	H→▯ T →▯	131	440
310	55	H→▯ T →▯	109	859

3.1.2 The Hand and the Trunk Moved in the Opposite Directions

3.1.2.1 The Hand Moved to the Right and the Trunk Moved to the Left

For reaction time, $MS_e = 10600$, $d = 81$ ms, $p < 0.05$; $d = 95$ ms, $p < 0.01$. As can be seen in Table 3.3, the largest difference between hand and trunk reaction time was 78 ms, which was close to be a significant difference (81 ms) at the 0.05 alpha level. No significant differences between the hand and the trunk in reaction time were found, all $ps > 0.05$.

For movement time, $MS_e = 165375$, $d = 324$ ms, $p < 0.05$; $d = 375$ ms, $p < 0.01$. As can be seen in Table 3.3, single-effector movement time for the easy task was shorter than its difficult counterpart as Fitts' Law predicts (152 ms shorter for the hand, $p > 0.05$, and 387 ms shorter for the trunk, $p < 0.01$). This effect was also evident for two-effector movements (413 ms shorter for the hand and 655 ms shorter for the trunk, both $ps < 0.01$). Hand movement time for single-effector movement was significantly shorter than that for two-effector movement of the same difficulty (885 ms shorter when the task was easy and 1146 ms shorter when the task was difficult, both $ps < 0.01$). Trunk movement time for single-effector movements was also significantly shorter than that for two-effector movement of the same difficulty (506 ms shorter when the task was easy and 774 ms shorter when the task was difficult, both $ps < 0.01$). Therefore, unlike the conditions in which the hand and the trunk moved in the same direction, both the hand and the trunk slowed down significantly to achieve the task goal. When the task demands were varied for each effector, movement time for the easy task was not significantly different from movement time for paired easy conditions (132 ms greater for the hand and 146 ms greater for the trunk, both $ps > 0.05$), and movement time for the difficult task was not significantly different from movement times for paired difficult conditions (228 ms shorter for the hand and 229 ms shorter for the trunk, both $ps > 0.05$). Clearly, it did not seem that the difficult task determined movement time in the two-effector conditions. Instead, movement time for each effector was determined by the difficulty of the task it performed in the two-effector conditions.

The movement time data in Table 3.3 also indicated that the two-effector movements of equal difficulty were not executed simultaneously when the tasks were

difficult (the hand led the trunk by 226 ms when the tasks were easy, p > 0.05, and the hand led the trunk by 468 ms when the tasks were difficult, p < 0.01). Furthermore, paired movements of varying difficulty were not executed simultaneously when the hand task was easy (the hand led the trunk by 520 ms when the hand task was easy, p < 0.01, and the hand led the trunk by 247 ms when the hand task was difficult, p > 0.05).

The mean absolute reaction time difference and movement time difference for the conditions in which the hand moved to the right and the trunk moved to the left are presented in Table 3.4. The hand and the trunk were initiated in greater than 99 ms of each other in the two-effector conditions. Compared to the hand and the trunk alone condition, the absolute reaction time difference for all conditions did not tend to decrease when the hand and the trunk moved together (The three decreases were 10, 28, and 35 ms, and the three percentages of decrease were 9%, 20%, and 25%; The increase was 15 ms and the percentage was 16% for the condition in which the hand moved to the large target and the trunk moved to the small target).

Similarly, movement of the hand and the trunk were executed in greater than 480 ms of each other in the two-effector conditions. Compared to the hand and the trunk alone condition, the absolute movement time difference for all conditions did not all decrease when the hand and the trunk moved together (The three decreases were 63, 132, and 277 ms, and the three percentages of decrease were 7%, 21%, and 28%; The increase was 41 ms and the percentage was 8% for the condition in which the hand moved to the small target and the trunk moved to the large target).

3.1.2.2   The Hand Moved to the Left and the Trunk Moved to the Right

For reaction time, $MS_e = 8740$, $d = 74$ ms, $p < 0.05$; $d = 86$ ms, $p < 0.01$. As can

be seen in Table 3.3, the largest difference between hand and trunk reaction time was

59 ms. No significant differences between the hand and the trunk in reaction time were

found, all ps > 0.05.

For movement time, $MS_e = 1920591$, $d = 349$ ms, $p < 0.05$; $d = 405$ ms, $p < 0.01$.

As can be seen in Table 3.3, single-effector movement time for the easy task was shorter

than its difficult counterpart as Fitts' Law predicts (292 ms shorter for the hand, p > 0.05,

and 377 ms shorter for the trunk, p < 0.05). This effect was evident for two-effector

movements (622 ms shorter for the hand and 433ms shorter for the trunk, both ps < 0.01).

Hand movement time for single-effector movement was shorter than that for two-effector

movement of the same difficulty (786 ms shorter when the task was easy and 1116 ms

shorter when the task was difficult, both ps < 0.01). Trunk movement time for single-

effector movements was also significantly shorter than that for two-effector movement of

the same difficulty (463 ms shorter when the task was easy and 529 ms shorter when the

task was difficult, both ps < 0.01). Similar to the results for the conditions in which the

hand moved to the right and the trunk moved to the left, both the hand and the trunk

slowed down significantly to achieve the task goal. When the task demands were varied

for each effector, movement time for the easy task was not significantly different from

movement time for paired easy conditions (279 ms longer for the hand and 183 ms longer

for the trunk, both ps > 0.05), and movement time for the difficult task was not

significantly different from movement times for paired difficult conditions (239 ms

shorter for the hand and 86 ms shorter for the trunk, both ps > 0.05). Similar to the results

for the conditions in which the hand moved to the right and the trunk moved to the left, the difficult task did not determine movement time in the two-effector conditions.

The movement time data in Table 3.3 also indicated that the two-effector movements of equal difficulty were executed simultaneously (the hand led the trunk by 163 ms when the tasks were easy, and the trunk led the hand by 16 ms when the tasks were difficult, both ps > 0.05). Furthermore, paired movements of varying difficulty were executed simultaneously (the hand led the trunk by 241 ms when the hand task was easy, and the trunk led the hand by 37 ms when the hand task was difficult, both ps > 0.05). These results were not the same as those for the conditions in which the hand moved to the right and the trunk moved to the left.

The mean absolute reaction time difference and movement time difference for the conditions in which the hand moved to the left and the trunk moved to the right are presented in Table 3.4. The hand and the trunk were initiated in greater than 86 ms of each other in the two-effector conditions. Compared to the hand and the trunk alone condition, the absolute reaction time difference for all conditions tended to decreased when the hand and the trunk moved together (The decreases were 11, 25, 29, and 31 ms, and the percentages of decrease were 11%, 22%, 24%, and 24%). Movement of the hand and the trunk were executed in greater than 427 ms of each other in the two-effector conditions. Compared to the hand and the trunk alone condition, the absolute movement time difference did not all decrease when the hand and the trunk moved together (The three decreases were 48, 69, and 236 ms, and the three percentages of decrease were 8%, 13%, and 27%; The increase was 166 ms and the percentage was 50% for the condition in which the hand moved to the small target and the trunk moved to the large target).

Table 3.3 Mean reaction time (ms) and movement time (ms) for the conditions in which the hand (H) and the trunk (T) moved in the opposite directions. The arrow direction indicates movement direction, and the relative size of rectangle indicates the relative target size.

Hand		Condition	Trunk	
Movement Time	Reaction Time		Reaction Time	Movement Time
Hand to Right & Trunk to Left				
954	327	H→□		
		□←T	316	1794
802	296	H→□		
		□←T	325	1407
1687	319	H→□ □←T	391	1913
2100	315	H→□ □←T	379	2568
1812	333	H→□ □←T	411	2059
1819	325	H→□ □←T	402	2339
Hand to Left & Trunk to Right				
		□←H	269	1081
1652	328	T→□		
		□←H	314	789
1275	343	T→□		
1738	382	T→□ □←H	315	1575
2181	385	T→□ □←H	326	2197
1921	369	T→□ □←H	310	1958
2095	386	T→□ □←H	345	1854

Table 3.4 Mean absolute difference (ms) in reaction time and movement time for the conditions in which the hand (H) and the trunk (T) moved in the opposite directions. The arrow direction indicates movement direction, and the relative size of rectangle indicates the relative target size.

Actual		Condition	Synthetic	
Movement Time	Reaction Time		Reaction Time	Movement Time
Hand to Right & Trunk to Left				
480	99	H→☐ ☐← T	109	612
784	105	H→▯ ▯← T	140	847
539	111	H→▯ ☐← T	139	498
723	108	H→☐ ▯← T	93	1000
Hand to Left & Trunk to Right				
427	94	T→☐ ☐← H	123	496
556	86	T→▯ ▯← H	97	604
512	89	T→☐ ▯← H	114	346
627	97	T→▯ ☐← H	128	863

In general, when the hand and the trunk moved in the opposite directions, consistent with Kelso et al. (1979 a, b), no significant difference in reaction time between the two effectors were found although some differences were close to be significant. In contrast to Kelso and colleagues (Kelso et al., 1979, a, b; Kelso et al., 1983), both effectors slowed down significant to achieve the task goal. More importantly, the hand and the trunk did not move in a synchronized fashion. The asynchrony was more obviously reflected in the absolute movement time, the asynchrony in the single-effector

conditions was not consistently reduced when the two effectors moved together (the largest portion of reduction was only 28%). Taken together, the coordination between the hand and the trunk when they moved in the opposite directions required different coordinative patterns other than the bimanual coordinative patterns (Kelso et al., 1979 a, b; Kelso et al., 1983).

In addition, the velocity coupling between hand movement and trunk movement was examined. The RMS velocity difference and correlation coefficient of velocity are presented in Table 3.5. Compared to the hand and trunk alone condition, the RMS velocity difference became smaller (the smallest decrease was 0.6) and the correlation coefficient of velocity became greater (the value increased from below 0.5 to above 0.9) when the hand and the trunk moved in the same direction. Thus, the velocity of the hand and the velocity of the trunk became more coupled when the hand and the trunk moved in the same direction. In contrast, compared to the hand and the trunk alone condition, the RMS velocity difference was not apparently different (all values were around 1.0) and the correlation coefficient of velocity was not apparently different (all values were around 0.5) when the hand and the trunk moved in the opposite directions. Thus, the hand and the trunk behaved as though they still moved independently when they moved to the opposite direction.

