2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC) | 979-8-3503-2447-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/EMBC40787.2023.10340722

# Redundancy Resolution in Trimanual vs. Bimanual Tracking Tasks

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*Abstract*— **Supernumerary limbs promise to allow users to perform complex tasks that would otherwise require the actions of teams. However, how the user's capability for multimanual coordination compares to bimanual coordination, and how the motor system decides to configure its limb contributions given task redundancy is unclear. We conducted bimanual and trimanual (with the foot as a third-hand controller) virtual reality visuomotor tracking experiments to study how 32 healthy participants changed their limb coordination in response to uninstructed cursor mapping changes. This used a shared cursor mapped to the average limbs' position for different limb combinations. The results show that most participants correctly identified the different mappings during bimanual tracking, and accordingly minimized task-irrelevant motion. Instead during trimanual coordination, participants consistently moved all three limbs concurrently, showing weaker ipsilateral hand-foot coordination. These findings show how redundancy resolution and the resulting coordination patterns differ between similar bimanual and trimanual tasks. Further research is needed to consider the effect of learning on coordination behaviour.**

## I. INTRODUCTION

Most bimanual actions possess redundancy, such that multiple coordination strategies can achieve the same performance. For example, when moving a tray, the two hands could be used symmetrically or one hand could apply greater forces while the other passively follows. As some tasks require more than two limbs (such as in industrial assembly or laparascopic surgery), robotic supernumerary limbs have been proposed to augment human abilities [1]. However, their use requires coordination with the natural limbs. *How does the Central Nervous System (CNS) naturally coordinate the limbs when performing a redundant task? And, how does this differ between bimanual and multimanual tasks?*

Redundancy resolution during bimanual tasks has typically been explored using a **virtual-coupling** consisting of a **shared cursor** mapped to the two hands' average position/force [2], [3], [4], [5], [6]. Here, humans tend to solve for redundancy by minimising effort while maximising performance [3]. One theory proposed to explain this is stochastic optimal control, which predicts that humans use a model to estimate their state and then distribute their actions to only minimize task-relevant variability without unnecessarily exerting effort when it is task-irrelevant [7]. This adaptation has been observed in continuous 1 degree-of-freedom (DoF) [8] virtually coupled bimanual tasks, where participants used their hands only when task-relevant. However, more complex mappings have resulted in participants failing to minimize task-irrelevant motions [6], such that it is unclear whether this adaptation occurs in more complex tasks.

During redundant virtually-coupled tasks, different relative non-dominant and dominant hand contributions have been observed [9] (possibly to favour the more skilled hand [10]). Moreover, hand functional "specializations" [11] have been reported, supporting the idea that each brain hemisphere specialises in different control aspects [12]. However, these results are highly task-dependent, varying with posture [13], temporal requirements [6], [8] and task congruency [14].

Besides bimanual tasks, other combinations for interlimb coordination have also been explored showing contrasting patterns. For example, while opposite directional movements tend to be accurate and stable during contralateral limb coordination (e.g., bimanual or right hand-left foot), they become unstable during ipsilateral limb coordination (e.g., right hand-right foot) [15], [16]. For multimanual tasks, where the use of foot-controlled additional DoFs has been investigated [17], [18], [19], [20], [21], these differences in coordination requirements likely impact the resulting motor behaviours and task performance. Indeed, while the underlying motor behaviours are still unclear, performance has been found to be compromised in tasks requiring trimanual coordination when compared to bimanual coordination [20] or dyads [21].

In this work, we studied the limbs' coordination and performance in a bimanual and a trimanual (with a foot-controlled third limb) virtually-coupled redundant tracking task, where the cursor mapping was altered to represent different limb coordination in a three-dimensional (3D) Virtual Reality (VR) environment. We hypothesized that our healthy participants would identify the task-relevant limbs in the bimanual task, and that both hands would contribute similarly and move in a coupled manner when influencing the shared cursor. For the trimanual task, it was unclear if the task-relevant limbs' identification would be constrained by the more complex mapping. We expected the hands to be strongly coupled and to contribute more than the foot, but for the foot's contribution to increase for one hand-foot cursor mappings, where the type of coordination involved (i.e., ipsilateral vs contralateral) could affect performance.

