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Joint Coordination During Bimanual Transport of Real and Imaginary Objects

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Abstract

We studied multi-joint coordination during tasks of transporting real and imaginary objects with two arms. One of the arms was unexpectedly arrested in one third of trials performed. In the absence of perturbation, multi-joint synergies stabilizing the distance between the arms early and late in the movement were seen in both conditions and even were stronger in the imaginary object condition. However, quick adjustments in the non-perturbed arm were seen only in the real object condition, whereas the non-perturbed arm did not react to the perturbation in the imaginary object condition. We conclude that tactile information is important for the central nervous system to quickly respond to perturbations in bimanual tasks. The results underscore potential differences between stability in the absence of external perturbations that may be ensured by setting a reference aperture between the hands and stability that requires adjustments in this reference aperture following a major perturbation.

Keywords

bimanual coordination; reference configuration hypothesis; synergy; uncontrolled manifold hypothesis; stability

Recent developments of the equilibrium-point hypothesis [6,7] to multi-joint, multi-effector, and whole-body movements have resulted in a view that voluntary movements are controlled with setting reference configurations for salient variables (reviewed in [8]). The neural control of an object transport action may be associated with setting time profiles of two control variables, reference aperture between the grasping effectors and reference position of the grasped object [14]. Setting the former variable translates into the generation of grip forces, while setting the latter variable leads to movement of the object in space. When two hands are used to carry a brick-shaped object by pressing on its sides, the reference aperture may be set as a single, higher-level control variable or it can emerge from setting reference positions for the two hands separately.

We explored these two possibilities using two methods. First, we quantified multi-joint synergies defined as co-varied changes in joint angles that (partly) reduce the across-trial

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variability of the distance between the hands [5,15,16]. For this purpose, joint angle co-variation was analyzed using the uncontrolled manifold hypothesis (UCM) method [12,15], which allows to compute an index corresponding to the relative amount of joint configuration variance compatible with average across trials trajectories. Second, we applied an unexpected perturbation to one of the hands and quantified the reaction of the other hand. Both analyses were run under two conditions, when the subjects transported a real object (and hence the two hands were mechanically coupled) and when they were asked to imagine an object and “transport it” (no direct mechanical coupling between the hands). Our specific hypotheses were: **H1**: Carrying an object (either real or imagined) is associated with setting a reference aperture between the hands resulting in a multi-joint synergy stabilizing the vectorial distance between the hands. **H2**: Tactile information is crucial for stabilization of the distance between the arms under unexpected mechanical perturbations applied to one of the arms [4,20].

Four male and four female healthy subjects without any known neurological disorders volunteered to participate in this study. Their average age was 26 ± 4 years; average height of 1.70 ± 0.05 m; average mass of 67.7 ± 7.7 kg. All subjects were right-handed with an average laterality quotient of +95, measured in accordance with the Edinburgh Handedness Inventory [13]. All subjects gave written consent according to the procedures approved by the institutional Ethics Committee (Centre for Interdisciplinary Research in Rehabilitation of Montreal area).

Subjects sat in a chair with both shoulders supported such that scapular motion was constrained to a small range of motion via straps crossing the chest. Subjects comfortably rested their forearms on a table of adjustable height. In one block of conditions, subjects were instructed to move an object (0.15 m wide, 0.15 m long, 0.07 m thick, mass 0.049 kg) quickly and accurately using a bimanual palmar opposition grasp from a fixed location on the left hand side of the body to a fixed final target located on the right hand side of the body (Figure 1). Each of the targets was located 0.19 m from the midline of the subject’s torso, 0.10 m away from the body in the mid-frontal plane. The beginning and final target locations were placed symmetrically with respect to the midline of the torso. Two target sizes were tested: wide target (0.15 m wide, 0.15 m long, and spaced 0.3 m apart) and narrow target (0.07 m wide, 0.15 m long, and spaced 0.38 m apart). The center of each target location was consistent for both target types across all subjects. Subjects were instructed to place the object (real or imaginary) on top of the final target in all trials. In the second block of conditions, subjects were instructed to move an imaginary object from the same initial location to the same final target location quickly and accurately as in the conditions with a real object. Overall, four main testing conditions were presented: real object (wide or narrow target) and no object (wide or narrow target). Object width was manipulated for exploratory purposes. The order of conditions was block randomized for each subject. One practice trial per block was given to subjects to familiarize them with each condition. No subjects reported difficulty in performing the task. Forty trials per block were recorded; a total of 160 trials were recorded for this experiment. Subjects were given 3 minutes of rest every 20 trials to prevent fatigue.

