Comparison of human trimanual performance between independent and dependent multiple-limb training modes

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***Abstract*— Human movement augmentation with a third robotic hand can extend human capability allowing a single user to perform three-hand tasks that would typically require cooperation with other people. However, as trimanual control is not typical in everyday activities, it is still unknown how to train people to acquire this capability efficiently. We conducted an experimental study to evaluate two different trimanual training modes with 24 subjects. This investigated how the different modes impact the transfer of learning of the acquired trimanual capability to another task. Two groups of twelve subjects were each trained in virtual reality for five weeks using either independent or dependent trimanual task repetitions. The training was evaluated by comparing performance before and after training in a gamified trimanual task. The results show that both groups of subjects improved their trimanual capabilities after training. However, this improvement appeared independent of training scheme.**

I. INTRODUCTION

Movement augmentation aims to extend natural human movement ability. It can do so by amplifying the users already existing ability, e.g. increasing the user's power through a wearable exoskeleton [1], or by granting the user with completely new degrees-of-freedom (DoFs). DoF augmentation in the form of supernumerary robotic fingers [2], [3], arms [4], [5] or legs [6], [7] have the potential to reshape human-environment interaction by allowing a single user to perform tasks that are impossible to perform with their natural limbs alone [8]. For instance, by possessing a third wearable arm, a single user can simultaneously attach a door to an overhead connector of an aircraft fuselage while supporting its mass [9]. Therefore, this form of augmentation can both extend one user's capability and avoid communication errors while saving manpower.

Trimanual control ability has only recently begun to be quantified, where it has been shown that humans can simultaneously control a supernumerary hand and their natural hands to conduct reaching movements [10]–[13] and simplified three-tool surgical procedures [14]. The resulting movement augmentation has also been shown to improve over the course of 1 or 2 sessions [15], [16]. However, despite this evidence of training induced performance improvement, the impact of different training schemes is not yet known.

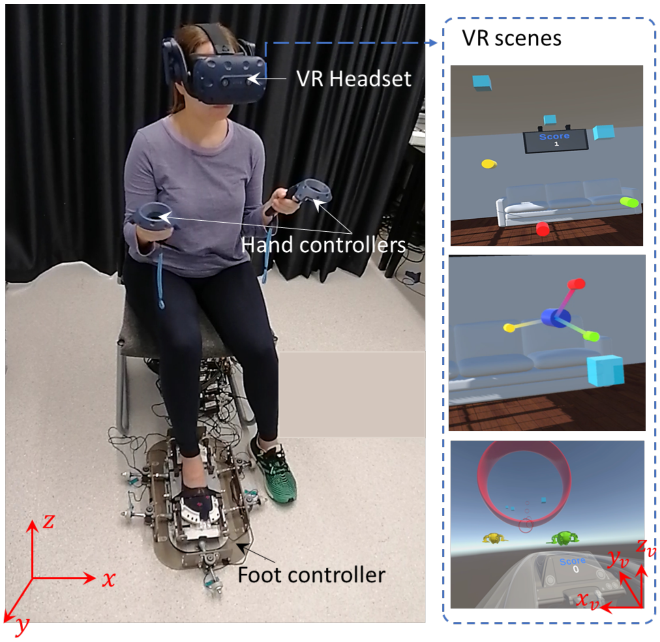

Fig. 1. Overview of the trimanual virtual reality (VR) platform with an operator. The operator wears a VR headset holding hand controllers with their natural hands and stepping their dominant foot on a foot interface.

Motor skill learning is a complex process for which the training efficiency depends on numerous factors including the training type, subject motivation, task difficulty and pre-existing skill level [17]. It is known that bimanual skills cannot be learned through unimanual training alone and instead require their own unique paradigms [18], [19]. Similarly, trimanual motor skills likely cannot be directly transferred from unimanual/bimanual operation [20]. Furthermore, unlike bimanual skills, they are completely novel due to the lack of naturally occurring instances of trimanipulation.

However, trimanual abilities may be able to be acquired through transfer learning after repeating basic trimanual actions. Many potential examples of trimanual coordination can be subdivided into actions classified based on the coupling between the hand dynamics and the number of independent activities for which the hands work together [8]. For example, the operator may need to pick three components located at different positions (all hand independent and uncoupled); or tie their shoelaces while holding an object (two hands dependent); or keep an object's balance using three hands while moving to the target area (all dependent and coupled).