## II. METHODS

### A. Participants and experimental setup

The Imperial College London Research Ethics Committee granted ethical approval and all 32 naive healthy participants

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This work was partly supported by the EU grant FETOPEN 899626 NIMA and the EPSRC Centre for Intelligent Games and Game Intelligence (EP/L015846/1). [1]Department of Bioengineering, Imperial College of Science, Technology and Medicine, London, UK. {`ana.sanmartin-senent21`, `e.burdet`}`@imperial.ac.uk`. [2]School of Electronic Engineering and Computer Science, Queen Mary University of London, UK. `n.penaperez@qmul.ac.uk`. [3]Mechanical Engineering Department, the University of Melbourne, Victoria, Australia. `eden.j@unimelb.edu.au`.

(16 per experiment), aged 26.4 ± 5.3, gave their informed consent prior to starting the experiment. The Edinburgh Handedness Inventory [22] was used to determine the handedness of each participant, with all *laterality quotients* $> 40$.

All experiments were conducted using the HTC Vive Pro headset and controllers (Fig. 1a). Participants were always seated and could freely move their hands and foot. For the trimanual experiment, a 6 DoF electromagnetic (Polhemus Liberty) tracker was attached to the participant's right foot.

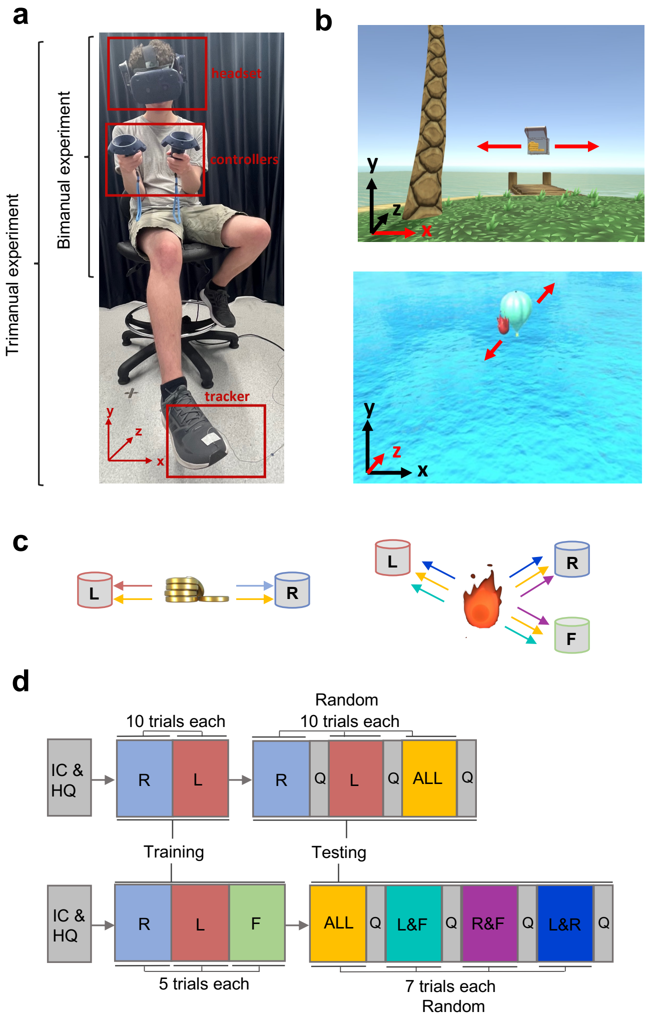

Fig. 1. Experiment setup and design. a) Participants were seated and set up with the VR headset, hand controllers and (for the trimanual experiment) an electromagnetic tracker attached to their right foot. b) The visual feedback consisted of a coin (cursor) and a treasure chest (target) and of a fire flame (cursor) and a hot air balloon (target) for the bimanual (top) and trimanual (bottom) experiments, respectively. c) The experimental conditions altered the cursor's visuomotor mapping, such that it could represent the position of the left hand (L), right hand (R), foot (F) or of all their combinations. The coloured arrows represent the limbs involved in each condition, as per the testing blocks in the d) experimental protocol. Participants gave their Informed Consent (IC) and filled a Handedness Questionnaire (HQ). They then performed the training and testing phases, where questionnaires (Q) were asked between blocks.

