

Human Performance of Three Hands in Unimanual, Bimanual and Trimanual Tasks

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Abstract—Trimanual operation using a robotic supernumerary limb is a new and challenging mechanism for human operators that could enable a single user to perform tasks requiring more than two hands. Foot-controlled interfaces have previously proven able to be intuitively controlled, enabling simple tasks to be performed. However, the effect of going from unimanual to bimanual and then to trimanual tasks on subjects performance and coordination is not well understood. In this paper, unimanual, bimanual and trimanual teleoperation tasks were performed in a virtual reality scene to evaluate the impact of extending to trimanual actions. 15 participants were required to move their limbs together in a coordinated reaching activity. The results show that the addition of another hand resulted in an increase in operating time, where the time increased in going from unimanual to bimanual operation and then increased further when going from bimanual to trimanual. Moreover, the success rate for performing bimanual and trimanual tasks was strongly influenced by the subject's performance in ipsilateral hand-foot activities, where the ipsilateral combination had a lower success rate than contralateral limbs. The addition of a hand did not affect any two-hand coordination rate and even in some cases reduced coordination deviations.

Clinical relevance — This work can contribute to build efficient training and learning framework on human multiple limbs motion control and coordination for both rehabilitation and augmentation.

I. INTRODUCTION

Many tasks in daily life require more than two hands. These include screwing an assembly together while the operating part has to be balanced, or operating two surgical tools to manipulate tissue while an assistant adjusts the camera in laparoscopic robotic surgery [1],[2]. Traditionally, two or more operators need to work together to complete such tasks, where inexperienced team members and communication errors may affect the operation efficiency and even endanger the patient's health [3],[4]. Robotic movement augmentation looks to enable one operator to control multiple limbs by themselves, removing communication issues while also saving manpower [5]. Robotic supernumerary limbs (SL) for movement augmentation have been developed [6]–[9], using dedicated interfaces [8],[10],[11] to control SLs concurrently to the natural limbs. These systems have proven able to reshape human-environment interactions, but it is still

unclear how well the users can accommodate the SL and coordinate them with their natural limbs.

To systematically investigate trimanipulation features and abilities, it has been proposed to classify operations with three end-effectors according to their physical coupling and the number of independent subtasks [5]. When the hands do not have physical coupling, studies with virtual end-effectors [12],[13] and supernumerary robotic arms [14],[15] commanded by the feet have shown that it is possible to control three or more limbs simultaneously for simple tasks. However, when compared to coupled tasks, independent tasks show less consistent foot behavioural patterns [16],[17] and are considered to be more difficult and less preferred [18]. While these findings show the potential of trimanipulation and the kinds of tasks that it is suited for, it is still unknown what features might limit subject performance and how performance is altered in going from bimanual to trimanual operations.

In this paper, we investigate coordination with multiple limbs through the relationship between unimanual, bimanual and trimanual performance in actions which require coupled motion between the hands. Fifteen subjects performed similar unimanual, bimanual and trimanual reaching tasks simulating object pick-and-placement, where in the bimanual and trimanual cases the subjects were also required to preserve the shape of an elastic membrane. We consider 1) how hand performance (including a foot-controlled third hand) varies when going from independent unimanual reaching to coordinated bimanual motion; 2) how the task success rate and operation time changes between unimanual, bimanual and trimanual operations; and 3) the effect of adding a hand to bimanual coordination in bimanual and trimanual tasks.

II. METHOD

The experiment was approved by the Research Ethics Committee of Imperial College London (21IC7042). It was carried out by 15 subjects (10 male, 5 female), aged 27.7 ± 4.5 years (min = 22, max = 35) without known impairment in their foot or hands. 14 of the subjects were right handed and right footed, while the remaining subject had right-handed and left-footed mixed-dominance.

The experiment was conducted with a trimanipulation robotic platform composed of two hand interfaces (Omega.7 from Force Dimension Inc., Switzerland), one foot interface [10], and a visual display, as shown in Fig. 1a. The operator sat comfortably in front of a horizontally placed monitor which showed the (virtual) task. The hand and foot positions were recorded by the interfaces and transmitted at 30 Hz

This work was supported in part by the EC grants H2020 ICT 871803 CONBOTS, FETOPEN 899626 NIMA, and UK EPSRC FAIR-SPACE EP/R026092/1.