Subjects were instructed to lift the object (real or not) off of the table prior to each trial. After a brief pause, in response to the auditory cue, subjects were to move to the target location quickly and accurately. In thirteen of the forty trials in each block (one third of the trials per block), a perturbation was introduced to the distal end of the left forearm after the onset of movement. The apparatus providing the perturbation consisted of two components: a plastic rod with an adjustable bracelet and a cylindrical electromagnet. The plastic rod was attached to the left distal forearm via the bracelet on one end; the other end was connected to the electromagnet using universal joints and ball bearings. When the electromagnet was activated, the rod was arrested and movement of the left distal forearm was prevented for approximately 300 ms. For further details on this apparatus, see Ustinova et al. [18]. The duration of all trials, perturbed and control, were time normalized for across trial comparisons and reduced to 100

evenly spaced data points. The onset of perturbation happened, on average, at $22 \pm 1\%$ of the normalized movement time in perturbed trials. The order of trials (control and perturbed) were randomly assigned within each block for each subject.

Three-dimensional movement kinematics were recorded at 100 Hz using a high-speed camera system (Optotrak, Northern Digital Inc., Waterloo, Canada) and 12 infrared light emitting diodes (IREDs). The IREDs were affixed using double-sided adhesive tape on the following anatomical landmarks of both the right and left sides of the body: the tip of the index finger, the styloid process of the radius, lateral epicondyle of the humerus, the greater tubercle of the humerus, the acromion process of the scapula, and the sternal end of the clavicle. Coordinates of the IREDs in the XZ plane (Figure 1B) were used to compute joint angles by using the scalar products of the XZ plane vectors joining the markers of adjacent segments [3]. The onset of each trial was determined as the first frame in which the IREDs of the two markers of the left hand began to move in the X-direction; the termination of trials was determined as the first frame in which the IREDs of the two markers of the left hand stopped moving in the X-direction near the final target location.

Variability in joint angle configurations was analyzed as described in detail by Domkin et al. [5]. Briefly, we used the framework of the uncontrolled manifold hypothesis (UCM) [12,15] to quantify, for each time sample of the time-normalized trials, the across-trials variance in the space of joint angles. Two components of the joint configuration variance were computed per degree-of-freedom; one that did (V_{BAD}) and one that did not (V_{GOOD}) affect a selected performance variable. The total variance (V_{TOT}) of the joint configuration was also computed in the same manner. The two variance components were computed for midpoint location of each hand and for the vectorial distance between the hand midpoints as performance variables. Note that this distance could vary even when the subjects carried the object between the hands, because the subjects did not put their palms flat on the object but were free to move the palms with respect to the object, as long as it did not drop. To quantify the relative amounts of V_{GOOD} and V_{BAD} at each time sample, we computed an index of co-variation, ΔV , such that $\Delta V = (V_{\text{GOOD}} - V_{\text{BAD}})/V_{\text{TOT}}$. If $V_{\text{GOOD}} > V_{\text{BAD}}$, then $\Delta V > 0$, which is interpreted as a synergy stabilizing the selected performance variable. If $\Delta V \leq 0$, this implied the absence of such synergy [11,17]. The quantities V_{GOOD} , V_{BAD} , and V_{TOT} were normalized based on the number of degrees of freedom (DOFs) in the corresponding sub-spaces. In the analysis of the vectorial distance, the DOFs are four, two, and six, respectively; while for the analysis of the hand endpoint coordinates, the DOFs are one, two, and three, respectively. The ΔV indices were analyzed during the first and last 10% of movement time across all trials.

All kinematic analyses were performed using customized Matlab software (Mathworks Inc., Natick, MA, USA). Prior to all analyses, the kinematic data were low-pass filtered at 10 Hz using a second -order, zero-lag Butterworth filter. The midpoint location of both hands, the vectorial distance between the hand midpoints, and elements of the Jacobian matrices for both the bimanual and unimanual variance analyses were computed using the symbolic math toolkit in Matlab. Additional kinematic analyses (in particular velocity and timing analyses) were also used to explore differences in kinematic performance among trials.

Statistical analyses were performed using t-tests and mixed-effects ANOVAs. In particular, we tested the following factors: *Object* (real object vs. no object), *Trial* (control vs. perturbed), *Hand* (right vs. left), and *Width* (narrow vs. wide). Analysis also included a factor of *Interval* (the initial vs. the final 10% of movement time), in particular to analyze the joint configuration variance before any perturbation and at the end of the movement. A random factor of *Subject* (8 levels) was used to control for variability found across subjects but its effects are not interpreted in this paper. The ΔV data were subjected to Fisher z-transformation prior to ANOVA testing to mitigate the ceiling effects; however, untransformed data are shown

in the figures to avoid confusion. Individual t-tests with Bonferroni corrections were performed to compare ΔV to zero.