## B. Tracking task

Participants had to follow a moving target as accurately as possible. The position of the hand controllers and/or foot sensor was linearly mapped into virtual world positions. These were not shown to participants during the trials, and instead a single cursor was displayed. Participants had to control the error in every translational dimension. For the bimanual experiment, a 1D $x$-axis (Fig. 1b, top) tracking task was used, to be consistent with [8], with reference trajectory

$$\begin{aligned} x^*(t) &= -0.4\sin(1.3t^*) + 0.4\sin(1.7t^*) \\ &\quad + 0.8\sin(2.58t^*) - 0.2\sin(3.1t^*) \\ t^* &= t + t_0, 0 \leq t \leq 25s \end{aligned} \tag{1}$$

For the trimanual study, the $z$-axis (Fig. 1b, bottom) was used instead of the $x$-axis to facilitate more comfortable foot motions via knee flexion/extension. This reference was chosen after a bimanual pilot study confirmed no differences in redundancy resolution for different motion directions, and used trajectory

$$\begin{aligned} z^*(t) &= -0.25\sin(1.7t^*) + 0.2\sin(2.7t^*) \\ &\quad + 0.4\sin(2.68t^*) - 0.15\sin(3.5t^*) \\ t^* &= t + t_0, 0 \leq t \leq 20s \end{aligned} \tag{2}$$

All trials started from a random time $t_0$ (constrained to be a reference trajectory zero) to reduce trajectory learning.

## C. Experimental protocol

The protocols (Fig. 1d) started with a *training phase* that was intended to familiarize participants with the task. This required them to perform the task unimanually with each of the different limbs involved in each study. Participants were explicitly instructed about which limb to use.

Participants then completed a *testing phase*, where different conditions altered the limbs' task influence through different cursor mappings. During the bimanual study, participants performed three cursor conditions (Fig. 1c): i) left hand; ii) right hand; and iii) center of mass of both hands. These conditions were tested in blocks of ten trials each, where the block order was randomly chosen from a subset of possible combinations. In the trimanual study, they performed four cursor conditions, each with the center of mass of the i) right hand and right foot (R&F); ii) left hand and right foot (L&R), iii) upper limbs (L&R), iv) all limbs (ALL). Each condition was tested in randomly ordered blocks of seven trials. Participants were not given explicit instructions on which limb to use, and were told they could use either limb individually or in any combination, as long as they were comfortable and tracking accurately. After each block, participants were asked about their perceived influence of each limb on the cursor during the condition. They were also presented with several questions after each block regarding their perception of effort and agency over the cursor.

## D. Data analysis

To account for the cursor mapping learning, the first three trials of all conditions were discarded and the data was averaged for each metric over the remaining trials. The performance was evaluated by computing the **tracking**

**error** as the Root Mean Squared Error (RMSE), across all dimensions, between the target and the visualized cursor.

To assess the limbs' contributions through their amount of motion in the direction of interest, the **normalized arc length** (nAL) was calculated by dividing the limbs' trajectory arc length over the target trajectory arc length. Therefore, the nAL equaled 1 when the limb moved as much as the target, was less than 1 when it moved less and was more than 1 when it moved more.

Finally, the **Spearman correlation** between the limbs trajectories was computed to assess interlimb coordination and the subjective assessment's question "could you influence the cursor with your right/left/foot hand/limb" was analyzed.

Normality was checked using Shapiro-Wilk tests. Since some conditions were not normally distributed for all metrics, non-parametric tests were conducted. To explore the effect of one factor, a Friedman test was conducted, i.e. effect of cursor condition (testing phase) and limb (training phase) on performance. To explore the effect of more than one factor, a repeated measures Aligned Rank Transformed ANOVA (ART ANOVA) was computed (limb and cursor on the nAL and response to subjective questionnaires). When an interaction was observed, post-hoc analysis was conducted by performing a series of tailored pairwise comparisons using paired Wilcoxon tests. To control for type I error in multiple comparisons, the p-values were adjusted using the Bonferroni corrections when there were 6 or less comparisons, the Benjamini and Hochberg correction when there were 30 or more comparisons and the Hommel correction for all other cases. The main effects are only reported in the text whenever an interaction was not found.