Coupling mechanisms are known to influence bimanual behavior [21], where dependent or independent training

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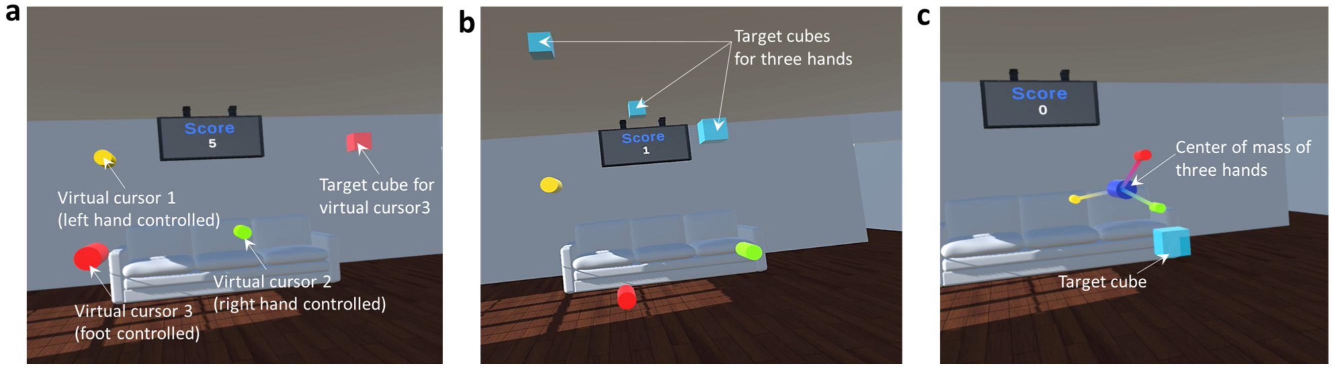

Fig. 2. Virtual tasks for familiarization and training phases. (a) A unimanual task was conducted by each single hand (left hand/right hand/foot) in each trial. One of three hands was required to perform the trial when the target displayed with the corresponding color (red for foot, yellow for left hand, green for right hand). (b) The independent trimanual task requires the participants to use both their hands and foot to control three virtual cursors to reach three target cubes at the same time. (c) In the dependent trimanual task, the participants were instructed to move the center of mass of the three virtual cursors to reach the target cube.

could be beneficial for learning new trimanual skills. In this paper, the impact of training with all independent and all dependent trimanual training modes was evaluated. It investigated how the trimanual training scheme impacts the transfer of learning on a final different task. A five-week training study on 24 subjects was conducted using a virtual reality (VR) trimanual system.

The paper is organized as follows: Section II describes the platform including the VR system and the considered tasks. Section III presents the methods and protocol. Section IV presents the results, which are then discussed in Section V.

II. TRIMANUAL VIRTUAL REALITY PLATFORM

A. System overview

The trimanual training system consisted of a HTC Vive Pro headset *(HTC Corporation, Taiwan)*, its two hand controllers and a foot interface [22]. Fig. 1 shows this setup and a human operator. Throughout the experiment the operator sat comfortably on a chair placed in the center of the HTC Vive play area, while holding both hand interfaces and with their dominant foot placed on the pedal of the foot interface.

The hand controllers' position was directly mapped to the position of the virtual cursor with a scaling factor on each axis. The foot interface was used to control the position of the user's 'third' hand. The position of the foot was mapped to three-DoF virtual cursor velocity commands, where the $x-y$ plane motion was controlled by the planar translation of the pedal and the z-axis motion by foot dorsiflexion and plantar flexion. The foot interface has a compact structure with continuous support, where dorsiflexion and plantar flexion were chosen instead of foot up and down motion to avoid fatigue while the interface provided gravity support.

The virtual environment was built in Unity. The user was given feedback of the virtual hand position through three colored cylindrically shaped cursors. The left hand controlled the yellow cursor, the right hand controlled the green cursor and the foot mapped to the red cursor. These virtual cursors were teleoperated to move in the VR space along the three translation axes with a workspace of $2.4\times2.1\times2$ m^3, located 1.5 m in front of the participant. Before starting all tasks, the subjects were asked to place their hands and foot interfaces into a neutral position which was used to calibrate the VC position at task activation. The position of the virtual cursors was recorded at 24Hz.