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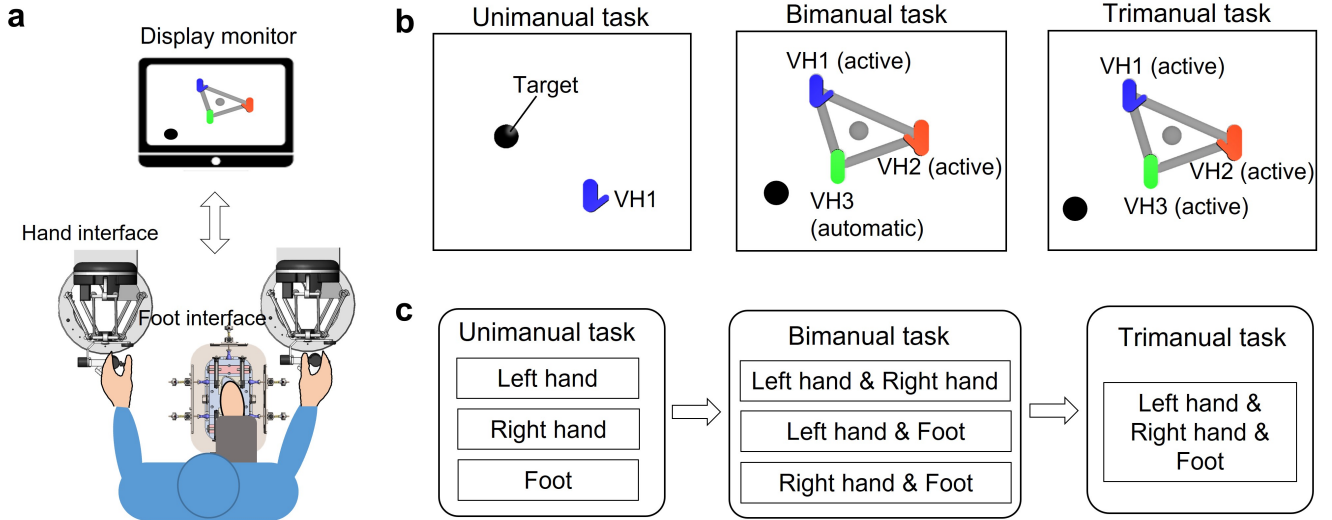


Fig. 1. (a) Experiment setup; (b) Visual display of the virtual tasks. In the unimanual task (left panel), only one hand was displayed and controlled by the operator; In the bimanual task (middle panel), two virtual hands were actively controlled by the operator, while the remaining hand automatically followed. The figure shows the example of bimanual task with left and right-hands actively controlling VH1 and 2; In the trimanual task, all three virtual hands were actively controlled by the operator. (c) Experiment procedure. In each task session, the operator followed the operation sequence from top to bottom. For example, in the unimanual task session, all participants started with the left hand, then the right and last the foot controlled third hand.

to the main computer through serial ports. The two-DoF position of the hands and foot in the horizontal plane were used to control similar monitor motions of virtual hands (VHs): VH1 for the right hand (R), VH2 for the left hand (L), and VH3 for the foot-controlled hand (F), respectively.

A. Task and procedure

Three virtual task sessions were conducted based on the number of virtual hands involved as shown in Fig. 1b. In the *unimanual task*, there were three control modes using the left hand (1H-L), right hand (1H-R) or third hand (1H-F) separately. For example, in the left-hand unimanual control mode, the operator was asked to use the left hand to control the corresponding VH to reach the target within the update period.

The other two tasks were designed to simulate everyday activities requiring physical coordination between hands e.g. holding a tray. In the *trimanual task*, an elastic triangle was held by the three VHs. The participants were asked to move the center of mass (CoM) to the target while maintaining the length of the three elastic edges within a set range. All three VHs were actively controlled by the operator using their hands and foot.

