Lateralization of Impedance Control in Dynamic Versus Static Bimanual Tasks

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Abstract— **In activities of daily living that require bimanual coordination, humans often assign a role to each hand. How do task requirements affect this role assignment? To address this question, we investigated how healthy right-handed participants bimanually manipulated a static or dynamic virtual object using wrist flexion/extension while receiving haptic feedback through the interacting object's torque. On selected trials, the object shook strongly to destabilize the bimanual grip. Our results show that participants reacted to the shaking by increasing their wrist co-contraction. Unlike in previous work, handedness was not the determining factor in choosing which wrist to co-contract to stabilize the object. However, each participant preferred to co-contract one hand over the other, a choice that was consistent for both the static and dynamic objects. While role allocation did not seem to be affected by task requirements, it may have resulted in different motor behaviours as indicated by the changes in the object torque. Further investigation is needed to elucidate the factors that determine the preference in stabilizing with either the dominant or non-dominant hand.**

I. Introduction

The hands are often used asymmetrically during bimanual object manipulation. For example, when opening a jar of jam, one hand will hold the jar while the other opens the lid. It has been suggested that the hands have pre-allocated roles. However, aspects of the task such as its congruence or the need to modulate force versus pure object stabilization may affect bimanual manipulation and its asymmetry.

The motor system interacts with the environment and can adapt the body's impedance in response to instability [1] by exploiting muscle and tendon viscoelastic properties [2]. In particular, a joint's mechanical impedance can be regulated by modulating antagonist muscle co-activation [3]. During bimanual manipulation, the hands simultaneously act on an object such that the effective impedance is the addition of the hands' impedance, thus making the control redundant as the impedance can be increased in both hands equally or in one hand preferentially. How does the motor system distribute hand impedance control? And does this distribution change depending on the dynamic requirements of the task?

Two main theories have been proposed for how impedance is coordinated among human hands. *Global dominance* states that the hemisphere contralateral to the dominant arm (left hemisphere for right-handers) specializes in all aspects of motor control, while *dynamic dominance* suggests that each hemisphere specializes in different control aspects [4]. This hypothesis suggests that to allow for positional stability in right-handers, the right hemisphere specialises in impedance control, while the left specialises in predictive control.

Several studies have presented results supporting the dynamic dominance hypothesis [5], [6], [7], [8], [9], [10]. Most of them concerned reaching motions, although other movements (e.g. turn and reach [11]) have also been considered. However, these studies have not tested simultaneous motions of the left and right arms and have instead compared their individual capabilities, which might overlook some aspects of inter-limb coordination affecting motor control [12], [13].

When the arms are tested simultaneously, different motor behaviours may stem from the task requirements. Woytowicz et al. explored an incongruent task, where the hands had a spring connection and one hand stabilized while the other reached for different targets [14]. Although they found that the non-dominant hand had superior positional stability, consistent with dynamic dominance, this could have been due to better interaction force prediction arising from the dominant hand's reaching motion. Thus, it is unclear whether the non-dominant hand is truly superior at positional stabilization.

Contrary to the conclusions of this study, a recent study by Takagi et al. [15] explored a congruent postural stabilization task, where participants had to stabilize a virtual shaking object. This was followed by a discrete incongruent transport task, where the object had to be moved horizontally by flexing/extending the wrists. Their results supported the global dominance hypothesis instead, suggesting that the circumstances under which the motor system allocates impedance control among the upper limbs may need to be re-examined.

In the aforementioned studies, task components that required the hands to move also pre-allocated them to a certain role (stabilizing/pointing [14] and stabilizing/pushing [15]). How does the motor system allocate impedance control when movement is involved in a task without pre-allocated roles?

This study investigates differences in impedance control between congruent static and dynamic tasks. Participants performed a one degree-of-freedom (DoF) object manipulation task, where they used both hands' wrist flexion/extension to hold a virtual object. The object could either remain static or dynamically grow and shrink, requiring participants to modulate their force to accommodate for this behaviour. Due to the tasks' congruence, roles are not pre-allocated. In both situations, the object could shake, creating instability.

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We hypothesized that our right-handed participants would co-contract more, and do so with their dominant hand, as the perturbation level increased. It was unclear how these patterns would change when force modulation was required. The resulting motor behavior could remain lateralized (i.e. with the right hand dominating the stabilization through a higher co-contraction and the left allowing for the object's growth). Alternatively, the symmetry of the object's motion could favour a more symmetric behaviour among the hands.