The velocity of the hand and the velocity of the trunk became coupled when they moved in the same direction. However, this was not the case when the hand and the trunk moved in the opposite directions. Therefore, the results of velocity coupling provided further evidence to support the notion that coordinative patterns were distinct for the same-direction conditions and the opposite-direction conditions.

Table 3.5 Mean RMS velocity difference (z unit) and correlation coefficient of velocity between the hand (H) and the trunk (T). The arrow direction indicates movement direction, and the relative size of rectangle indicates the relative target size.

Actual		Condition	Synthetic	
Correlation Coefficient	RMS Velocity Difference		Correlation Coefficient	RMS Velocity Difference
H & T Moved in the Same Direction				
0.92	0.44	▯← **H** ▯← **T**	0.31	1.17
0.91	0.45	▯ ← **H** ▯ ← **T**	0.46	1.05
0.91	0.46	▯ ← **H** ▯← **T**	0.47	1.05
0.92	0.43	▯← **H** ▯ ← **T**	0.30	1.18
0.94	0.40	**H**→▯ **T**→▯	0.34	1.16
0.92	0.45	**H**→▯ **T**→▯	0.45	1.06
0.92	0.43	**H**→▯ **T**→▯	0.42	1.09
0.92	0.44	**H**→▯ **T**→▯	0.35	1.15
H & T Moved in the Opposite Direction				
0.53	0.99	**H**→▯ ▯← **T**	0.36	1.14
0.47	1.04	**H**→▯ ▯ ← **T**	0.44	1.08
0.52	1.00	**H**→▯ ▯← **T**	0.42	1.09
0.46	1.05	**H**→▯ ▯ ← **T**	0.36	1.14
0.52	0.99	**T**→▯ ▯← **H**	0.33	1.17
0.54	0.97	**T**→▯ ▯ ← **H**	0.51	1.01
0.54	0.97	**T**→▯ ▯ ← **H**	0.50	1.02
0.46	1.05	**T**→▯ ▯← **H**	0.33	1.16

3.2   Effects of Movement Direction

To further support the finding that the coordinative patterns were distinct between when the hand and the trunk moved in the same direction and when they moved in the opposite directions, the effects of movement direction in the 16 hand-trunk conditions were examined on two separate aspects of the data. First of all, the behavioral data (reaction time and movement time) were compared in terms of different combinations of movement directions, such that the performances of each effector and the synchrony in the initiation and execution of the two effectors can be examined. The second analyses examined the kinematic aspects of movement of each effector, in which the velocity coupling between the hand movement and the trunk movement was compared relative to the combination of movement directions.

3.2.1   Behavioral Data

3.2.1.1   Hand Reaction Time in the Hand-Trunk Conditions

The means for hand reaction time for the 16 hand-trunk conditions ranged from 269 to 345 ms (Figure 3.1). In Table 3.6, the results of ANOVA on hand reaction time are presented. Hand reaction time when the hand moved to the small target (309 ms) was significantly shorter than that when the hand moved to the large target (321 ms). Given the difference in hand reaction time was only about 12 ms, the significant effect of hand target width was not meaningful. Meanwhile, trunk target width did not play any role in affecting hand reaction time. There was a significant interaction between hand movement direction and trunk movement direction.

Figure 3.1 Hand reaction time for the 16 hand-trunk conditions. H-L / H-R: The hand moved to the left/right; T-L / T-R: The trunk moved to the left/right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

Table 3.6 The results of four-way repeated measures ANOVA for hand reaction time and trunk reaction time for the 16 hand-trunk conditions. HD stands for hand movement direction, TD stands for trunk movement direction, HW stand for hand target width, and TW stands for trunk target width.

Source	Hand Reaction Time			Trunk Reaction Time		
	$F(1, 27)$	MS_e	p	$F(1, 27)$	MS_e	p
TD				4.40	4022	< 0.05
HW	5.06	3224	0.03			
HD × TD	6.48	5024	0.02	27.94	9050	< 0.01
TD × TW				4.80	2617	0.04

To further examine the interaction between hand movement direction and trunk movement direction, hand reaction time was averaged across both hand target width and trunk target width (Figure 3.2). There was a 6 ms difference in hand reaction time between the hand-left trunk-left condition (310 ms) and the hand-right trunk-right condition (304 ms), $p > 0.05$. Hand reaction time was virtually identical between the hand-left trunk-right condition (324 ms) and the hand-right trunk-left condition (323 ms), $p > 0.05$. In contrast, hand reaction time tended to be shorter when the hand and the trunk moved in the same direction than when they moved in the opposite directions (the differences were 13, 14, 19, and 20 ms), all $ps > 0.05$.

Figure 3.2 The interaction between hand movement direction and trunk movement direction on hand reaction time averaged across hand target width and trunk target width for the 16 hand-trunk conditions.

3.2.1.2   Trunk Reaction Time in the Hand-Trunk Conditions

The means for trunk reaction time for the 16 hand-trunk conditions ranged from 316 to 411 ms (Figure 3.3). In Table 3.6, the results of ANOVA on trunk reaction time are presented. The patterns of the interaction between hand movement direction and trunk movement direction were quite similar for each combination of target widths, though there was a significant interaction between trunk movement direction and trunk target width.

Figure 3.3 Trunk reaction time for the 16 hand-trunk conditions. H-L / H-R: The hand moved to the left/right; T-L / T-R: The trunk moved to the left/right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

To further examine the interaction between movement directions, trunk reaction time was averaged across hand target width and trunk target width (Figure 3.4). There was a 10 ms difference in trunk reaction time between the hand-left trunk-left condition (345 ms) and the hand-right trunk-right condition (335 ms), $p > 0.05$. There was also a 15 ms difference in trunk reaction time between the hand-left trunk-right condition (380 ms) and the hand-right trunk-left condition (395 ms), $p > 0.05$. However, trunk reaction time was shorter when the hand and the trunk moved in the same direction than when they moved in the opposite directions (the differences were 35, 45, 50, and 60 ms), all ps > 0.05, except the difference of 60 ms between the hand-right trunk-right condition and the hand-right trunk-left condition, $p < 0.05$.

Figure 3.4 The interaction between hand movement direction and trunk movement direction on trunk reaction time averaged across both hand target width and trunk target width for the 16 hand-trunk conditions.

In summary, the initiation of either effector tended to be sooner when the hand and the trunk moved in the same direction than when they moved in the opposite directions. The initiation did not apparently differ between conditions in which the hand and the trunk moved in the same direction, and between conditions in which they moved in the opposite directions. The specific combinations of target widths did not affect reaction time of either the hand or the trunk.

3.2.1.3   Hand Movement Time in the Hand-Trunk Conditions

The means for hand movement time for the 16 hand-trunk conditions ranged from 789 to 2197 ms (Figure 3.5). In Table 3.7, the results of ANOVA are presented. It was clear that hand movement time increased when either the hand or the trunk moved to the small target. There were also interactions between movement directions within each combination of target widths. The patterns of interaction were very similar across different combinations of target widths, except when the hand moved to the large target and the trunk moved to the small target. In terms of the exception, hand movement time when the hand and the trunk moved to the right was much shorter than when the hand and the trunk moved to the left. To further examine the four-way interaction, hand movement time was examined on the two levels of trunk target width using two three-way repeated measures ANOVAs.

When the trunk moved to the large target, the three-way ANOVA on hand movement time revealed that there was a significant hand target width effect, $F(1, 27) = 37.84$, $MS_e = 6103845$, $p < 0.01$, indicating that hand movement time was longer when the hand moved to the small target (1737 ms) than when the hand moved to the large target (1472 ms). There was a significant interaction between hand movement

direction and trunk movement direction, $F(1, 27) = 54.09$, $MS_e = 98015$, $p < 0.01$. To further examine the two-way interaction, hand movement time was averaged across the two levels of hand target width (Figure 3.6). Hand movement time for the hand-left trunk-left condition (1477 ms) was only 53 ms longer than that for the hand-right trunk-right condition (1424 ms), $p > 0.05$. Similarly, hand movement time for the hand-right trunk-left condition (1749 ms) was only 18 ms shorter than that for the hand-left trunk-right condition (1767 ms), $p > 0.05$. In contrast, hand movement time was shorter when the hand and the trunk moved in the same direction than when they moved in the opposite directions (the differences were 272, 290, 325, and 343 ms), all $ps < 0.05$.

Figure 3.5 Hand movement time for the 16 hand-trunk conditions. H-L / H-R: The hand moved to the left/right; T-L / T-R: The trunk moved to the left/right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

Table 3.7 The results of four-way repeated measures ANOVA for hand movement time and trunk movement time for the 16 hand-trunk conditions. HD stands for hand movement direction, TD stands for trunk movement direction, HW stands for hand target width, and TW stands for trunk target width.

Source	Hand Movement Time			Trunk Movement Time		
	$F(1, 27)$	MS_e	p	$F(1, 27)$	MS_e	p
HD	8.05	84085	0.01	12.67	64909	< 0.01
TD				21.16	119410	< 0.01
HW	63.14	108318	< 0.01	26.03	106827	< 0.01
TW	69.45	56777	< 0.01	75.83	151639	< 0.01
HD × TD	54.15	259720	< 0.01			
HW × TD						
TD × TW	5.90	63144	0.02	12.64	64382	< 0.01
HW × TW						
HD × TD × TW				6.78	75193	0.02
HD × HW × TD × TW	4.50	54041	0.04			

When the trunk moved to the small target, the three-way ANOVA on hand movement time revealed that there were a significant hand movement direction effect, $F(1, 27) = 9.14$, $MS_e = 88314$, $p = 0.01$, and a significant hand target width effect, $F(1, 27) = 45.15$, $MS_e = 65241$, $p < 0.01$. There was a significant interaction between hand movement direction and trunk movement direction, $F(1, 27) = 35.58$, $MS_e = 253150$, $p < 0.01$. As expected, there was a significant three-way interaction, $F(1, 27) = 6.56$, $MS_e = 57922$, $p = 0.02$. As shown in Figure 3.5, the pattern of interaction between movement directions when the hand moved to the small target and the trunk moved to the small target should be the same as those when the trunk moved to the large target.