## III. RESULTS

### A. Bimanual experiment

Participants had a similar tracking accuracy when tracking with either hand during the training ($V = 60, p > .05$) and during all cursor conditions during the testing phase ($\chi^2(2) = 0.875, p > .05$).

The interaction between hand and cursor impacted the normalized arc length (nAL) ($F(2, 30) = 46.98, p < .001$). As hypothesized, participants moved both hands when they were virtually-coupled ($V = 38, p > .1$), with both hands having a nAL (Fig. 2b) close to 1. Instead, whenever the hands were not coupled, the hand that could not impact the cursor had a lower nAL (left hand during right cursor: $V = 3, p < .001$, right hand during left cursor: $V = 133, p < .001$). Additionally, the cursor condition also impacted the correlation between the hands ($\chi^2(2) = 15.9, p < .001$), leading to less correlated motions during the left ($V = 1, p < .001$) and right ($V = 6, p < .01$) conditions compared to when virtually-coupled (Fig. 2c).

These changes in hand contribution were perceived by participants (Fig. 2d), as indicated by the interaction between the hand and cursor factors on the responses to the question "Could you influence the cursor with the right/left hand as you intended?" ($F(2, 30) = 63.58$). Participants perceived a greater influence of their right hand in the right cursor condition than in the left cursor condition ($V = 135, p < .01$), but a similar contribution than in the virtually-coupled condition ($V = 47.5, p > .05$). In addition, a greater influence of the left hand was perceived in the left cursor condition when compared to both the right ($V = 8.5, p < .01$) and virtually-coupled conditions ($V = 92, p < .05$).

### B. Trimanual experiment

During the training phase, the limb being trained affected the tracking accuracy ($\chi^2(2) = 24.5, p < .001$). The foot was less accurate than both the right ($V = 0, p < .001$) and left ($V = 0, p < .001$) hands, while no clear difference was observed between the right and left hands ($V = 26, p > .05$). During the testing phase, the cursor mapping impacted the tracking accuracy ($\chi^2(3) = 21.8, p < .001$, Fig. 2e). Here, the R&F condition had a higher tracking error than both the ALL ($V = 7, p < .005$) and the L&R ($V = 134, p < .001$) conditions. Interestingly, while the L&F condition had a higher tracking error than the L&R condition ($V = 120, p < .05$), no difference was found when comparing it to the ALL ($V = 80, p > .05$) condition.

The interaction between limb and cursor was observed to impact the nAL ($F(90, 6) = 6.1597, p < .001$, Fig. 2f). Post-hoc analysis showed that the left hand contributed more than the right hand in the ALL ($V = 120, p < .05$) and L&F ($V = 132, p < .01$) conditions. In addition, it contributed less than the foot in the R&F condition ($V = 18, p < .05$).

For the correlation, a limb combination main effect was found ($F(30, 2) = 14.0072, p < .001$, Fig. 2g). In general, the upper limbs were more correlated than the foot with the right ($V = 1863, p < .001$) or left hand ($V = 1724, p < .001$). Moreover, the foot and left hand were more correlated than the foot and right hand ($V = 579, p < .01$).

Although the interaction between limb and cursor was found to impact the responses to "Could you influence the cursor with the right-hand/left-hand/right-foot?" ($F(90, 6) = 4.65, p < 0.001$), post-hoc analysis showed no differences among the different conditions (Fig. 2h, all $p > .05$).

## IV. DISCUSSION

We investigated the coordination of healthy right-handed participants during the continuous bimanual and trimanual visuomotor tracking of a 1 DoF target in a 3D VR environment. As hypothesised, our bimanual results showed that most participants correctly identified the task requirements and adjusted their hand contributions accordingly, displaying similar contributions and strong correlation patterns only when they could impact a shared cursor. In contrast, our trimanual results suggested that participants were less capable of understanding the cursor mapping when the foot was involved in the task, and had a preference to use the three limbs together in all conditions.