II. Methods

A. Participants and experimental setup

The experiment was approved by the Joint Research Compliance Office at Imperial College London (reference 15IC2470) and carried out by 14 right-handed healthy participants (five female, nine male), aged 21-24 years (mean = 22, sd = 1.11). Participants were naïve about the experimental conditions and gave informed written consent before starting the experiment. Their handedness was determined using the Edinburgh Handedness Inventory [16] and their Laterality Quotient (LQ) was calculated, with all $LQ > 80$.

The experiment was conducted using the Hi5 dual robotic interface (Fig. 1a, [17]). This one DoF device allows wrist flexion/extension motions while measuring angle and torque. Hi5 can apply computer controlled torques on each wrist independently to provide haptic feedback of the interaction with the virtual object. The device was controlled at 1000 Hz, while data was recorded at 100 Hz. A g.GAMMASYS system recorded surface electromyography (EMG) at 1000 Hz from the flexor carpi radialis (FCR) and extensor carpi radialis longus (ECRL) muscles in the left and right wrists.

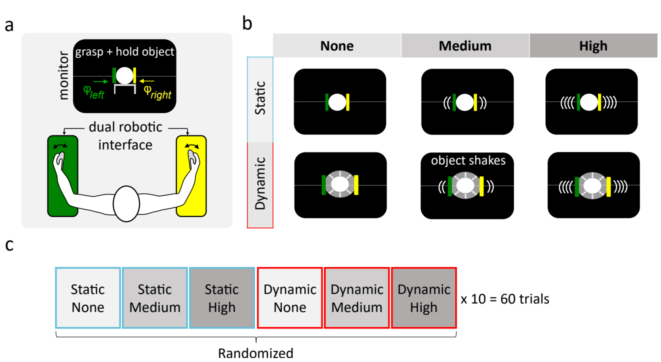

Fig. 1. Setup, conditions and protocol. a) Participants sat before a monitor showing the task and controlled two cursors with their left (ϕ_{left}) and right (ϕ_{right}) wrists to hold a virtual object. b) The object had a static or dynamic width and vibrated with three possible amplitudes. c) Ten blocks were completed, each with one trial of each of the six conditions randomly ordered.

B. Manipulation task

Participants were asked to hold a virtual object (stiffness $K = 0.7$ Nm/°) with two cursors, each controlled by a wrist's flexion/extension. The virtual object was rendered with either a fixed width ($w = 10°$) or a dynamically growing and shrinking width ($w(t) = 5\,\sin(t) + 10°$). Visual feedback of the two cursors and the object was displayed on a monitor (Fig. 1a). Additionally, participants received haptic feedback of the interaction between each wrist (with position ϕ) and the object (with position θ) through the torques:

$$\tau_L = -K(\phi_L - \max\{\phi_L, \theta_L\})\,,$$
$$\tau_R = -K(\phi_R - \min\{\phi_R, \theta_R\})\,, \qquad (1)$$

such that θ_L and θ_R were $5°$ to the left and right of the object's centre, respectively, at rest. Both the angle and the torque are positive in the counterclockwise direction.

Participants had to grasp the object, with a minimum 0.2 Nm torque, to stop it from falling, but without exceeding 1.25 Nm to avoid breaking it. Successful trials required the object to be held for 12 seconds. The object was not horizontally constrained (i.e. allowing movements around the origin). A 5 Hz perturbation torque ($\tau_p = A\,\sin(10\pi\,t)$) was exerted in some trials, with $A \in \{0, 0.5, 1.25\}$ Nm.

C. Experimental protocol

The combination of the two factors (object type and perturbation level) gave six experimental conditions (Fig. 1b). Participants performed ten blocks of trials (Fig. 1c), with each block consisting of six trials (one per condition in a random order). At the experiments' completion, participants were presented a series of short questions.

Each trial began with the participant grasping the object. Once the minimum object torque was applied, it was "lifted" and the trial started. To "succeed", they held the object for at least 12 seconds without dropping or breaking it. In perturbed trials, the perturbation amplitude linearly ramped up to reach its maximum two seconds after the object was lifted.

D. Data analysis

EMG activity was processed by filtering the raw signal using a 6th order Butterworth high-pass filter (20 Hz cutoff), rectifying and then low-pass filtering (5 Hz cutoff). The FCR and ECRL activity of both arms (in volts) was calibrated by linearly regressing each muscle's activity with its torque produced during isometric contraction (see [15]), providing torque-normalized EMG readings.