Figure 3.6 The interaction between hand movement direction and trunk movement direction on hand movement time averaged across hand target width when the trunk moved to the large target. Means and standard errors are presented.

Therefore, a two-way ANOVA was performed only on the conditions in which the hand moved to the large target and the trunk moved to the small target. There was a significant hand movement direction effect, $F(1, 27) = 7.96$, $MS_e = 73755$, $p < 0.01$. There was also a significant interaction between hand movement direction and trunk movement direction on hand movement time, $F(1, 27) = 22.63$, $MS_e = 125635$, $p < 0.01$. Hand movement time for the hand-right trunk-left condition (1819 ms) was only 35 ms shorter than that for the hand-left trunk-right condition (1854 ms), $p > 0.05$. Hand movement time for the hand-right trunk-right condition (1390 ms) was 255 ms shorter than that for the hand-left trunk-left condition (1645 ms), $p < 0.05$. Hand movement time was shorter for conditions in which the hand and the trunk moved in the same direction

than that for conditions in which they moved in the opposite directions (174, 208, 428, and 463 ms), all ps < 0.05, except the difference of 174 ms between the hand-left trunk-left condition and the hand-right trunk-left condition, p > 0.05.

In general, hand movement time was significantly shorter when the hand and the trunk moved in the same direction than when the hand and the trunk moved in the opposite directions. Hand movement time was not different for the conditions in which the hand and the trunk moved in the opposite directions. Furthermore, hand movement time was also not different for the conditions in which the hand and the trunk moved in the same direction, except when the trunk moved to the small target and the hand moved to the large target.

3.2.1.4   Trunk Movement Time in the Hand-Trunk Conditions

The means for trunk movement time for the 16 hand-trunk conditions ranged from 1275 to 2568 ms (Figure 3.7). In Table 3.7, the results of ANOVA are presented. The significant hand target width effect indicated that trunk movement time was 157 ms shorter when the hand moved to the large target (1816 ms) than when the hand moved to the small target (1973 ms). Trunk movement time increased when the trunk moved to the small target. To further examine the three-way interaction, trunk movement time was averaged across the two levels of hand target width. Then, two two-way ANOVAs were applied to each level of trunk target width.

When the trunk moved to the large target (Figure 3.8a), there were a significant hand movement direction effect, $F(1, 27) = 6.70$, $MS_e = 35276$, $p = 0.02$, and a significant interaction between hand movement direction and trunk movement direction, $F(1, 27) = 79.67$, $MS_e = 42265$, $p < 0.01$. Trunk movement time for the hand-right trunk-

right condition (1575 ms) was only 27 ms longer than that for the hand-left trunk-left

condition (1548 ms), p > 0.05. Trunk movement time for the hand-left trunk-right

condition (1829 ms) was 157 ms shorter than that for the hand-right trunk-left condition

(1986 ms), p < 0.05. In contrast, trunk movement time when the hand and the trunk

moved in the same direction was significantly shorter than when they moved in the

opposite directions (the differences were 255, 281, 411, and 438 ms), all ps < 0.05.

Figure 3.7 Trunk movement time for the 16 hand-trunk conditions. H-L / H-R: The hand moved to the left/right; T-L / T-R: The trunk moved to the left/right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

When the trunk moved to the small target (Figure 3.8b), there were a significant trunk movement direction effect, $F(1, 27) = 28.18$, $MS_e = 55061$, $p < 0.01$, and a significant interaction between hand movement direction and trunk movement direction, $F(1, 27) = 65.68$, $MS_e = 98927$, $p < 0.01$. Trunk movement time for the hand-right trunk-right condition (1736 ms) was 156 ms shorter than that for the hand-left trunk-left condition (1892 ms), $p > 0.05$. Trunk movement time for the hand-left trunk-right condition (2138 ms) was 315 ms shorter than that for the hand-right trunk-left condition (2453 ms), $p < 0.05$. Trunk movement time when the hand and the trunk moved in the same direction was significantly shorter than when they moved in the opposite directions (the differences were 246, 402, 561, and 717 ms), all ps < 0.05.

In general, trunk movement time was shorter when the hand and the trunk moved in the same direction than when the hand and the trunk moved in the opposite directions. Interestingly, trunk movement time was not different between the conditions in which the hand and the trunk moved in the same direction, but was significantly different between the conditions the hand and the trunk moved in the opposite directions. Overall, the initiation and execution of movement of each effector was faster when the hand and trunk moved in the same direction than when they moved in the opposite directions.

3.2.1.5   Absolute Reaction Time Difference

The means for absolute reaction time difference for the 16 hand-trunk conditions ranged from 52 to 111 ms (Figure 3.9). In Table 3.8, the results of ANOVA are presented. There was only a significant interaction between hand movement direction and trunk movement direction. Neither hand target width nor trunk target width affected the absolute reaction time difference.

(a)

(b)

Figure 3.8 The interaction between hand movement direction and trunk movement direction on trunk movement time averaged across hand target width when (a) the trunk moved to the large target and (b) the trunk moved to the small target. Means and standard errors are presented.

Figure 3.9 The absolute reaction time difference for the 16 hand-trunk conditions. H-L / H-R: The hand moved to the left / right; T-L / T-R: The trunk moved to the left / right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

To further probe the interaction between hand movement direction and trunk movement direction, the absolute reaction time difference was averaged across both hand target width and trunk target width (Figure 3.10). The absolute reaction time differencefor the hand-left trunk-left condition (63 ms) was 8 ms greater than that for the hand-right trunk-right condition (55 ms), $p > 0.05$. The absolute reaction time difference for the hand-left trunk-right condition (91 ms) was 15 ms smaller than that for the hand-right trunk-left condition (106 ms), $p > 0.05$. The absolute reaction time difference was

significantly smaller when the hand and trunk moved in the same direction than when

they moved in the opposite directions (the differences were 28, 36, 43, and 51 ms),

all ps < 0.05.

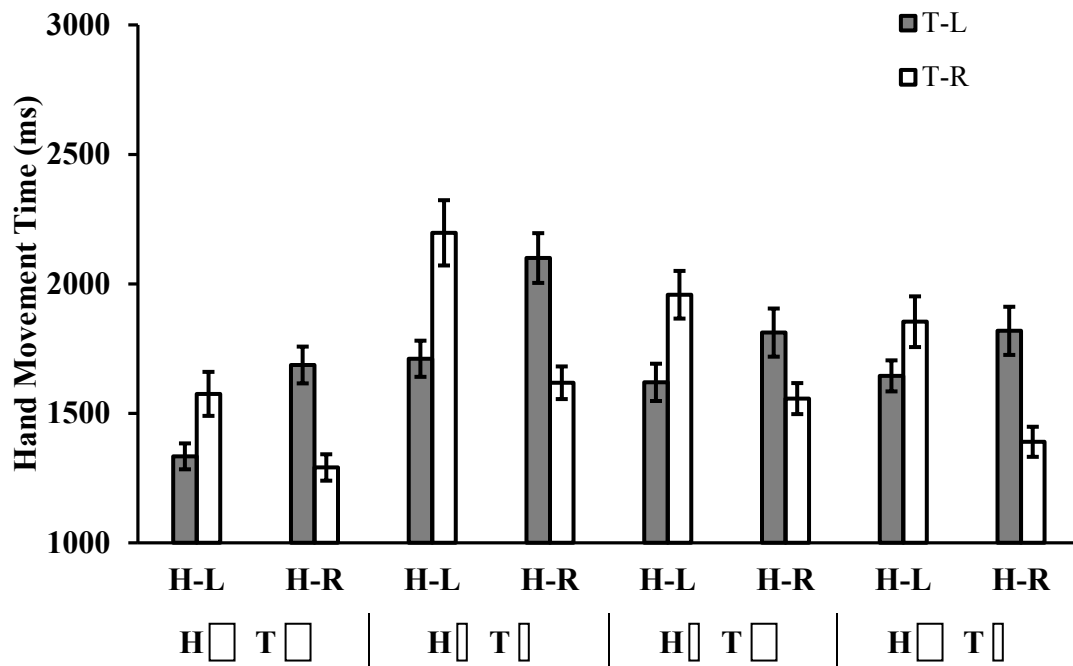In general, the initiation of hand movement and trunk movement was more

synchronized when they moved in the same direction than when they moved in the

opposite directions. The initiation synchrony of hand and trunk movements did not differ

for the conditions in which they moved in the same direction, and did not differ for the

conditions in which they moved in the opposite directions. The manipulation of target

width did not affect the absolute reaction time difference.

Table 3.8 The results of four-way repeated measures ANOVA for the absolute reaction
and movement time difference for the 16 hand-trunk conditions. HD stands for hand
movement direction, TD stands for trunk movement direction, HW stands for hand target
width, and TW stands for trunk target width.

Source	Reaction Time			Movement Time		
	$F(1, 27)$	MS_e	p	$F(1, 27)$	MS_e	p
HD				5.69	55125	0.02
TD				8.17	31796	< 0.01
TW				34.37	51764	< 0.01
HD × TD	30.55	5748	< 0.01	107.56	111222	< 0.01
HW × TW				5.60	42016	0.03
HD × TD × TW				13.41	27082	< 0.01

Figure 3.10 The interaction between hand movement direction and trunk movement direction on the absolute reaction time difference averaged across both target widths. Means and standard errors are presented.

3.2.1.6   Absolute Movement Time Difference

The means for absolute movement time difference for the 16 hand-trunk

conditions ranged from 176 to 784 ms (Figure 3.11). In Table 3.8, the results of ANOVA

on the absolute movement time difference are presented.