In the following paragraphs, the basic kinematics are described, followed by analysis of the variance indices described above. All data are presented in the text and figures as means and standard errors.

In control trials, subjects performed the task accurately with both hands moving in parallel for both real and imagined objects; an example of typical trajectories along the X-axis (for both real and imaginary objects) can be found in panels A and B of Figure 2. In perturbed trials with a real object, after the perturbation of the left hand, the right hand endpoint stopped to prevent dropping the object (Figure 2C). Since the perturbation was applied above the left wrist, left wrist motion into flexion continued after the perturbation, which gave the right arm enough time to adjust without dropping the object. In perturbed trials with an imaginary object, the two arms moved independently along the X-axis after the perturbation (Figure 2D). In these perturbed trials, the right hand continued to move towards a final location while the left hand was arrested. The right hand would stop at the final location and “waited” there for the left hand. Analysis of the time ($t_{V=0}$) until the right endpoint velocity along the X-axis was zero in perturbed trials indicated that the right hand endpoint stopped after the onset of perturbation much earlier in the trials with the real object (“real”) compared to conditions with no object (“none”): $t_{V=0; \text{real}} = 264 \pm 59$ ms, $t_{V=0; \text{none}} = 494 \pm 57$ ms ($F_{1,22} = 21.42$, $p < 0.001$). The duration of trials was also noticeably different between control and perturbed trials; however, effects of object type were not found. On average, control trials lasted 688 ± 34 ms while perturbed trials lasted 1055 ± 40 ms. This difference was confirmed via ANOVA, with *Trial* ($F_{1,51} = 150.84$, $p < 0.001$) being the only significant factor.

For both the narrow and wide target widths, mean scalar distance (D_S) between the hands was computed over the trial duration. When the subjects moved the real object, D_S did not differ between the control and perturbed trials. In contrast, D_S was nearly twice as large for the perturbed trials as compared to the control trials when the subjects moved an imaginary object (control $D_S = 112.1 \pm 9.5$ mm, perturbed $D_S = 211.7 \pm 18.5$ mm). These differences were confirmed with ANOVA, with significant effects of *Object* ($F_{1,47} = 10.48$, $p < 0.005$), *Trial* ($F_{1,47} = 36.86$, $p < 0.001$), and their interaction *Object x Trial* ($F_{1,47} = 36.23$, $p < 0.001$).

In the subsequent section, analysis of the co-variation index ΔV is presented for three different measures: ΔV_V for the vectorial distance between the midpoints of the two hands; ΔV_R , for the midpoint coordinate of the right hand; and ΔV_L for the midpoint coordinate of the left hand. Recall that $\Delta V > 0$ is consistent with co-variation of joint angles that stabilizes the selected performance variable, which we refer to as a synergy; while $\Delta V \leq 0$ implies the absence of such a synergy. We asked two main questions: Is there a synergy stabilizing the vectorial distance between the hand midpoints; and, Are there synergies stabilizing the individual hand midpoints? To remind, the analysis was run over the first 10% of movement time and the last 10% of movement time to avoid the effects of poorly reproducible, perturbation related variations in joint configuration.

Synergies stabilizing the vectorial distance, as well as the left midpoint coordinate were found ($\Delta V > 0$, $p < 0.05$). A synergy stabilizing vectorial distance for the right hand midpoint coordinate was found only for conditions involving a real object. Further investigation of the differences between ΔV indices for real and imagined objects were performed using individual t-tests with Bonferroni corrections. The ΔV_V index was found to be significantly greater than zero for the imaginary object condition, while ΔV_R and ΔV_L indices were significantly greater than zero for the real object conditions ($t > 2.83$, $p < 0.01$ all indices), as shown in Figure 3.

The other ΔV indices (ΔV_V for real objects, ΔV_R and ΔV_L for imaginary objects) were not significantly different from zero.

For vectorial distance between the hands, ΔV_V was larger for the imagined object (Figure 3). This was confirmed with ANOVA that showed a significant effect of *Object* ($F_{1,112} = 7.17$, $p < 0.01$) with no interactions. For the right endpoint coordinate, ΔV_R magnitude was larger for the real object, confirmed with ANOVA that showed a significant effect of *Object* ($F_{1,112} = 4.75$, $p < 0.05$) with no interactions. For the left endpoint coordinate, ΔV_L was also larger for the real object (Figure 3); however, this effect was not found to be statistically significant.