The bimanual results are consistent with findings in a simpler 1 DoF robotic interface setup using a similar cursor mapping [8]. This shows that in a 3D VR environment most

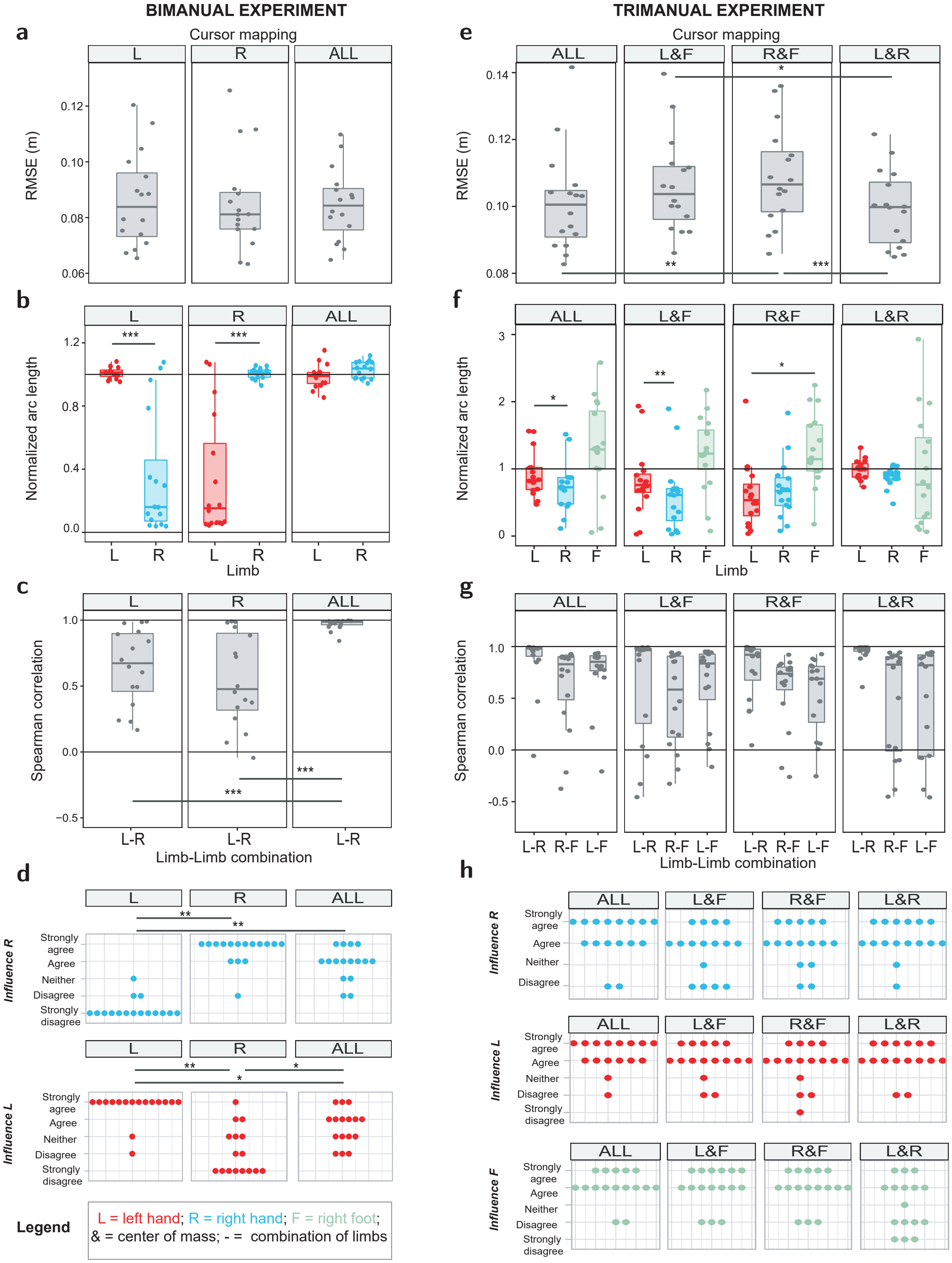

Fig. 2. Results for the a-d) Bimanual experiment and e-h) Trimanual experiment. a,e) Mean tracking error for each participant and experimental condition. b,f) Mean normalized arc length for all limbs of each participant. c,g) Mean Spearman correlation coefficient between the different combination of limbs trajectories for each participant. d,h) Likert-scale questionnaire answers given by participants at the end of each experimental condition when asked whether they could influence the cursor with each of the different limbs. Only significant comparisons after an interaction was found are represented, where *** : $p<.001$, ** : $p<.01$, * : $p<.05$. The symbol & is used to represent the combination of limbs influencing the shared cursor during a particular experimental condition. The symbol - is used to represent the limb combination being correlated, when calculating the Spearman correlation coefficient.