B. Virtual reality tasks

The experiment was composed of four VR tasks: a unimanual task for familiarization; an all hand independent training task; an all hand dependent training task; and a hybrid trimanual testing task. Each task is described below in detail and demonstrated in the supplementary video.

1) Unimanual task: A three-DoF unimanual task, illustrated in Fig. 2a was designed to familiarize the user with the operation platform including the use of the hand/foot interfaces, and the mapping between the physical limbs and virtual cursors. In this task, the operator was required to move the virtual cursors to reach a series of target cubes. The target cubes would appear one at a time randomly with either a green, yellow or red color. Each color corresponded to a virtual cursor which was required to reach the cube. The user had ten seconds to reach the target. If reached or after ten seconds, the target cube would disappear and a new cube would appear with a random color in a random location.

2) Independent/dependent trimanual task: The independent trimanual training task, depicted in Fig. 2b, required the subjects to control each virtual hand to concurrently reach for three target cubes. The subject was free to allocate any virtual hand to any target, where once all three targets had been reached or ten seconds had elapsed, a new set of three targets would appear in new locations. The task was inspired by the pick and placement activities that are required in robotic surgery and industrial assembly.

Fig. 2c depicts the dependent trimanual training task in which the user needed to manipulate a single cursor, corresponding to the center of mass (CoM) of the three virtual hands, to track a single blue target cube. The motion of the

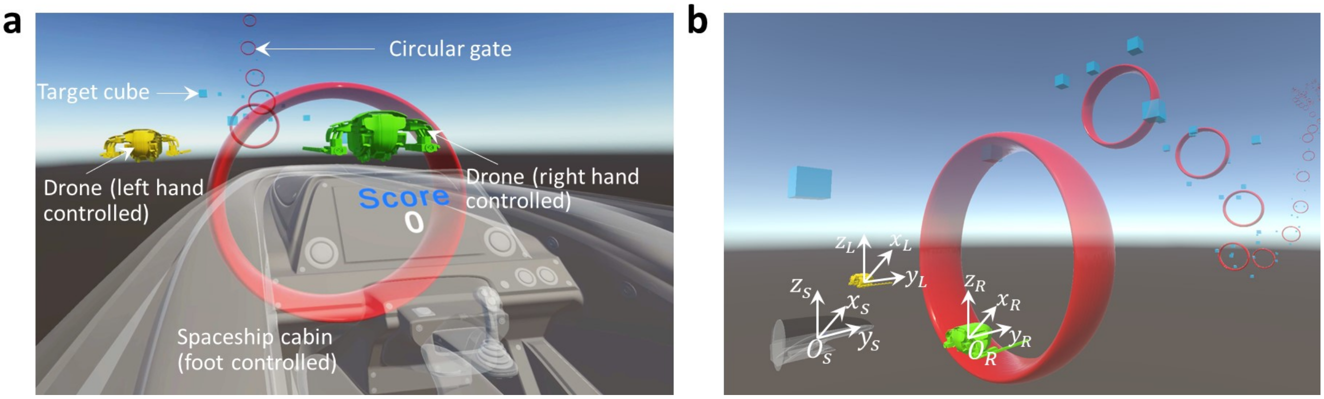

Fig. 3. Virtual task for baseline and test phases in (a) operator's view and (b) perspective view. The participants were instructed to move, in three DoFs, a virtual spaceship under the operator's view using the foot interface. In the meanwhile, the participants' natural hands controlled the relative movements of two small drones in three DoFs with respect to the spaceship. These two drones were located in the front and two sides of the spaceship, and they followed the motion of the spaceship.

virtual hands was unconstrained and therefore any combination of motion could be used to move the CoM. However, the target locations were chosen such that all three hands would be required to move for some targets. The target cube location would be randomly reset after either reaching the target or after ten seconds.