The first two trials of each condition were discarded. Out of the remaining eight trials per condition, only successful trials were considered. For the static object, with increasing perturbation amplitude, participants succeeded in 7.93 ± 0.27, 7.93 ± 0.27 and 5.57 ± 2.68 trials. For the dynamic object they succeeded in 7.71 ± 0.61, 7.79 ± 0.58 and 4.21 ± 2.89 trials, respectively. Additionally, the first two seconds of data in each trial were discarded to avoid including the response when the perturbation was not yet maximal, such that a minimum of ten seconds of data was analyzed per trial.

Two main metrics assessed the impedance control allocation. First, the *co-contraction imbalance* was calculated as the left minus right wrist co-contractions, where the co-contraction of each wrist was defined as the minimum between its flexor and extensor torque-normalized activity. Second, to measure positional stability, the *absorption imbalance* was calculated as the absolute value of the right minus the left wrist's positions after they were 6th order high-pass Butterworth filtered (4 Hz cut-off). Both metrics

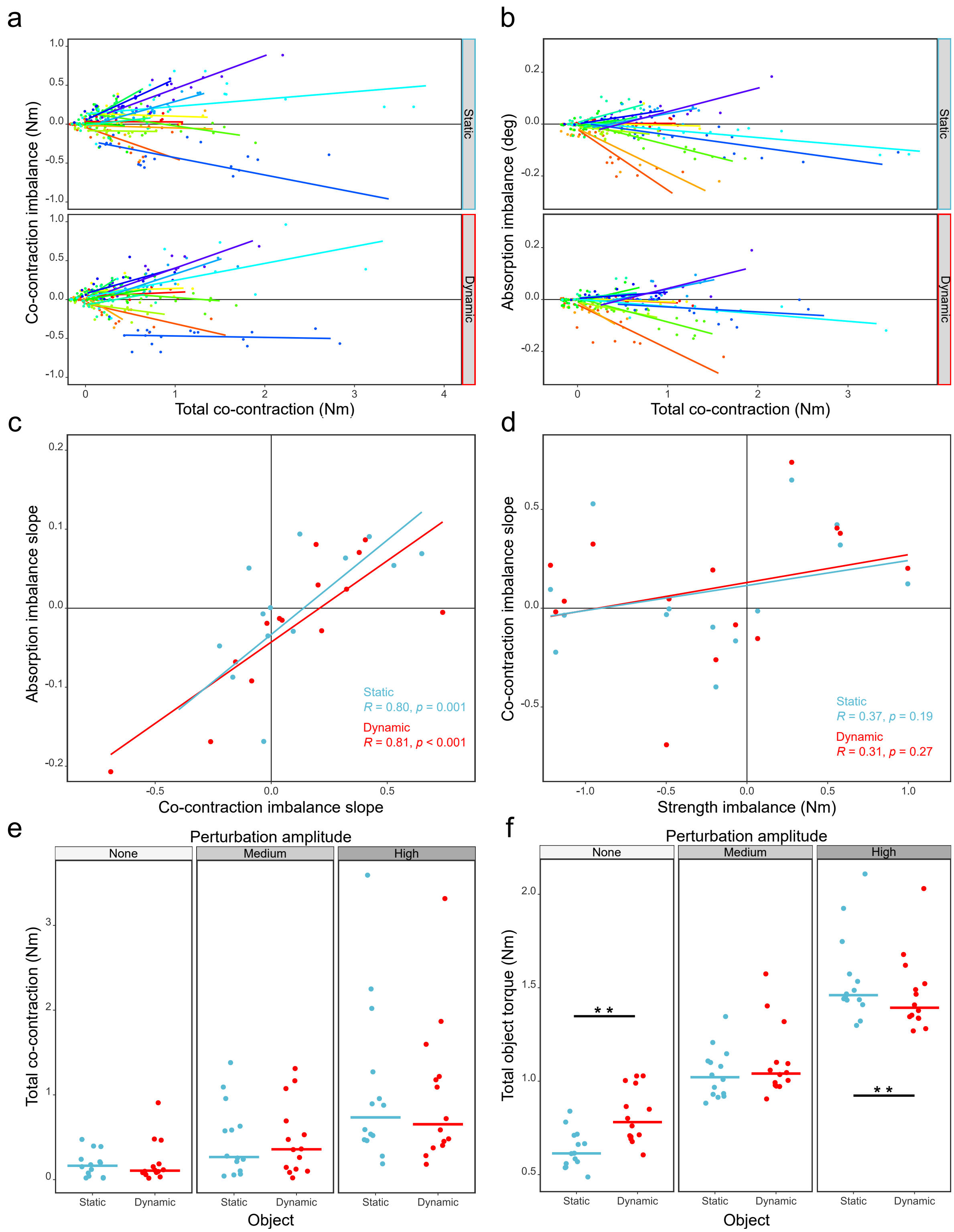

Fig. 2. Experimental results in successful trials. For figures a) to d) positive values of the y-axis imply that the left hand is co-contracting or absorbing more. In a) the co-contraction imbalance and in b) the absorption imbalance were collected for each participant per trial for linear regression as a function of the total co-contraction. Mean values for each trial are depicted as dots of the same color for each participant. c) The linear regression slopes for both the co-contraction and absorption imbalance for each participant. d) Slope of the co-contraction imbalance as a function of the strength imbalance between the hands. In e) and f) the mean across trials per participant is displayed, with horizontal lines representing each group's median and only showing significance for comparisons among the two object types. e) Total co-contraction. f) Total object torque.

were averaged for each trial. From the co-contraction, the *strength imbalance* was defined as the maximum voluntary co-contraction of the left minus the right wrist during the last two seconds of co-contraction calibration trials (see [15]).

In addition to the main metrics, the *total co-contraction* was calculated as the sum of the left and right wrist co-contraction values and the *total torque* exerted by the object was obtained as the addition of the absolute interaction torque values (1). The mean values across trials per participant were calculated. Shapiro-Wilk tests showed that some groups were not normally distributed in both metrics. Therefore, repeated measures Aligned Rank Transformed ANOVA (ART ANOVA) was used to explore the two factors' effects – perturbation level and object type – and their interaction. Post-hoc analysis was conducted by performing a series of tailored pairwise comparisons using Wilcoxon signed-rank tests. P-values were adjusted using the Bonferroni correction to control for type I error in multiple comparisons.

The average co-contraction and absorption imbalance for each trial were linearly regressed as a function of the average total co-contraction for each trial and participant. Spearman's correlation analysis was used to assess the relationship between the slopes of the co-contraction imbalance and both the slopes of the absorption and the strength imbalance.