participants could also (without explicit instruction) recognize the cursor mappings and subsequently tended to avoid using a hand if it was not task-relevant (Figs. 2b,d). This is in contrast to previous findings during 2D (planar) motions [6], where task-irrelevant motions were observed using a more complex cursor mapping (i.e., each hand controlled an independent cursor direction). This could indicate that the ability to recognise task-relevance (and to accordingly prevent effort in task-irrelevant motions [7], [10]) is mapping dependent rather than motion dependent. However, it is noted that in our experiment and that of [8] a minority of participants always used both hands across all conditions, despite correctly recognising which hand was task-relevant. This suggests that the correct identification of the mapping is not the only factor in the suppression of task-irrelevant motion. Here, the constant adjustments required by tracking tasks may lead some participants to prefer strongly coupled hand motions [23].

Our trimanual results differ to the bimanual in that participants struggled to identify the task relevant limbs (Fig. 2h) and showed a preference to always use all limbs (Fig. 2f). The addition of the foot therefore appears to have made our mappings more difficult to understand and adapt to, possibly due to it being too difficult to separate the effect of each limb in real-time (like in [6]) or due to the foot-cursor relationship being less intuitive. Moreover, the lower tracking accuracy during the foot training and generally larger foot's normalized arc length are likely influenced by differences in the foot and hand's fine motor control abilities. These results highlight the need to consider the differing biomechanical properties of supernumerary limbs when evaluating multimanual coordination.

Interestingly, despite using a more complex mapping that involved the less accurate limb (i.e., the foot), the addition of the foot to a bimanual mapping (ALL compared to L&R) did not impact performance(Fig. 2e), suggesting that participants were still able to use the available redundancy within the task. Consistent with previous findings [15], [16], we did however observe a generally lower correlation of the ipsilateral hand-foot pair (Fig. 2g), which may explain the worse performance during the R&F condition, compared to the ALL and L&R conditions. This implies a potential limitation in concurrent trimanual manipulation that could impose limits in performance for tasks that are more complex than our tracking task.

Our findings therefore suggest that while virtual coupling through cursor mappings can induce changes in hand contributions for bimanual tasks, this does not appear to work for trimanual activities using the foot as an additional cursor. The trimanual results show possible limitations in the exploitation of foot-control interfaces for human augmentation. This suggests that special care should be taken to account for the difficulties that participants possess in recognising the foot's contribution to coupled activities and the constraints that ipsilateral hand-foot coordination imposes. Additional research is required to explore the effect of learning on the resulting coordination patterns.

## REFERENCES

[1] J. Eden, M. Bräcklein, J. Ibáñez, D. Y. Barsakcioglu, G. Di Pino, D. Farina, E. Burdet, and C. Mehring, "Principles of human movement augmentation and the challenges in making it a reality," *Nature Communications*, vol. 13, no. 1, p. 1345, 2022.

[2] F. Mechsner, D. Kerzel, G. Knoblich, and W. Prinz, "Perceptual basis of bimanual coordination," *Nature*, vol. 414, pp. 69–73, 2001.

[3] J. Diedrichsen, "Optimal task-dependent changes of bimanual feedback control and adaptation," *Current Biology*, vol. 17, pp. 1675–1679, 2007.

[4] F. R. Sarlegna, N. Malfait, L. Bringoux, C. Bourdin, and J.-L. Vercher, "Force-field adaptation without proprioception: can vision be used to model limb dynamics?," *Neuropsychologia*, vol. 48, pp. 60–7, 2010.

[5] R. Ranganathan, R. Gebara, M. Andary, and J. Sylvain, "Chronic stroke survivors show task-dependent modulation of motor variability during bimanual coordination," *Journal of Neurophysiology*, vol. 121, pp. 756–763, 2019.