3) Hybrid trimanual task: The test task is a two hand dependent trimanual task that requires both dependent and independent behavior. It is designed as a gamified spaceship navigation and drone control task. The operator was placed in first-person view inside the spaceship (diameter: 2.4 m, height: 5.6 m), such that they could view the interaction environment from the cabin (Fig. 3a). There are two drones ($2.3 \times 2.4 \times 1.1\, m^3$) attached to the spaceship and located in front of it. The initial positions of the drones and spaceship are shown in Fig. 3b, the spaceship is controlled through user's foot; the left side drone in yellow is controlled by the left hand; right side drone in green is controlled by the right hand.

The drone positions moved with respect to the spaceship position with a workspace of $x_L, x_R \in [-60, 60]m$, $y_L, y_R \in [0, 60]m$ and $z_L, z_R \in [-60, 60]m$. The drones could not move backwards to avoid the operator to lose visibility of them. The absolute position of the drones was dependent on the position of the foot, such that each drone's final position was the sum of the foot-controlled absolute spaceship position and the relative hand-controlled drone.

In this task, there are multiple circular gates (diameter: 29.29 m) located in space. The distances between successive gates was varied with an average of 132.9 ± 38.2 m. On the path from one gate to another, five target cubes were placed randomly within the workspace of the drones. The operator was asked to drive the spaceship through multiple circular gates (diameter: 29.29 m) as fast and accurately as possible, while also reaching as many target cubes (side length: 3 m) as possible with the drones. The foot motion controlled the speed of the spaceship which could move up to 144 m/s. This task was inspired by endoscopic surgery, where the endoscope must be moved while the surgeon controls the relative position of different tools with respect to it.

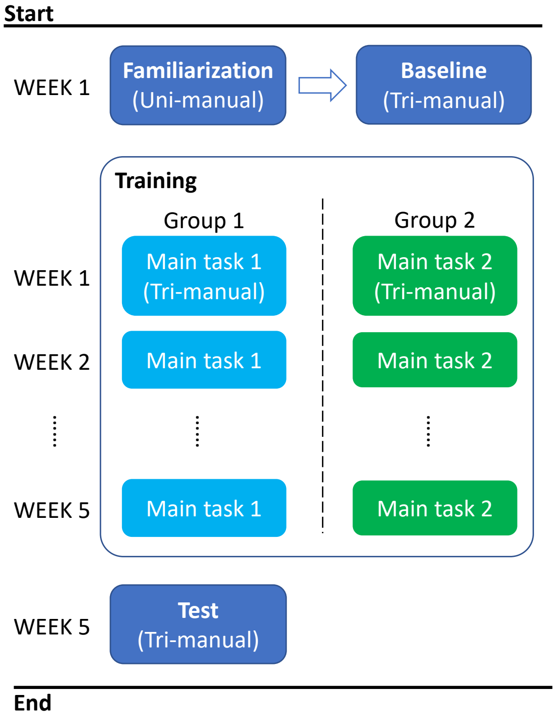

Fig. 4. Experiment procedure. All the participants conducted the same familiarization task (Fig. 2a) and the hybrid trimanual task (Fig. 3) on week 1. Then the participants were randomly assigned to two training groups. They were trained by either independent trimanual task (group 1, Fig. 2b) or dependent trimanual task (group 2, Fig. 2c) from week 1 to week 5, each day for one week. Finally, they were tested in the 5th week with the hybrid trimanual task (Fig. 3).

III. EXPERIMENT

The experiment was approved by the College Research Ethics committee of Imperial College London (21IC6935). All subjects were informed about the experiment's purpose and protocol, and signed a consent form before starting. Twenty-four subjects without motor impairment (11 male, 13 female; mean age = 24.2 ±3.15 years) participated in the study. Their hand and foot dominance was determined using their Edinburgh handedness inventory (EHI) score [23] and the ball-kick dominant leg test [24]. 21 participants were right-side dominant, 2 left-side dominant, 1 mixed dominance (right-handed and left-footed). The participants were assigned to two groups, each with a different training protocol consisting of only performing either the independent or dependent trimanual tasks. Twelve participants (4 male; mean age = 23.5 ± 1.6; EHI score = 68.5 ± 36.8) were randomly assigned to the *independent trimanual group* and the *dependent trimanual group* (7 male; mean age = 24.9 ± 4.1; EHI score = 72.3 ± 44.5). One participant in the dependent group did not complete the final session and was therefore excluded from the transfer analysis.