In general, when the hand moved to the large target, the absolute movement time

was greater when the trunk moved to the small target than to the large target. However,

the absolute movement time did not tended to be affected by trunk target width when the

hand moved to the small target. The interaction between movement directions was

observed in each combination of target widths. The patterns of interaction were slightly

different in terms of trunk target width. Specifically, when the trunk moved to the small

target, the absolute movement time difference for the hand-right trunk-left condition was

the greatest. To examine the three-way interaction, the absolute movement time difference was averaged across the two levels of hand target width. The three-way interaction then was separated to two two-way ANOVAs based on trunk target width (Figure 3.12).

Figure 3.11 The absolute movement time difference for the 16 hand-trunk conditions. H-L / H-R: The hand moved to the left / right; T-L / T-R: The trunk moved to the left / right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

When the trunk moved to the large target (Figure 3.12a), there was a significant interaction between hand movement direction and trunk movement direction,

F(1,27) = 68.35, MS_e = 29838, p < 0.01. The absolute movement time difference

different for the hand-left trunk-left condition (206 ms) was 27 ms shorter than the hand-

right trunk-right condition (233 ms), p > 0.05. The absolute movement time difference for

the hand-left trunk-right (470 ms) was 39 ms smaller than that for the hand-right trunk-

left condition (509 ms), p > 0.05. In contrast, the absolute movement time difference was

significantly smaller when the hand and the trunk moved in the same direction than when

they moved in the opposite directions (the differences were 237, 264, 276, and 303 ms),
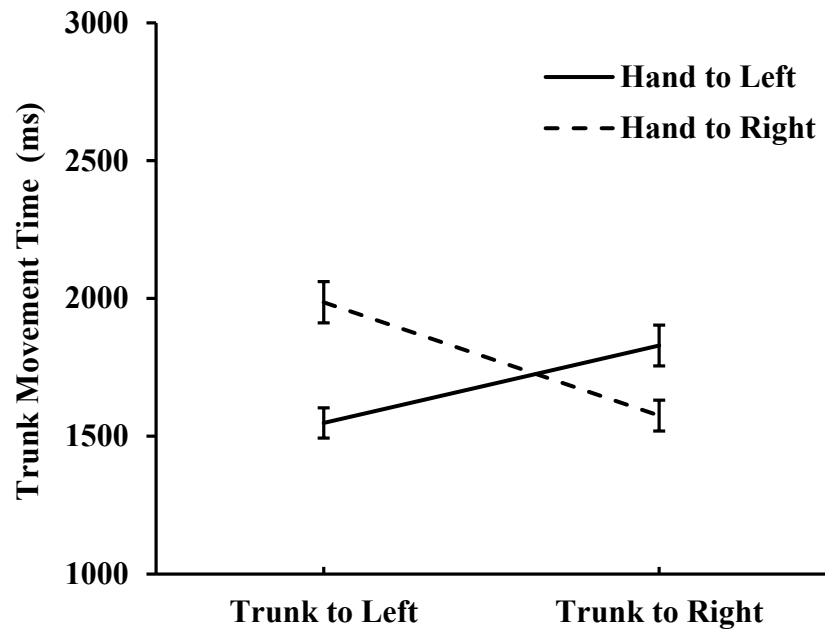
all ps < 0.05.

When the trunk moved to the small target (Figure 3.12b), there were a significant

hand movement direction effect, F(1,27) = 6.38, MS_e = 22754, p = 0.02, and a significant

trunk movement direction effect, F(1,27) = 9.50, MS_e = 24075, p < 0.01. These main

effects were modified by a significant interaction between hand movement direction and

trunk movement direction, F(1,27) = 104.90, MS_e = 39314, p < 0.01. The absolute

movement time difference for the hand-left trunk-left condition (298 ms) was 19 ms

greater than that for the hand-right trunk-right condition (279 ms), p > 0.05. However, the

absolute movement time difference for the hand-left trunk-right condition (591 ms) was

163 ms smaller than that for the hand-right trunk-left condition (754 ms), p < 0.05. In

contrast, the absolute movement time difference was significantly smaller when the hand

and the trunk moved in the same direction than when they moved in the opposite

directions (the differences were 293, 312, 456, and 475 ms), all ps < 0.05.

In general, the absolute synchrony between hand movement execution and trunk

movement execution was greater when they moved in the same direction than when they

moved in the opposite directions. The absolute execution synchrony did not differ for
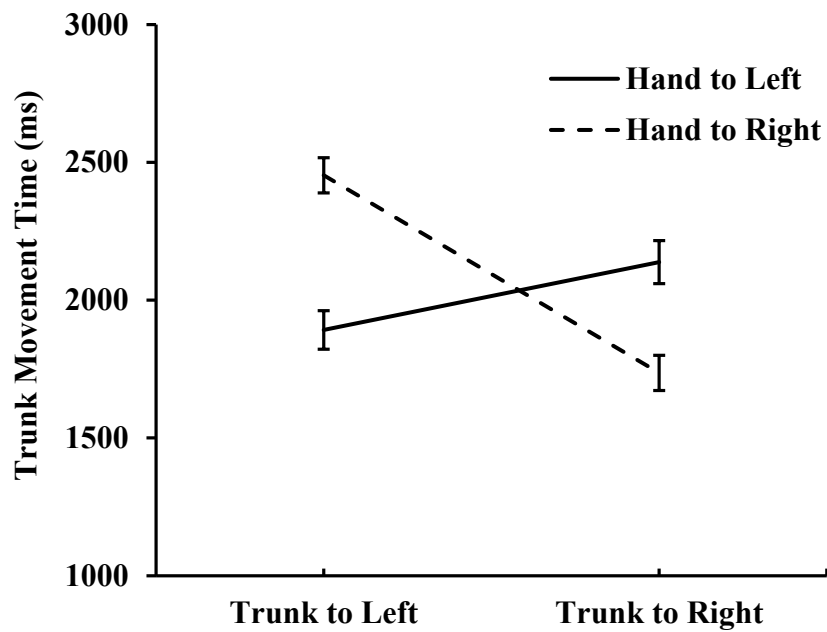
(a)

(b)

Figure 3.12 The interaction between hand movement direction and trunk movement direction on the absolute movement time difference averaged across hand target width (a) when the trunk moved to the large target and (b) when the trunk moved to the small target. Means and standard errors are presented.

conditions in which the hand and trunk moved in the same direction. However, this was not always the case when the hand and the trunk moved in the opposite directions.

3.2.2 Velocity Coupling between the Hand and the Trunk

3.2.2.1 RMS Velocity Difference

The mean RMS velocity difference for the 16 hand-trunk conditions ranged from 0.40 to 1.05 z-units (Figure 3.13). In Table 3.9, the results of ANOVA are presented. There was only a significant interaction between hand movement direction and trunk movement direction. Neither target width affected the RMS velocity difference.
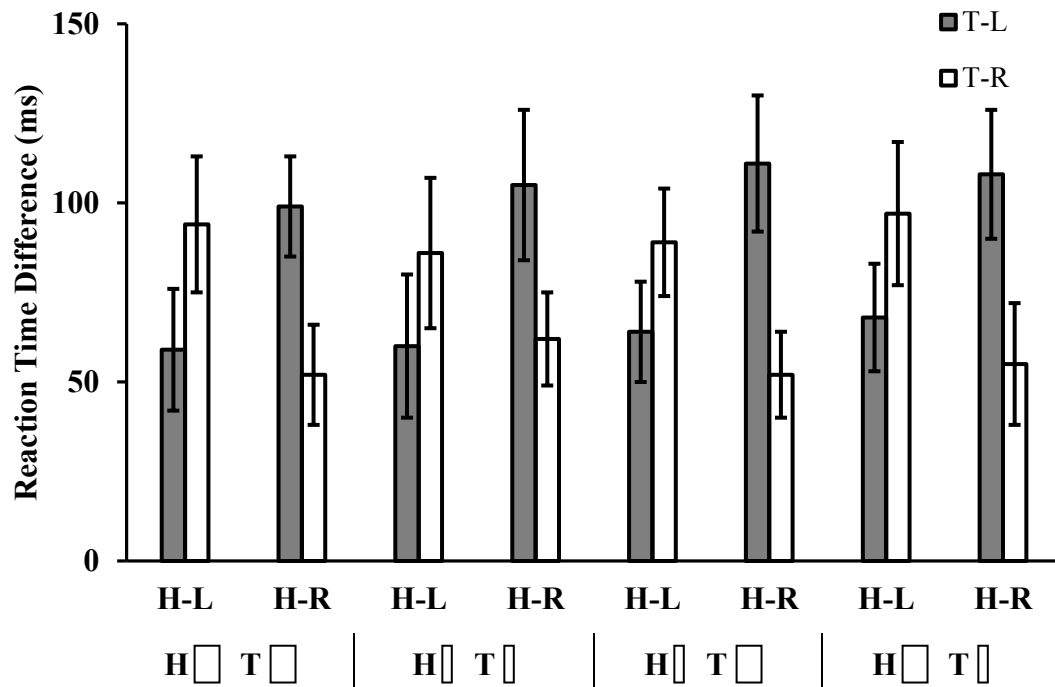

Figure 3.13 The RMS velocity difference for the 16 actual hand-trunk conditions. H-L / H-R: The hand moved to the left / right; T-L / T-R: The trunk moved to the left / right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

Table 3.9 The results of four-way repeated measures ANOVA for the RMS velocity difference and the correlation coefficient of velocity for the 16 hand-trunk conditions. HD stands for hand movement direction, TD stands for trunk movement direction, HW stands for hand target width, and TW stands for trunk target width.