In the *bimanual task* the subjects controlled only two VHs actively while the other VH automatically followed the active hands to preserve the triangle shape. Similar to the unimanual task, there were three control modes in the bimanual task: left and right-hand control (2H-LR), left and third hand control (2H-LF) and right and third hand control (2H-RF). The subjects were asked to use these combinations to conduct the task.

The experimental procedure is shown in Fig. 1c, the subjects first performed the unimanual task, then the bimanual task and then finally the trimanual task. In all three tasks,

the target was updated on the screen every three seconds. Its color changed from black to green if it was reached within the update period. In the bimanual and trimanual tasks, when an elastic edge was larger than 1.3 times the initial length it 'broke', and when it was smaller than 0.7 it 'collided'. Each control mode was tested by one block of 32 trials. The targets were shown at the same distance with respect to the current position of the CoM and could take one of eight directions. The direction of the target was randomised and the same target sequence was used for each block. The eight chosen directions corresponded to a uniform partition of directions such that from directly forward every 45° was considered (with four repetitions for each direction within a block).

B. Performance analysis

Task completion was analyzed using two measures. The *success rate* was computed as the number of trials where the CoM was held within the target for more than 0.1 s divided by the total number of trials in each block. The *completion time* represented the time taken from the target's appearance to the time that the triangle's CoM reached it. This was only computed in successful trials.

Performance was also analyzed through the coordination between the limbs. The average coordination or *coordination rate* was computed as the ratio of time when the elastic bar was in the proper range (0.8-1.2 of its original length) divided by the total time of the trial (3 seconds). The *coordination deviation* measured the accumulated dynamic deviation of each elastic bar $E^{ij} = \sum_{t=2}^{t_e} ||L^{ij}(t) - L^{ij}(t-1)||$, where $L^{ij}(t)$ is the dynamic length of the elastic bar connecting VHs i and j ($i \neq j \in \{1, 2, 3\}$), and t_e is either the completion time in successful trials or update time in failed trials.

C. Statistical analysis

A Shapiro-Wilk test showed that the data in some of the groups was not normally distributed. Therefore, non-parametric tests were chosen to analyse the results. For the success rate and completion time, we used a Friedman test for repeated measures with the control mode as a predictor and Nemenyi tests for a post hoc comparison between single conditions. Since the Nemenyi test is quite conservative, no adjustment for multiple comparisons was required. For the coordination rate and deviation, we employed 2×3 repeated measures ART ANOVA with one factor on bimanual/trimanual mode and another factor on the combination of the hands that were involved in the task. We compared the single conditions using t-test contrasts with Holm-Bonferroni correction.

III. RESULTS

A. Reaching performance

The success rate for the unimanual, bimanual and trimanual modes is plotted in Fig. 2a. A Friedman test showed a significant effect of the control mode on the success rate ($\chi^2(6) = 52.461, p < 0.0001$). As expected, no differences were found between the unimanual conditions (all $p > 0.45$) showing a relatively consistent performance even when controlling the third hand with the foot. The bimanual conditions were also not clearly different while completing the task with the 2H-LR mode and with the 2H-LF mode and they were not different to the unimanual conditions ($p > 0.14$ for all pairwise comparisons). In contrast, in the trimanipulation condition the success rate was lower than all other groups ($p < 0.02$ for all pairwise comparisons with 3H mode) except when comparing to the 2H-RF mode ($p = 0.915$). Interestingly, the combination of the right and third hand (2H-RF) showed a lower success rate than other bimanual modes: a significant difference to 2H-LR was found ($p = 0.0003$) and a tendency to a lower success rate was also observed for the 2H-LF, however, this difference was not clear ($p = 0.087$). Moreover, 2H-RF had a lower performance than the right and left unimanual modes ($p = 0.0071$ for 1H-L, $p = 0.0032$ for 1H-R) but similar to unimanual third arm mode ($p = 0.536$).