Finally, each condition's total co-contraction and torque evolution along (all) trials was explored using linear mixed effects analysis via restricted maximum likelihood (REML), with the trial number as a fixed slope and a random intercept and slope for each grouping factor (participant id). The Satterthwaite approximation was used for the DoFs.

III. Results

No clear hand dominance was seen in the co-contraction (Fig. 2a) or the absorption imbalance (Fig. 2b). Instead, participants seemed to each have their own consistent personal preference during both the static and the dynamic tasks. Larger total co-contraction tended to increase the size of this lateralization, resulting in larger co-contraction and absorption imbalance values. These two metrics were positively correlated for both the static (r_s=0.80, p=0.001) and dynamic (r_s=0.81, $p<0.001$) objects, implying that an increase in right hand co-contraction led to less right-hand oscillation (Fig. 2c). Participants did not show a preference in co-contracting with the strongest wrist, which is supported by the lack of a correlation between the co-contraction imbalance slope and the strength imbalance for both the static (r_s=0.37, p=0.19) and the dynamic (r_s=0.31, p=0.27) tasks (Fig. 2d). These results suggest that the emergent lateralized behaviour did not differ between the two tasks.

As expected, participants increased their total co-contraction with increasing perturbations. This was confirmed by a main effect of the perturbation level (F(2,26)=37.80, $p<0.001$) in the total co-contraction (Fig. 2e). For both objects, higher perturbation levels resulted in higher total co-contraction (all $p<0.001$).

Linear mixed effects analysis showed a significant negative slope in the total co-contraction for the dynamic object when no perturbation was applied (s=-0.04, $t(11.21)=-2.91$, p=0.014). With medium perturbations, the static object slope was significant and negative (s=-0.08, t(13.08)=-2.83, p=0.014), while for the dynamic object it was negative but not significant (s=-0.06, t(12.89)=-1.92, p=0.077). All other conditions showed non-significant slopes. This suggests that in some conditions participants learned to reduce total co-contraction with trial repetition, but this was not the case for the high perturbations and was different across object types.

Analysis of the total object torque revealed that it was constant along trials in all conditions, and a significant main effect of the perturbation level (F(2,26)=214.68, $p<0.001$), the object type (F(1,13)=11.14, p=0.005) and the interaction between them (F(2,26)=22.01, $p<0.001$). This suggests that participants squeezed the static and the dynamic objects differently depending on the perturbation (Fig. 2f). Post-hoc analysis showed that the object torque increased with the perturbation amplitude in both tasks (all $p<0.01$). Interestingly, participants exerted more torque on the dynamic object when there was no perturbation (V=1, Z=-3.06, p=0.002), but this tendency changed when the perturbation amplitude was high (V=101, Z=-2.67, p=0.008). A similar torque between the two object types was found with the medium perturbations.