[6] J. Mathew, A. de Rugy, and F. R. Danion, "How optimal is bimanual tracking? the key role of hand coordination in space," *Journal of Neurophysiology*, vol. 123, pp. 511–521, 2020.

[7] E. Todorov and M. I. Jordan, "Optimal feedback control as a theory of motor coordination," *Nature Neuroscience*, vol. 5, pp. 1226–35, 2002.

[8] N. Peña Pérez, J. Eden, E. Ivanova, I. Farkhatdinov, and E. Burdet, "How virtual and mechanical coupling impact bimanual tracking," *Journal of Neurophysiology*, vol. 129, no. 1, pp. 102–114, 2023.

[9] Y. Salimpour and R. Shadmehr, "Motor costs and the coordination of the two arms," *Journal of Neuroscience*, vol. 34, pp. 1806–18, 2014.

[10] I. O'Sullivan, E. Burdet, and J. Diedrichsen, "Dissociating variability and effort as determinants of coordination," *PLOS Computational Biology*, vol. 5, no. 4, pp. 1–8, 2009.

[11] E. J. Woytowicz, K. P. Westlake, J. Whitall, and R. L. Sainburg, "Handedness results from complementary hemispheric dominance, not global hemispheric dominance: evidence from mechanically coupled bilateral movements," *Journal of Neurophysiology*, 2018.

[12] R. L. Sainburg, "Evidence for a dynamic-dominance hypothesis of handedness," *Experimental Brain Research*, vol. 142, no. 2, pp. 241–258, 2002.

[13] D. Córdova Bulens, F. Crevecoeur, J.-L. Thonnard, and P. Lefèvre, "Optimal use of limb mechanics distributes control during bimanual tasks.," *Journal of Neurophysiology*, vol. 119, pp. 921–932, 2018.

[14] A. Takagi, S. Maxwell, A. Melendez-Calderon, and E. Burdet, "The dominant limb preferentially stabilizes posture in a bimanual task with physical coupling," *Journal of Neurophysiology*, vol. 123, 2020.

[15] K. Nakagawa, T. Muraoka, and K. Kanosue, "Factors that determine directional constraint in ipsilateral hand-foot coordinated movements.," *Physiological reports*, vol. 1, p. e00108, 2013.

[16] K. Nakagawa, T. Muraoka, and K. Kanosue, "Potential explanation of limb combination performance differences for two-limb coordination tasks.," *Physiological reports*, vol. 3, 2015.

[17] E. Abdi, E. Burdet, M. Bouri, and H. Bleuler, "Control of a supernumerary robotic hand by foot: An experimental study in virtual reality," *PLoS ONE*, vol. 10, 2015.

[18] E. Abdi, E. Burdet, M. Bouri, S. Himidan, and H. Bleuler, "In a demanding task, three-handed manipulation is preferred to two-handed manipulation," *Scientific Reports*, vol. 6, 2016.

[19] Z. Dougherty and R. C. Winck, "Evaluating the Performance of Foot Control of a Supernumerary Robotic Limb," in *Dynamic Systems and Control Conference*, vol. 59162, p. V003T16A003, 2019.

[20] Y. Huang, J. Eden, L. Cao, E. Burdet, and S. J. Phee, "Tri-manipulation: An evaluation of human performance in 3-handed teleoperation," *IEEE Transactions on Medical Robotics and Bionics*, vol. 2, no. 4, pp. 545–548, 2020.

[21] A. Noccaro, J. Eden, G. Di Pino, D. Formica, and E. Burdet, "Human performance in three-hands tasks," *Scientific reports*, vol. 11, p. 9511, 2021.

[22] R. C. Oldfield, "The assessment and analysis of handedness: the edinburgh inventory," *Neuropsychologia*, vol. 9, no. 1, pp. 97–113, 1971.

[23] R. Sleimen-Malkoun, J.-J. Temprado, L. Thefenne, and E. Berton, "Bimanual training in stroke: How do coupling and symmetry-breaking matter?," *BMC neurology*, vol. 11, no. 1, pp. 1–9, 2011.