Source	RMS			Correlation Coefficient		
	$F(1, 27)$	MS_e	p	$F(1, 27)$	MS_e	p
HD × TD	328.06	0.11	< 0.01	326.19	0.35	< 0.01

The RMS velocity difference was averaged across levels of both hand target width and trunk target width to further examine the interaction (Figure 3.14). The RMS velocity difference for the hand-left trunk-left condition (0.45 z-units) was virtually the same as that for the hand-right trunk-right condition (0.43 z-units), $p > 0.05$. The RMS velocity difference for the hand-left trunk-right condition (1.00 z-units) was also virtually the same as that for the hand-right trunk-left condition (1.02 z-units), $p > 0.05$. In contrast, the RMS velocity difference was significantly smaller when the hand and trunk moved in the same direction than when they moved in the opposite directions (the differences were 0.55, 0.56, 0.57, and 0.59 z-units), all ps < 0.05.

The results of ANOVA for the RMS velocity difference for movement before the trunk peak velocity (Figure 3.15a) and movement after the trunk peak velocity (Figure 3.15b) are presented in Table 3.10. The RMS velocity difference before the peak trunk velocity seemed to be not different from that after the peak trunk velocity. The results of ANOVA for the RMS velocity difference for the low-frequency velocity component (Figure 3.16a) and the high-frequency component (Figure 3.16b) are presented in Table 3.11. The RMS velocity difference for the high-frequency component

was about 0.5 z-units greater than that for the low-frequency component. Similar patterns of interactions between hand movement direction and trunk movement direction were all observed.
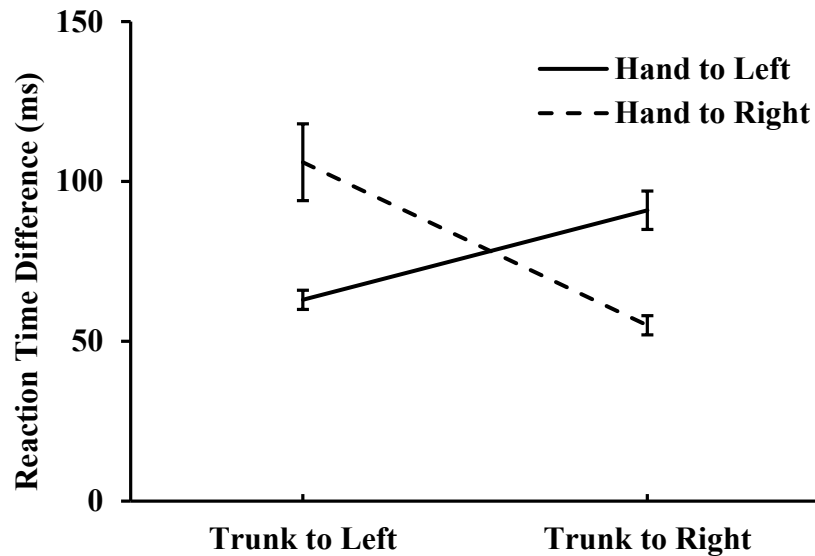

Figure 3.14 The interaction between hand movement direction and trunk movement direction on the RMS velocity difference averaged across target widths. Means and standard errors are presented.

3.2.2.2   Correlation Coefficient of Velocity

The correlation coefficients of velocity were converted to Z scores using the Fisher's r to Z transformations for statistical analyses, and then the resulted Z scores were converted back to correlation coefficients and presented. The means of correlation coefficient of velocity for the 16 hand-trunk conditions ranged from 0.48 to 0.94 (Figure 3.17). The four-way repeated measures ANOVA was performed on the Fisher's Z scores.

(a)

(b)

Figure 3.15 The RMS velocity difference (a) before the peak trunk velocity and (b) after the peak trunk velocity for the 16 hand-trunk conditions. H-L / H-R: The hand moved to the left/right; T-L / T-R: The trunk moved to the left/right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

(a)

(b)

Figure 3.16 The RMS velocity difference for (a) the low-frequency component and (b) the high-frequency component for the 16 hand-trunk conditions. H-L / H-R: The hand moved to the left/right; T-L / T-R: The trunk moved to the left/right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

Table 3.10 The results of four-way repeated measures ANOVA for the RMS velocity difference between hand movement and trunk movement before the peak trunk velocity (Before) and after the peak trunk velocity (After) for the 16 hand-trunk conditions. HD stands for hand movement direction, TD stands for trunk movement direction, HW stands for hand target width, and TW stands for trunk target width.

Source	Before			After		
	$F(1, 27)$	MS_e	p	$F(1, 27)$	MS_e	p
TW	7.31	0.05	0.01			
HD × TD	236.13	0.18	< 0.01	394.03	0.08	< 0.01
HD × TD × TW	4.52	0.04	0.04			

Table 3.11 The results of four-way repeated measures ANOVA for the RMS velocity difference between hand movement and trunk movement for the low-frequency velocity component (Low-Frequency) and the high-frequency component (High-Frequency) for the 16 hand-trunk conditions. HD stands for hand movement direction, TD stands for trunk movement direction, HW stands for hand target width, and TW stands for trunk target width.

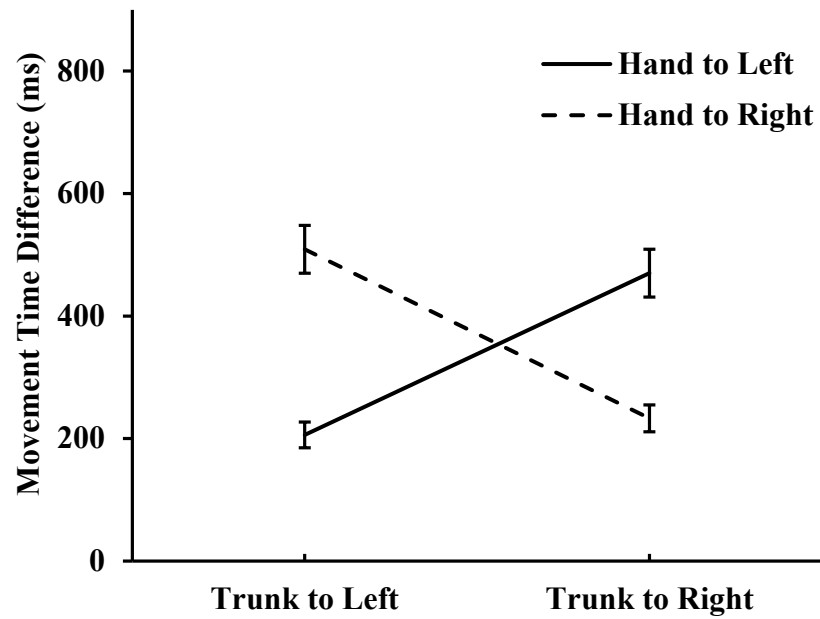| Source	Low-Frequency			High-Frequency		
	$F(1, 27)$	MS_e	p	$F(1, 27)$	MS_e	p
TD				10.49	0.02	< 0.01
HW				9.61	0.02	< 0.01
TW				8.49	0.02	< 0.01
HD × TD	255.90	0.13	< 0.01	5.56	0.16	0.03
HD × TD × HW				4.33	0.02	< 0.05

Figure 3.17 The correlation coefficient of velocity for the 16 hand-trunk conditions. H-L / H-R: The hand moved to the left / right; T-L / T-R: The trunk moved to the left / right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

In Table 3.9, the results of ANOVA are presented. There was a significant interaction between hand movement direction and trunk movement direction. To examine the interaction between movement directions (Figure 3.18), the Fisher's Z scores were averaged across levels of hand target width and trunk target width. The final results were converted back to correlation coefficients from the Fisher's Z scores. The correlation coefficient of velocity for the hand-left trunk-left condition (0.92) was same as that for

the hand-right trunk-right condition (0.92), p > 0.05. The correlation coefficient of velocity for the hand-left trunk-right condition (0.53) was not different from that for the hand-right trunk-left condition (0.51), p > 0.05. The correlation coefficient of velocity was significantly greater when the hand and trunk moved in the same direction (greater than 0.90) than when they moved in the opposite directions (about 0.50), all ps < 0.05.

Figure 3.18 The interaction between hand movement direction and trunk movement direction on the correlation coefficient of velocity averaged across target widths. Means and standard errors are presented.

The results of the ANOVA for the correlation coefficient of velocity (performed on the Fisher's Z scores) for movement before the peak trunk velocity (Figure 3.19a) and movement after the peak trunk velocity (Figure 3.19b) are presented in Table 3.12. The correlation coefficient before the peak trunk velocity was not apparently different from

after the peak trunk velocity. The results of ANOVA for the correlation coefficient of velocity (performed on the Fisher's Z scores) for the low-frequency velocity component (Figure 3.20a) and the high-frequency component (Figure 3.20b) are presented in Table 3.13. The correlation for the high-frequency velocity component was not as strong as that for the low-frequency component. Similar patterns of interactions between hand movement direction and trunk movement direction were all observed.

Overall, hand velocity and trunk velocity were more coupled when they moved in the same direction than when they moved in the opposite directions. The degree of velocity coupling was not different for the conditions in which the hand and the trunk moved in the same direction, and for the conditions in which the hand and the trunk moved in the opposite directions.

3.2.2.3   Lagged Velocity Coupling Analyses

Weak velocity coupling does not mean that the velocity of hand and the velocity of trunk were independent. If the velocity of hand and the velocity of trunk were dependent on each other but out of phase, the velocity coupling could also appear to be weak. The asynchrony of movement onset between the hand and the trunk tended to support this claim. In other words, the reason for the weak velocity coupling between the hand and the trunk when they moved in the opposite directions could be that there was a lag between the movement onset of the hand and the trunk. If this was the case, the minimum value of the lagged RMS velocity difference should be similar for all conditions. Similarly, the maximum values of the lagged correlation coefficient of velocity should also be similar for all conditions.