Fig. 2b shows the result of the completion time. Statistical analysis showed a significant influence of the control mode on the time that participants spent to finish the task ($\chi^2(6) = 82.657, p < 0.0001$). Unimanual operation used the least time compared to bimanual and trimanual operation as it only required reaching without requirements on multiple-limb coordination: $p < 0.03$ for all pairwise comparisons with 2H and 3H except the contrast between 2H-LR to the unimanual left ($p = 0.451$) and to the unimanual third hand ($p = 0.980$). Within the unimanual mode, the right hand was the fastest to reach the target in 0.72 ± 0.02 seconds. The left hand was the second fastest using an average of 0.83 ± 0.03 seconds. And the third hand was the lowest among the single hands using 0.93 ± 0.03 seconds. However, we did not find significant differences among the unimanual groups

(all $p > 0.25$). 2H-LR took 1.16 ± 0.07 seconds to complete the task, slower than the unimanual right hand ($p = 0.029$), but faster than 2H-RF ($p = 0.0486$) or the trimanual mode ($p = 0.0014$). The time did increase for the bimanual operation using the right, left and third-hand operations with respect to the corresponding single hands ($p = 0.0020$ for comparison between 1H-L and 2H-LF, $p < 0.0001$). When actively using the third hand, the average completion time was increased to 1.78 seconds (2H-LF) and 2.08 seconds (2H-RF). The 2H-RF mode as well as the trimanipulation used a considerably longer time than every other condition (all $p < 0.04$) except for the 2H-LF ($p > 0.396$).

A representative subject's motion trajectories are shown in Fig. 2c. It can be observed that the third hand had a less consistent motion pattern than the left and right-hands in unimanual tasks. The effect of the third hand was clear in any bimanual operation including the third hand. While it is worth noting that when all three hands are involved, the effect of the third hand was mitigated.

B. Coordination performance

The coordination rate of each two-handed combination in the bimanual and trimanual tasks is plotted in Fig. 3a. ART ANOVA revealed a significant influence of the hand combination on the coordination rate ($F(2, 70) = 104.33, p < 0.0001$). However, the interaction of the hand pairs and task was found to not be significant ($F(2, 70) = 2.54, p = 0.086$). Task completion with two or three hands did not influence the coordination rate either ($F(1, 70) = 0.017, p = 0.895$). Over both the bimanual and trimanual conditions, the left and right-hands showed a better coordination rate than when including the third hand (both $p < 0.0001$). Moreover, with the combination of left and third hands, subjects were able to complete the task in a more coordinated manner than when using the right and third hands ($p < 0.0001$).

The coordination deviation result is shown in Fig. 3b. Both main factors and the interaction were found to be significant for these metrics: $F(2, 70) = 79.40, p < 0.0001$ for hands combination, $F(1, 70) = 31.72, p < 0.0001$ for bimanual/trimanual mode and $F(2, 70) = 8.27, p = 0.0006$ for the interaction between them. The coordination deviation of the left and right-hands in both the bimanual and trimanual tasks were not different from one another ($p = 1.00$). So in this case, adding a third hand did not seem to affect the left and right-hands' coordination. The coordination error was even reduced for the left and third-hands condition in the trimanual task compared with the bimanual mode ($p = 0.0001$). This difference was weaker but still clear on the right and third hand pair ($p = 0.012$). The left and right-hands' coordination always had less error than the natural and third-hands combination in both bimanual and trimanual tasks (all $p < 0.002$). The coordination deviation was similar between 2H-LF and 2H-RF ($p = 0.893$), as well as between 3H-LF and 3H-RF ($p = 1.00$).