As seen in Fig. 3a, while most participants found the static object easier to handle (71% versus 14%), a majority preferred the dynamic object (64% versus 7%). Similarly, Fig. 3b shows that while most participants felt that the unperturbed task was easier (86%), the medium perturbation was preferred by the same number (36% for both).

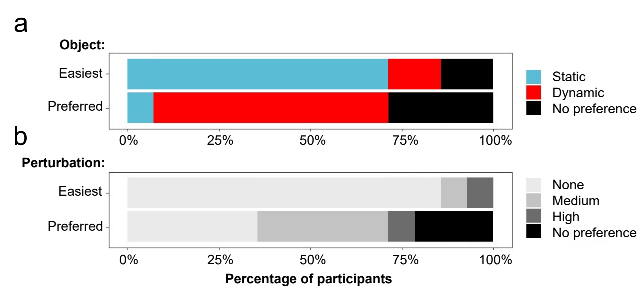

Fig. 3. Participants were asked to select a) which object they found the easiest to handle and which one they preferred and b) which perturbation level they found the easiest and which one they preferred.

IV. Discussion

We investigated the differences in impedance control for healthy right-handers between a static (i.e. postural stabilization) and a dynamic task (i.e. requiring force modulation and stabilization). Contrary to our hypothesis, we observed a co-contraction and absorption imbalance increase that was not uniformly dominated by the same hand across participants (Fig. 2a and b). In both tasks, participants reacted to the environmental instabilities by increasing their total co-contraction, with higher perturbations inducing higher total co-contraction (Fig. 2e). This increase was associated with an increase in the co-contraction and the absorption imbalance (Figs. 2a and b), suggesting that as participants compensated for higher instability levels, their motor behaviour became more lateralized. Moreover, the strong positive correlation between the co-contraction and absorption imbalance (Fig. 2c), and the similarity of the trends between the object types, suggest that participants reacted to the perturbations by both co-contracting and absorbing more with a particular hand, and did so in a consistently across tasks.

Unlike in previous works [14], [15], our right-handed participants showed no clear common hand preference for stabilization via co-contraction. However, individuals did display a preference in co-contracting one hand over another, which was consistent when stabilizing both object types. These results could not be explained by the handedness of our participants or their wrist strength (Fig. 2d), and so the reason behind this preference is unclear.

It is possible that the task's congruence influenced our results. Since both the static and dynamic conditions are inherently symmetric, and any asymmetry in the performance should only be due to participant preference, it is unlikely that wrist roles were pre-allocated. This was not the case Woytowicz et al. [14], where participants were explicitly instructed to reach with one hand while stabilizing with the other. In the study of Takagi et al. [15], the object had to be lifted, then transported to either the left or the right, unlike in our task where the object needed to only be stabilized without transport. The added difficulty of both stabilizing and transporting the object may have biased their participants to systematically co-contract their dominant hand more.

Another possible explanation for these results is that the Edinburgh Handedness Inventory is not suited to classifying the motor ability of the hands. The laterality quotient is known to cluster around -100 and +100 [16], and is more suited for binary classification. A continuous measure of the motor ability of each hand (e.g. maximal finger-tapping rate [18] or Annett's pegboard test [19]) may provide a more representative evaluation of the participant's handedness that reflects the tendency to stabilize with one hand over another.

Our results suggest that lateralization of impedance control, measured as the co-contraction and absorption imbalance, did not differ among the tasks. However, while task requirements seem to have not affected impedance control allocation, they may have resulted in different motor behaviours, as indicated by the changes in object torques across tasks (Fig. 2f). When the task was stable, the dynamic object torque was higher. This suggests that this task was more challenging, which could be reflected by participants preferring the dynamic object despite finding the static easier (Fig. 3a) and by the decreasing tendency of the total co-contraction along trials which may suggest adaptation. However, when a medium amplitude perturbation was introduced, participants tended to exert a similar torque on both objects, with a clearer trend of decreasing co-contraction when manipulating the static object. Interestingly, the high perturbation induced participants to interact with the dynamic object (i.e. when force modulation was required) by using a lower torque.

In summary, these findings suggest that despite both tasks inducing seemingly different overall behaviours, the different task requirements did not affect how each individual distributed the impedance amongst their hands. Additionally, this study did not observe a clear common preference in stabilizing the object via the co-contraction of either hand. This suggests that the circumstances under which impedance control is allocated need to be re-examined.

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