(a)

(b)

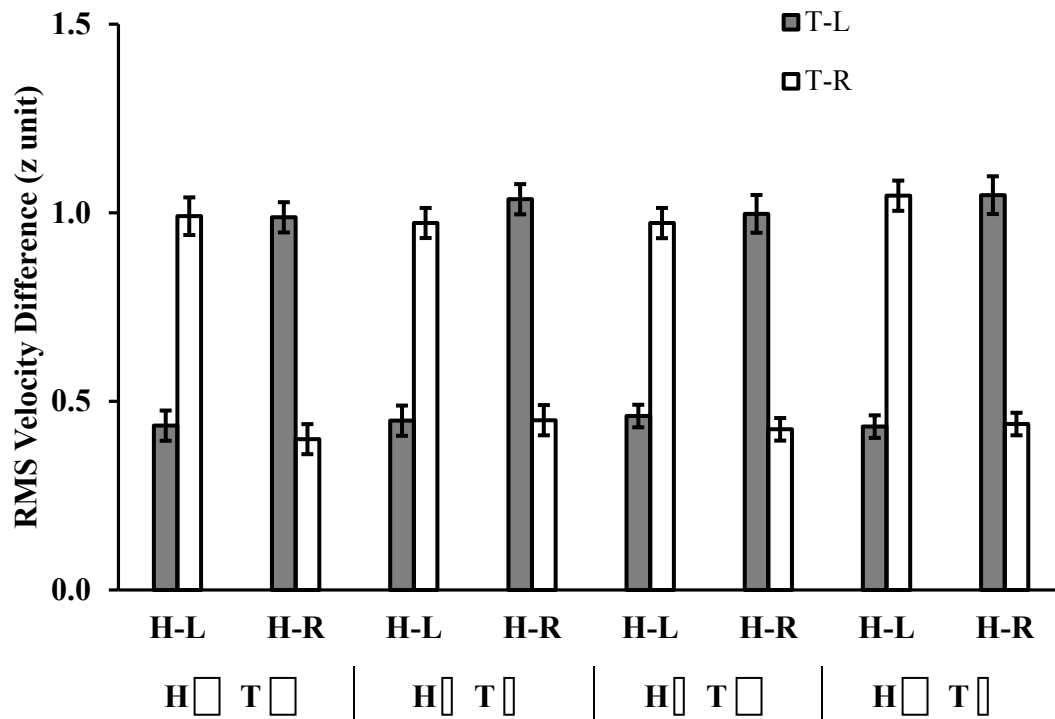Figure 3.19 The correlation coefficient of velocity (a) before the peak trunk velocity and (b) after the peak trunk velocity for the 16 hand-trunk conditions. H-L / H-R: The hand moved to the left/right; T-L / T-R: The trunk moved to the left/right. H (large rectangle) / H (small rectangle): The hand moved to the large / small target; T (large rectangle) / T (small rectangle): The trunk moved to the large / small target. Means and standard errors are presented.

(a)

(b)

Figure 3.20 The correlation coefficient of velocity for (a) the low-frequency component
and (b) the high-frequency component for the 16 hand-trunk conditions. H-L / H-R: The
hand moved to the left/ right; T-L / T-R: The trunk moved to the left / right.
H (large rectangle) / H (small rectangle): The hand moved to the large / small target;
T (large rectangle) / T (small rectangle): The trunk moved to the large / small target.
Means and standard errors are presented.

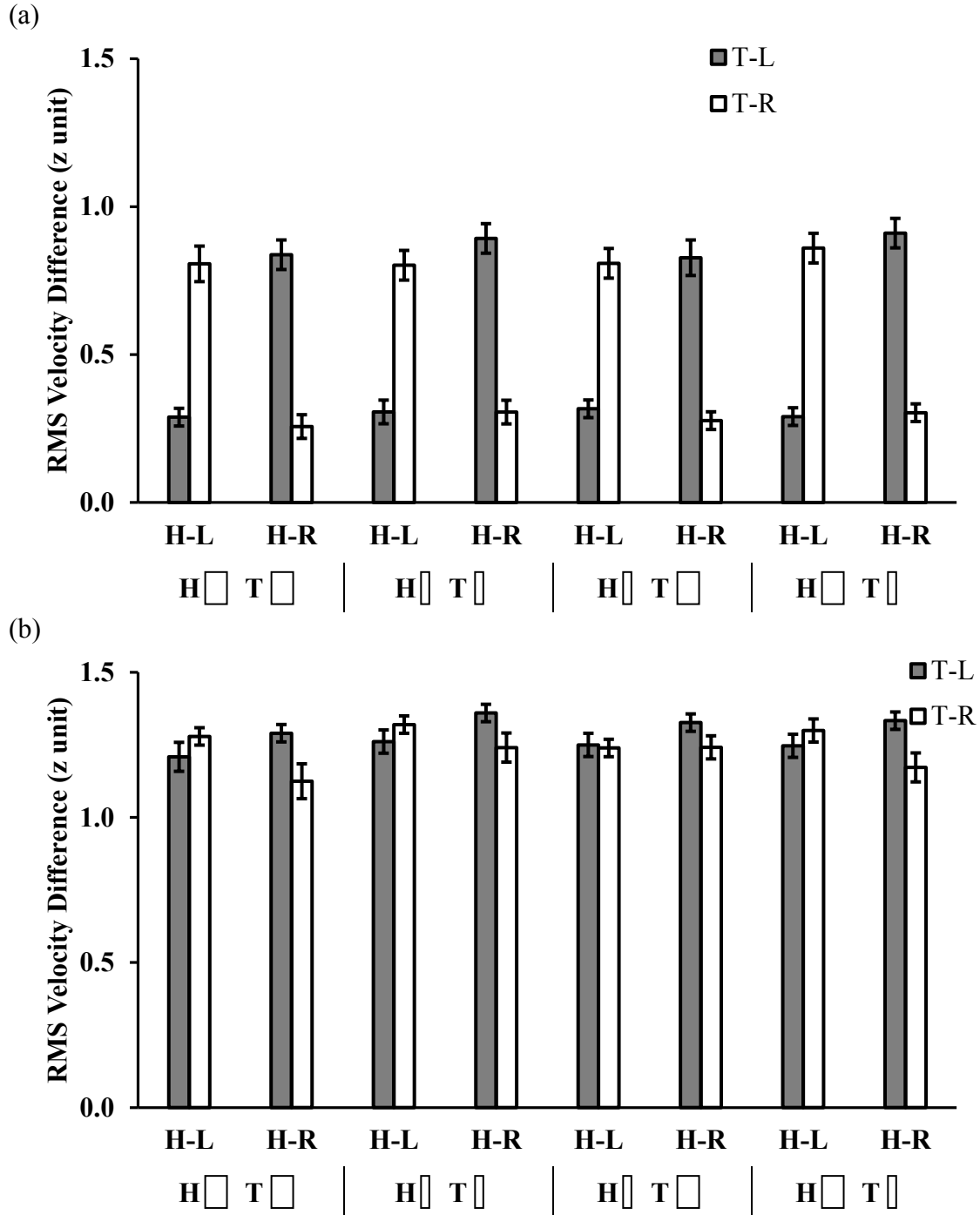Table 3.12 The results of four-way repeated measures ANOVA for the correlation coefficient of velocity between hand movement and trunk movement before the peak trunk velocity (Before) and after the peak trunk velocity (After) for the 16 hand-trunk conditions. HD stands for hand movement direction, TD stands for trunk movement direction, HW stands for hand target width, and TW stands for trunk target width.

Source	Before			After		
	$F(1, 27)$	MS_e	p	$F(1, 27)$	MS_e	p
TW				10.37	0.07	< 0.01
HD $\times$ TD	182.73	0.67	< 0.01	496.18	0.34	< 0.01

Table 3.13 The results of four-way repeated measures ANOVA for the correlation coefficient of velocity between hand movement and trunk movement for the low-frequency velocity component (Low-Frequency) and the high-frequency component (High-Frequency) for the 16 hand-trunk conditions. HD stands for hand movement direction, TD stands for trunk movement direction, HW stands for hand target width, and TW stands for trunk target width.

Source	Low-Frequency			High-Frequency		
	$F(1, 27)$	MS_e	p	$F(1, 27)$	MS_e	p
TD	5.77	0.09	0.02	15.05	0.03	< 0.01
HW				17.07	0.03	< 0.01
TW	6.05	0.15	0.02	8.32	0.01	0.01
HD $\times$ TD	285.50	0.63	< 0.01	10.74	0.17	< 0.01
HD $\times$ TD $\times$ HW				6.62	0.03	0.02
HD $\times$ TD $\times$ HW $\times$ TW				7.64	0.02	0.01

The lagged RMS velocity difference for the 16 hand-trunk conditions is presented in Figure 3.21a. When examined across conditions, the lagged RMS velocity difference when the hand and the trunk moved in the same direction was similar. Meanwhile, the lagged RMS velocity difference when the hand and the trunk moved in the opposite directions was also similar. When the hand and the trunk moved in the same direction, the mean lag where the minimum RMS velocity difference occurred was -1.63% (SD = 0.52%). When the hand and the trunk moved in the opposite directions, the mean lag where the minimum RMS velocity difference occurred was -4.75% (SD = 1.39%). The mean lag when both hand and trunk moved in the same direction (-1.63%) was significantly greater than when hand and trunk moved in the opposite direction (-4.75%), $t(7) = 5.69$, $p < 0.01$. The mean minimum RMS velocity difference when the hand and the trunk moved in the same direction (0.42 z-units) was significantly smaller than when the hand and the trunk moved in the opposite directions (0.96 z-units), $t(7) = -50.46$, $p < 0.01$.

The lagged correlation coefficient of velocity for all 16 actual hand-trunk conditions is presented in Figure 3.21b. When the hand and the trunk moved in the same direction, the mean lag when the maximum correlation coefficient of velocity occurred was -1.00% (SD = 0.76%). Meanwhile, when the hand and the trunk moved in the opposite directions, the mean lag when the maximum correlation coefficient of velocity occurred was -4.50% (SD = 1.60%). The mean lag when the hand and the trunk moved in the same direction (-1.00%) was significantly greater than when hand and trunk moved in the opposite direction (-4.5%), $t(7) = 4.95$, $p < 0.01$. The mean maximum correlation coefficient of velocity when the hand and the trunk moved in the same direction (0.92)

(a)

(b)

Figure 3.21 Lagged correlation coefficient of velocity for the 16 actual hand-trunk conditions. A positive lag means the trunk leads the hand. H stands for hand, T stands for trunk, -R stands for moving to the right, -L stands for moving to the left.

was significantly greater than that when the hand and the trunk moved in the opposite

directions (0.55), $t(7) = 60.22$, $p < 0.01$.