The correlation matrix of the two-handed coordination in the bimanual and trimanual tasks can be visualized in Fig. 3c for the metrics of coordination rate (upper panel) and

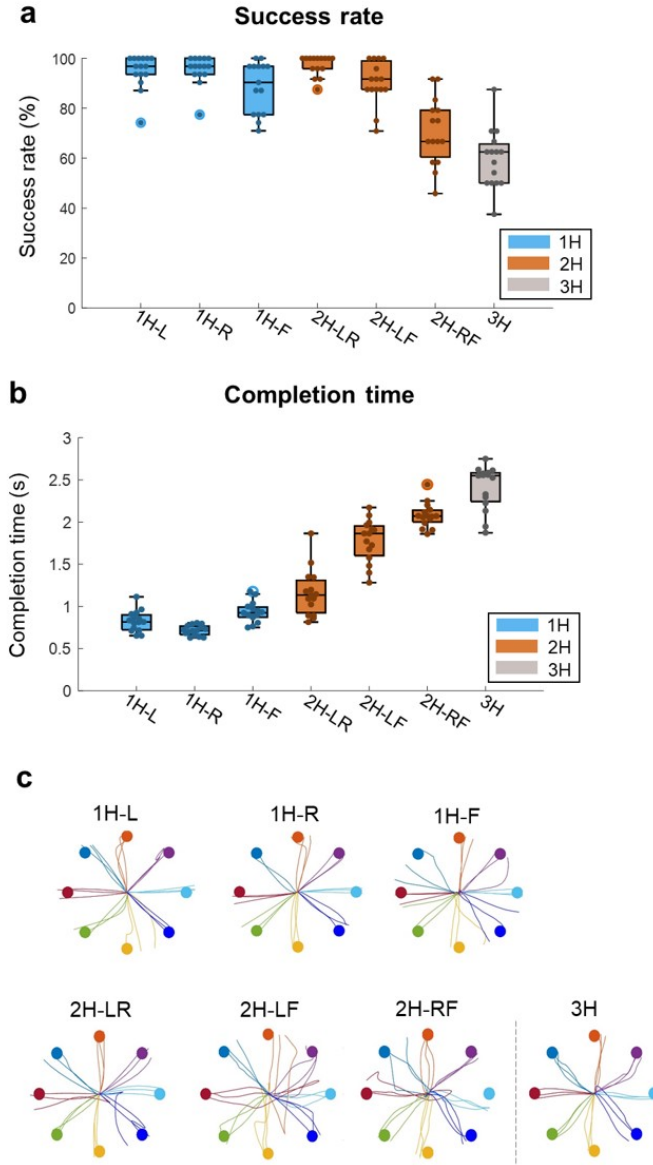


Fig. 2. (a) Success rate and (b) completion time of unimanual, bimanual and trimanual operations. (c) A representative subject's motion trajectories for three trials in each of the eight directions. (1H/2H/3H are short for one-hand, two-hand and three-hand operations; 2H-LF, LF, RF means left and right-hands, left and third-hands and right and third-hands in bimanual tasks, respectively.)

deviation (lower panel). This coordination rate in bimanual and trimanual tasks suggest weak relationships with all r values being less than 0.5 with p values larger than 0.055 except 2H-RF and 3H-RF ($r = 0.52$, $p = 0.048$). The coordination deviation also shows weak relationships between 2H-LR, 2H-LF to 3H (all $r < 0.5$, all $p > 0.08$). While it is interesting to observe that 2H-RF has relatively stronger relationship to 3H, especially with 3H-RF ($r = 0.57$, $p = 0.03$) and 3H-LF ($r = 0.70$, $p = 0.003$).

IV. DISCUSSION

We studied human performance in unimanual, bimanual and trimanual operations with a coordinated reaching task.

The left, right and third hands did not show clearly different performance in their success rate and completion time for the unimanual task which may reflect the overall simplicity of the task, where subjects can quickly adapt to the third hand control in this simple reaching task.

It was expected that the left and right-hand's bimanual control would have better performance than either combination that required the use of the third hand. However, the contralateral pair of the left hand and right foot showed no difference in its success rate compared to the left and right hands. This was not the case for the right and third-hand pair where the success rate decreased. This suggests that subjects struggled to simultaneously control their ipsilateral foot and hand combination in this coordination task. A similar decreased performance has been observed for ipsilateral combinations when compared to contralateral combinations for anti-phase motions [19]. This suggests that the results are likely reflective of difficulties arising in hand-foot coordination when they use similar brain resources.