Our results provided mixed answers to the two specific hypotheses. With respect to the first hypothesis, we observed a two-hand synergy that stabilized the vectorial distance between the hands, which was stronger (had larger ΔV indices) as compared to the synergies stabilizing the trajectories of the endpoints of each arm. These results are similar to those reported by Domkin et al. [5] in their study of bimanual pointing movements. However, this was true only for movements with an imaginary object. During movements with the real object, the ΔV indices for the individual arm endpoints were higher than the index for the vectorial distance between the hands. These results look counter-intuitive. Indeed, in trials with the real object, the object constrained the vectorial distance between the hands and could be expected to contribute to higher ΔV indices. On the other hand, the presence of the object could make the subjects' performance sloppier because they did not have to concentrate on keeping the distance between the hand midpoints constant. When transporting an imaginary object, subjects had to purposefully stabilize the distance between the hands. This might have contributed to the low V_{BAD} under those conditions while the subjects might allow themselves relatively large joint configuration variability.

With respect to the second hypothesis, we observed quick reactions in the non-perturbed arm when the subjects transported a real object, but not when they transported an imaginary object. When the subjects "moved" the imaginary object, the right arm did not react to the applied perturbation, but rather moved to a final position and waited for the left arm. These observations contrast earlier reports on quick adjustments to perturbations of one effector in two-effector tasks where the effectors were linked not mechanically, but by presentation of their combined effect. In those studies, both effectors showed adjustments to the perturbation [4,20]. In previous studies, tactile information from hand-object interfaces was shown to have strong effects in manipulation tasks [1,2,9,10,19]. In our experiment, it is likely that such information was used in conditions with a real object to maintain object grasping, while the lack of such information led to the dissociation of the arms in the imaginary object tasks. The loss of stability of the distance between the arms after the perturbation contrasts the higher indices of synergy stabilizing this same distance.

It is possible that, in perturbed trials with the real object, the drop in the resistive force acting on the right (unperturbed) hand contributed to its reversal. Although we did not measure the pressing force, it was unlikely to be very high given the very light object and moderate movement time (and correspondingly modest acceleration). Hence, we do not think that the removal of this force was by itself sufficient to reverse the endpoint motion. However, without a special experiment, this question remains open.

Synergy indices reflect neural organization that ensures co-variation among relatively small spontaneous deviations of elemental variables (joint angles) as long as the important variable (distance between the hands) does not deviate too much from its required pattern. Synergic mechanisms that ensure such local stability by setting a reference aperture between the two hands [14] cannot handle the mechanical effects of a major perturbation. So, irrespectively of whether the synergy is weak or strong, a corrective response to perturbation is necessary, but

this correction is possible only if the hands interact with the object and the tactile feedback is available. At the end of movement, when both hands approach a final position, the synergy stabilizing the distance between the hands is restored under both conditions. Based on the results of the current study, we conclude that synergic local stability may be immune to the presence or absence of tactile information while global stability in the presence of major external perturbations requires this information.

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Figure 1.

A schematic of the experimental setup. **A:** The subject is shown moving a real object. The perturbation device is attached to the left forearm, near the distal end. **B:** Joint angles and coordinate system used for the UCM analysis are labeled similar to Domkin et al. [5].

Figure 2.

Typical right and left hand endpoint trajectories in control and perturbed trials. The vertical bars in Panels C and D denote the onset and end of the perturbation to the left arm. The continuous black line indicates the left hand endpoint trajectory while the dashed line indicates the right hand endpoint trajectory. **A:** Endpoint trajectories during a control trial with a real object. **B:** Endpoint trajectories during a control trial with a no object. **C:** Endpoint trajectories during a perturbed trial with a real object. In this panel, the right and left limb endpoints move together during the perturbation. **D:** Endpoint trajectories during a perturbed trial with a no object. In this panel, the right limb endpoint continues to move to the target location during the perturbation.

Figure 3.

Mean and standard error of the indices of co-variation of the vectorial distance between the midpoints of the hands (V), as well as midpoint location for the right (R) and left hands (L) for real and imaginary objects. The ΔV_V index was larger for imaginary objects while the ΔV_R and ΔV_L indices were larger for real objects. The bars show data analyzed across all subjects. Data for real objects are shown by white bars and data for imaginary objects is shown in gray bars. * $F_{1,112} = 7.17$, $p < 0.01$; ** $F_{1,112} = 4.75$, $p < 0.05$.