CHAPTER 4.   DISCUSSION

In the present study, the coordination between hand and trunk was examined. For bi-effector Fitts' tasks, Kelso and colleagues showed that movements of the hands share a common timing process to produce spatiotemporally coupled movements (Kelso et al., 1979 a, b; Kelso et al., 1983). Do the hand-trunk movements exhibit similar coordinative patterns compared to limb movements? To answer this question, the participants were required to perform a bi-effector Fitts' task using the hand and the trunk.

Previously, we observed that the movement of trunk follows the same control principles as the movement of hand (Cai et al., in preparation; Kim et al., 1996; Ryu et al., in preparation). Thus, I expected to find that the coordination of hand and trunk exhibit the same coordinative patterns as the limbs. Kelso et al. (1979 a, b) showed that when task difficulty was unequal, movement to the easy target was slowed down when compared with the corresponding unimanual condition while movement time of the other hand to the difficult target was kept relatively unchanged. In other words, the difficult task determined movement time in bimanual Fitts' tasks. In the present study, the tasks performed by the trunk alone always yielded longer movement time than those performed by the hand alone but the accuracy of trunk movement was lower than hand movement, even when the hand task was more difficult than the trunk task. Therefore, it was always more difficult to perform the task while controlling the trunk than controlling the hand. If

this was the case, it was expected that the hand should always slow down to accommodate the trunk movement, while the trunk movement time should not be affected (Kelso et al., 1979 a, b; Kelso et al., 1983; Marteniuk et al., 1984). Indeed, hand movement time increased whenever trunk movement was involved as expected. Trunk movement time tended to be unaffected in the bi-effector conditions when the hand moved in the same direction, but increased when the hand moved in the opposite direction.

When the hand and the trunk were explicitly required to be coordinated, I expected the two effectors to achieve the movement goal in a spatiotemporal coupled manner (Kelso et al., 1979 a, b; Kelso et al., 1983; Marteniuk et al., 1984). Hand movement and trunk movement became more synchronized, and velocities became more coupled only when the hand and the trunk moved in the same direction. In other words, the hand and the trunk were shown to be controlled as a single coordinative structure when they moved in the same direction, but were controlled more independently when they moved in the opposite directions. Therefore, it seems that the coordination between the hand and the trunk when they moved in the same direction and bimanual coordination obeyed same coordinative principles. The tendency to produce spatiotemporal coupled movements was not maintained when the hand and the trunk moved in the opposite directions. Instead, the two effectors gained more independence.

It is worth noting that there are perceptual aspects in the tasks. When the hand and the trunk moved in the same direction, the two combinations of starting position and target were on the same side of the screen. Meanwhile, the target distance for the hand was the same as that for the trunk. There was a possibility that the participant perceived

the two Fitts' tasks as a single task. Therefore, the participant chose to move the hand and

the trunk together in a coupled fashion. In contrast, when the hand and the trunk moved

in the opposite directions, the two combinations of starting position and target were

mirrored on the opposite sides of the screen. It was less likely for the participant to

perceive the two tasks as a single task. Therefore, the hand and the trunk moved

independently. The reaction time results tended to support that there were perceptual

differences related to movement directions. Specifically, reaction time for conditions in

which the two effectors moved in the same direction was shorter than that for conditions

in which the two effectors moved in the opposite directions. However, the difference was

not significant (except one comparison), indicating the perceptual aspects played a

limited role. Furthermore, there is no evidence that bimanual tasks are perceived

differently in terms of movement directions (Kelso et al., 1979 a, b; Kelso et al., 1983).

Specifically, the limbs moved in the same coupled fashion either moving towards/away

from each other or moving in the same direction. Taken together, although the tasks in

the present study were both perceptual and motor, they weighed heavily on motor

aspects.

There is a traditional view that the tendency to produce symmetric bimanual

movement is due to a bias towards co-activation of homologous muscles (Kelso, 1984;

Johnson et al., 1998). The "homologous muscle coupling principle" (Swinnen, 2002) was

referred to the fact that bilaterally symmetrical limb movements with respect to the

longitudinal axis of the body, requiring the simultaneous activation of homologous

muscles, are more synchronized and performed more accurately and consistently than

asymmetrical movements in which one limb moves toward the body midline and the

other is moved away (Kelso, 1984; Riek, Carson, & Byblow, 1992). The similarity in inter-hemispheric transmission time and in the efferent network controlling both limbs might be the mechanisms underlying the tendency of bimanual synchronization (Swinnen, 2002). The "homologous muscle coupling principle" was shown to also hold when isofunctional muscles (muscles that have the same functions) of the limbs were considered (Kelso et al., 1991; Salesse et al., 2005). The "homologous muscle coupling principle" indicates that coordinative principles depend on the anatomical and functional similarity of muscles activated during the coordination of the two effectors.

During the medial-lateral voluntary whole-body movement, Torricelli et al. (2012) showed that when the load is being shifted laterally to one leg, the agonist-antagonist muscles around the ankle joint are co-activated to ensure higher ankle stiffness for the leg loading, and hip joint stability is maintained by co-activation of rectus femoris and glutei. Concurrently, the biceps femoris and rectus femoris of the unloaded leg are activated to stabilize the knee joint preventing it from flexing. The coordination of these muscles was not influenced by movement speed and mainly involved hip and ankle joints. Therefore, shifting the trunk required muscle activations of both lower limbs and the hip, making the controlling efferent network more complex than the controls of the upper limbs.

The "homologous muscle coupling principle" is not applicable to the coordination between the hand and the trunk. If the tendency of spatiotemporal coupling of the two effectors solely depends on the muscles, it should not be obtained in the coordination between the hand and the trunk. Unlike the hands in bimanual coordination, the trunk and the hand did not usually move in a synchronized fashion when either involuntary or

voluntary trunk movement was involved in a goal-directed movement of the hand. For example, the activations of muscles involved in anticipatory postural adjustments preceded the activations of primal movers in the hand (Massion, 1992), and voluntary trunk movement was initiated before the hand movement started and terminated after the hand movement stopped in reaching (Ma et al., 1995). However, if the same coordinative patterns are observed for the coordination between the hand and the trunk as that between upper limbs, this should be the stronger evidence to support the notion that coordinative principles are independent of muscular skeletal structure. The results that the hand and the trunk moved in a synchronized and coupled fashion when they moved in the same direction indicates that bimanual coordinative patterns can be observed in the coordination of the hand and the trunk in certain task configurations, and thus partially supports the notion that coordinative principles are independent of muscular skeletal structure. However, this was not the case when the hand and the trunk moved in the opposite directions. Thus, some aspects of coordination other than muscular skeletal structure of the two effectors caused the distinctive patterns of coordination when the hand and the trunk moved in the opposite directions.

It is possible that the central nervous system exerted different control processes on the hand and the trunk depending on the combination of movement directions. Kelso and colleagues suggested that there is one simple underlying process or structure producing bilateral commands to the two limbs leading to the limbs being in-phase or synchronized during movement execution (Kelso et al., 1979 a, b; Kelso et al., 1983). In other words, the central commands do not prescribe the details of the intended movements for each

hand. Instead, the central commands are referred to functional grouping of joint muscles such that the limbs are constrained to act as "a single unit".

In contrast, Marteniuk and colleagues suggested that there are two separate streams of commands controlling the limbs with prescribed specifications for each limb (Marteniuk et al., 1984; Marteniuk & Mackenzie, 1980). The proximal musculature involved in the limb movement is controlled by bilateral distributed descending pathways (Brinkman & Kuypers, 1972). For example, the activity from the motor cortex or other neural structure in the right brain destined to the proximal musculature of the left limb should also affect the right limb through ipsilateral descending pathways. The two commands engage in "neural crosstalk" (Preilowski, 1975) and thus the specifications become similar. As a result, the movements of the limbs are more similar and coupled when compared with that each limb moved alone, called the "assimilation effects". In addition, Sherwood (1990) suggested that "neural cross-talk" is greater between the left and right sides than between upper and lower limbs.

However, neither of these ideas can explain the results of the present study. The control process of Kelso and colleagues (Kelso et al., 1979 a, b; Kelso et al., 1983) that the two effectors are controlled as "a single unit" can only explain the coordination patterns when the hand and the trunk moved in the same direction. On the other hand, it is difficult to explain why "neural cross-talk" only took place when the hand and the trunk moved in the same direction assuming the hand and the trunk are controlled by two separate commands. Because the muscle involvement for trunk movement is distinct from that for hand movement (Torricelli et al., 2012) and thus the command specifications are not shared, it is possible that "neural cross-talk" did not take place in

the coordination of the hand and the trunk. Taken together, perhaps the hand and the trunk are controlled by a single process when they move in the same direction, but are controlled by two separate processes when they move in the opposite direction.

According to the dynamical system theorists, coordination emerges as a consequence of the constraints imposed on action (Kugler, Kelso, & Turvey, 1980; Kugler, Kelso, & Turvey, 1982). Constraints are viewed as boundaries or features that limit motion possibilities. Constraints imposed on the actions eliminate certain configurations of response dynamics, and the pattern of coordination produced is the optimal result of self-organizing of the biological system. Newell (1985; 1986) proposed three categories of constraints: organismic constraints, environmental constraints, and task constraints. Newell (1985, 1986) also suggests that an optimal pattern of coordination is specified by the interaction of organismic constraints, environmental constraints and task constraints. Taken together, it is possible that the emergence of two distinct coordinative patterns in the present study is because of the performers tried to optimize performance with the presence of the constraints or the interaction between these constraints (Newell, 1985).