Adding one hand and introducing the need for coordination slowed down the operation in all cases regardless of if the task involved the third hand or not. This suggests that the increase in time is likely associated with the greater planning requirements in both the transition from unimanual to bimanual and the transition from bimanual to trimanual. The effect of the additional hand in the success rate was varied. The left and right-hands' pair was not affected from the unimanual to bimanual cases. Interestingly, the left and third-hand pair also did not decrease the success rate compared to single left and third hand. But the right and third-hand's performance did decrease with respect to the single right hand. Furthermore, comparing bimanual and trimanual operations, the addition of the extra hand did not affect the success rate when compared to the ipsilateral bimanual pair. This might suggest that the limiting factor to trimanual operation is specifically the ipsilateral coordination of the hand and foot rather than the overall operation of all three limbs. The moderately correlated 2H-RF and 3H-RF coordination also strengthened this assumption.

Our previous findings [17] showed that adding a new hand did not affect the left and right-hands' motion characteristics. In this work, we further investigated whether adding a hand affected the coordination of the original two hands in a coordinated reaching task. The results show no difference in coordination of the left and right-hands was observed when going from bimanual to trimanual operation. The two-handed coordination in the trimanual mode even showed a improved tendency when compared to the bimanual modes, especially when the the third hand was considered. This potential improvement may be because both the left and right-hands could aid the third hand in the trimanual task which compensated for some of the operation barriers of use.

These results suggest the trimanipulation is not simply a composition of unimanual or bimanual operations. The subjects can go from bimanual to trimanual operations with losses in performance like operation time but not coordina-

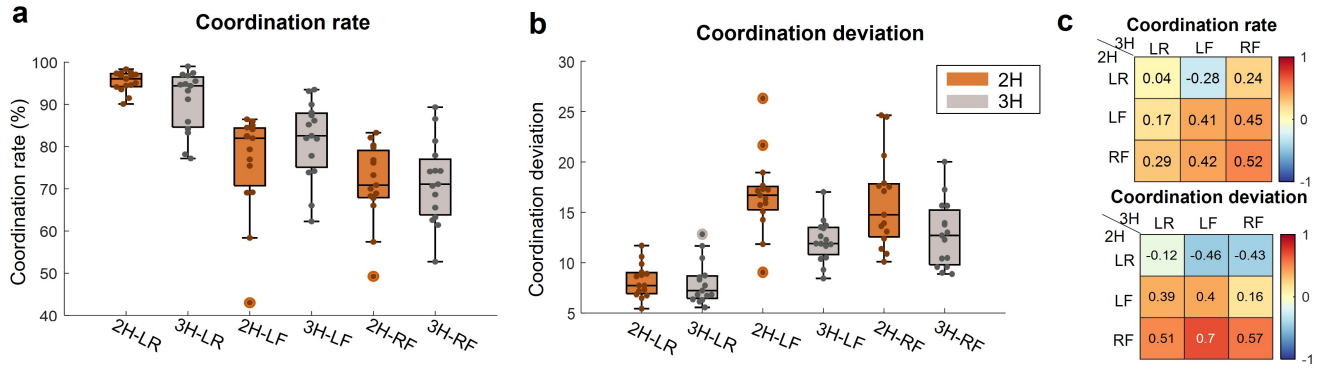


Fig. 3. (a) Coordination rate and (b) deviation of the two hands in bimanual and trimanual operations. 2H-LR/3H-LR represents left hand and right-hand coordination in two-hand task or three-hand task. (c) Correlation heatmap of the coordination in two-hand and three-hand operations (the value in the box is the Pearson correlation coefficient r value).

tion of hands. The main limiting factor of trimanipulation appears to be the simultaneous coordination of an ipsilateral hand and foot. Most of the participants in this study are right-handed and right-footed, it is still unclear whether different dominance play a role in the result. Future work will look to model the process of going from unimanual and bimanual to trimanual operations and this result will contribute to build an efficient training framework for human to gain the capability on motor augmentation. We will also investigate human performance and behavior patterns in different trimanipulation task scenarios with larger sample size and representative groups.

ACKNOWLEDGMENTS

We thank the participants for joining the experiment.

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