What constraints or interaction of constraints caused the difference in coordinative patterns when the hand and the trunk moved in the same direction compared with when they moved in the opposite directions? To answer this question, one should not ignore mutual physical influence (biomechanical constraints) of the two effectors. When participants perform the bimanual Fitts' Law tasks, the limbs are not directly physically connected (Kelso et al., 1979 a, b; Kelso et al, 1983; Martenuik et al., 1984). Instead, the limbs are indirectly connected by the trunk. Because the mass of the trunk

(43.02% of total body weight) is much greater than that of the limb (4.72% of total body weight) (de Leva, 1996), movement of one limb does not significantly affect the stability of the trunk, and thus does not physically affect the movement of the other limb. Therefore, the limbs can be viewed as physically independent of each other. In contrast, there is direct physical connection between the hand and the trunk. Although hand movement exerts limited physical influence on the trunk, trunk movement directly affects hand movement because the shoulder joint has to move with the trunk. It is possible that the physical connection between the hand and the trunk become another constraint that the central nervous system should take into consideration when planning and executing coordinated movements. In other words, I propose that availability or not of a direct physical connection between the two effectors introduced different coordinative patterns.

Recently, Hughes and colleagues explored interlimb coordination during the manipulation of physically coupled objects (Hughes, 2010; Hughes, Haddad, Franz, Zelaznik, & Ryu, 2011). Hughes et al. (2011) examined the relationship between end-state comfort and bimanual coupling when participants manipulated two spring-connected objects compared to when they manipulated two independent objects. The relationship between the end-state comfort and bimanual coupling constraints was not affected when the two objects were connected by a spring. However, the degree of interlimb coupling decreased when the participants manipulated two objects connected by a spring, as indicated by increased absolute movement offset and increased RMS velocity difference during the deceleration portion of the movement. The authors argued that controlling two limbs as "a single unit" (Kelso et al., 1979 a, b; Kelso et al., 1983) does not hinder performance when the two objects are independent because the hands do not

physically influence each other, but it is inflexible and limits the ability of the central nervous system to attenuate movement perturbations. Therefore, the central nervous system adopts a different strategy to control and coordinate independent degrees of freedom when executing bimanual movements in which objects are physically connected.

Moreover, Hughes (2010) showed that inerlimb coupling changed as a function of the stiffness of the connecting spring. Specifically, the hands were less coupled only when the stiffness of spring was medium (70 N·m) or high (193 N·m), but not when the stiffness was low (35 N·m). In the present study, the direct physical connection between the hand and the trunk is perhaps much more rigid than the spring connection between hands, because trunk movement directly introduces displacement of the hand not just forces on the hand. Consistent with Hughes and colleagues (Hughes, 2010; Hughes et al., 2011), the hand and the trunk moved independently when they moved in opposite direction. However, despite the physical connection, the hand and the trunk are still appeared to be controlled as a single structure when they moved in the same direction. Therefore, the strong physical connection between the two effectors does not necessarily introduce movement independence.

Perhaps, the role of the physical connection playing in the coordination determines coordinative patterns of the two effectors. In other words, the interaction between biomechanical constraints and task constraints perhaps plays a decisive role in determining coordinative patterns. When manipulating two objects connected by a spring (Hughes et al., 2011), movement of hands away from each other stretches the spring. The spring resists, and thus the force produced by the spring on each hand hinders the hands from moving away. Similarly, movement of hands towards each other compresses the

spring. The force produced by the spring then hinders the hands from moving towards

each other when they are supposed to. Therefore, the spring connection always can be

perceived as a perturbation, and thus the hands should be decoupled in order to

compensate the perturbations during the course of movement (Hughes et al., 2011). The

physical connection between the hand and the trunk plays a similar role when the hand

and the trunk move in the opposite direction. When the trunk moves to one direction, the

whole arm (the hand) should also move to the same direction with the trunk while the

hand is supposed to move to the opposite direction. Hand movement to the task goal

should be achieved by compensatory adjustments of the shoulder and elbow joint.

Therefore, the hand and the trunk move more independently as the hands showed in

Hughes and colleagues (Hughes, 2010; Hughes et al., 2011).

In contrast, when the hand and the trunk move in the same direction, the physical

connection plays a facilitating role. When the trunk moves in one direction, it

automatically moves the whole arm (the hand) in the same direction as required in the

task. Furthermore, the target distance for the hand and that for the trunk are the same in

the present study. This design makes the facilitating role of the trunk more viable. Indeed,

the hand and the trunk do not move independently, but act as a single structure when the

hand and the trunk move in the same direction. Therefore, it is possible that the tendency

of producing spatiotemporal coupled movements when the two effectors are physically

connected breaks down only when the physical connection causes a fair amount of

incompatibility between the two movement goals. When little or no incomparability is

caused by the physical coupling, for example the physical connection facilitates the

effectors to achieve movement goals, or the connection is made by a very low stiffness

spring or a stretchable light rod (Hughes, 2010), the tendency of producing

spatiotemporal coupled movements are well maintained.

Newell (1986) suggests that coordinative patterns emerge as an optimal solution

of the coordination with various constraints. How is the coordination between the hand

and the trunk optimized given the presence of interaction between constraints? It is

proposed that coordination involves a reduction of the degrees of freedom of the motor

apparatus (Bernstein, 1967; Turvey, 1977). To achieve the coordination, the nervous

system subdivides the degrees of freedom into number of synergies specified in a time-

ordered sequence, which is the solution to reduce the effective number of degrees of

freedom and thus simplify the motor command from the center nervous system

(Bernstein, 1967; Saling, Stelmach, Mescheriakov, & Berger, 1996).

Kelso and colleagues (Kelso et al., 1979 a, b; Kelso et al., 1983) suggested that

the central nervous system controls the limbs as "a single unit" in order to reduce the

number of degrees of freedom that is independently controlled. In other words, the

central nervous system controls both limbs with a single synergy. In the present study,

when the opportunity to reduce the number of degrees of freedom is offered, the central

nervous system takes advantage of it. When the hand and the trunk move in the same

direction, the nervous system freezes the shoulder and elbow joint so that the hand moves

along with the trunk in the medial-lateral direction. The strategy successfully reduces the

degrees of freedom that are independently controlled, and the hand and the trunk appears

to be controlled as "a single unit". According to Kelso et al. (1979 a, b), the hand and the

trunk are controlled by a single central command (as a single synergy) in the present

study. In contrast, when the hand and the trunk moved in the opposite directions, the

shoulder and elbow joint should be always controlled in order to compensate for the perturbation caused by trunk movement to hand movement. There is no viable way to reduce the degrees of freedom that are independently controlled. Instead of forming a single synergy for the two effectors, the central nervous system uncouples the two effectors such that it has the flexibility to attenuate perturbations in one or some degrees of freedom using other degrees of freedom (Turvey, 1991). In other words, a single synergy cannot account for both the hand and the trunk. Taken together, it appears that synergy formation does not depend on the comprised degrees of freedom, but depends on the interaction between biomechanical constraints and task constraints. The optimal coordinative pattern is achieved through the formation of synergies depending on the interaction between constraints.

Unlike performing bimanual Fitts' tasks, the hand-trunk version of Fitts' task in the present study required participants to stand. When standing, there is a synergy that always exists to control the equilibrium, regardless whether the goal-directed movement is performed by the hand or the trunk (Massion, 1992; Alexandrov et al., 2001 a, b). When voluntary trunk bending movement was performed, the equilibrium control was achieved through the ankle synergy while the trunk bending movement was achieved through the hip synergy (Alexandrov et al., 2001 a, b). In the present study, when the hand and the trunk moved in the same direction there were at least two synergies formed: a synergy to generate the trajectory for the hand and the trunk together and a synergy to maintain the equilibrium. When the hand and the trunk moved in the opposite directions, it was possible that more synergies were required: synergies to generate hand trajectory, synergies to generate trunk trajectory and a synergy to maintain the equilibrium. It was

possible that more synergies exploited the degrees of freedom leaving no room for the central nervous system to manipulate and optimize. As a result, performance was worse when the hand and the trunk moved in the opposite directions than when they moved in the same direction.

The functional goals of synergies should be compatible in order to produce more efficient movements. When participants were seated, Ma et al. (1995) proposed that reaching movements resulted from two independent control synergies. The first synergy coordinated trunk and arm movements so that the endpoint position kept unchanged (compensatory). The second synergy produced interjoint coordination to shift the endpoint to the target (transport). The two synergies were compatible, and thus hand movement accuracy and trajectory were not affected (Archambault et al, 1999; Kaminski et al, 1995; Ma et al., 1995; Wang & Stelmach, 1998). When standing, adding another functional goal (maintaining body balance in challenging conditions) to trunk that was not compatible with the other goal (assisting to transport the hand to the target) could make hand reaching trajectory curved (Pozzo et al., 2002), indicating a change in synergies and movement performance. In the present study, the trunk was required to perform a goal-directed movement with high accuracy demand. Therefore, the compensatory role of trunk movement played in the hand reaching movement was supposed to be altered. Instead, trunk movement itself was one of the task goals. Therefore, the synergy formation should be different in the present study compared to reaching tasks involving trunk motion. It is difficult to explain exactly how many synergies were formed. Perhaps, the differences in performance were not because of the

number of synergy formed. Instead, it is possible that the synergies when the hand and the trunk moved in the same direction were more functionally compatible.

In conclusion, coordinative principles of bimanual coordination were not all shared in the coordination between hand and trunk. The coordinative patterns are not determined by the muscular skeletal structure involved in the coordination, but are determined by the interaction of biomechanical constraints and task constraints imposed on the action of the effectors. Meanwhile, the central nervous system controls the formation of synergies to optimize the coordination also depending on the constraints. These findings support the idea that coordination is the result of the constraints imposed on the action of the effectors.

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PUBLICATIONS AND PROCEEDINGS

Publications

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Ryu, J. H., Cai, F., Haddad, J. M., & Zelaznik, H. N. (in preparation). The trade-off of variability between the postural and focal movement.

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