A. Experimental procedure

The experimental procedure is shown in Fig. 4. In the first week the participants conducted the *familiarization phase*, where they performed the unimanual task for 5 minutes (see Section II-B.1). After this phase, there was a *baseline phase* for all participants. They were asked to perform the hybrid trimanual task (section II-B.3) for five blocks, each 2 minutes with a break of at least 30 seconds between the blocks (Fig. 4b). The participants then started the *training phase*, in which they were randomly assigned to two training groups. Each group has twelve subjects, and they were trained either independent or dependent trimanual tasks (see Sections II-B.2). This training phase included five sessions and totally lasted for five weeks with each session roughly a week apart (7.6 ± 2.1 day). In each session, the subject repeated their group dependent training task for five blocks. These multiple sessions and blocks were chosen to understand the retention of the learning as well as within session learning. In the final week after the training task, the subjects performed the *test phase*. This involved repetition of the test task (section II-B.3) in a manner consistent to the baseline phase.

B. Performance metrics

The third hand's performance and the characteristics of the trimanual operation in the baseline and test phases were evaluated and compared. The third hand's performance was assessed by checking three metrics which are the *number of successfully crossed gates* N_{gate}, the *motion smoothness* [25] and the average *completion time* T_{gate} in each block. T_{gate} represents the average amount of time to successfully reach a gate during a trial.

$$N_{gate} = \sum_{i=1}^{N} n_t(i) \tag{1}$$

$$T_{gate} = \frac{\sum_{i=1}^{N} [n_t(i)(t(i) - t(i-1))]}{\sum_{i=1}^{N} n_t(i)} \tag{2}$$

where N is the total number of gate the operator reach, n_t represent the success coefficient of the third hand, if the spaceship successfully pass gate i, $n_t(i)$ = 1; otherwise, $n_t(i)$ = 0. $t(i)$ is the moment when the third hand controlled spaceship successfully crossed gate i.

The trimanual operation was evaluated through the *Coordination score* and the *Performance score*. The *Coordination score* (C_{score}) computed the total number of hand targets reached for each gate passed. If the foot-controlled spaceship did not pass the corresponding gate successfully, the reached targets by hands were not counted in the coordination score. The *Performance score* (P_{score}) reflected the scores from both the targets reached by hands and the gated passed successfully by foot:

$$C_{score} = \sum_{i=1}^{N} n_t(i) n_{2h}(i) \tag{3}$$

$$P_{score} = \alpha \sum_{i=1}^{N} n_{2h}(i) + \beta \sum_{i=1}^{N} n_t(i) \tag{4}$$

where n_{2h} is the hand reached target number before foot pass gate i, $n_{2h}(i) \in \mathbb{Z}[0, 5]$; α and β are score weights for natural hands and third hand. In the experiment, we set α = 1 and β = 5, to allow the score points equally distributed in space for hands and foot.

C. Statistical analysis

Before the analysis, the data was averaged over all five blocks in each session for each metric. Kolmogorov-Smirnov tests showed that all metrics were normally distributed in each group (all p>0.05). Therefore, we used a 2×2 mixed ANOVA with one within-factor – session (first/fifth) – and one between factor – the trimanual task that was trained (independent/dependent). Since we had an unbalanced design, we used a Type II sum of squares [26]. The effect size was evaluated using the Generalized Eta-Squared measure (η_G^2) [27].

IV. RESULTS

A. Foot-controlled third hand performance

The foot-controlled hand performance is shown in Fig. 5a. An ANOVA revealed that the session had a significant effect on the number of successfully crossed gates ($F(1, 21) = 67.015$, $p < 0.0001$, $\eta_G^2 = 0.318$), where the N_{gate} for the third hand was higher after five weeks of training compared to the initial performance. However, the trained trimanual mode had no effect on the test task for N_{gate} ($F(1, 21) = 0.022$, $p = 0.8825\, \eta_G^2 = 0.001$), such that participants improved after training regardless of their group. Similar results were found for motion smoothness and completion time T_{gate} (Fig. 5b,c). Subjects improved their smoothness after five weeks ($F(1, 21) = 24.285$, $p < 0.0001$, $\eta_G^2 = 0.293$) independently of which task they trained with ($F(1, 21) = 0.0241$, $p = 0.8781$, $\eta_G^2 = 0.001$). T_{gate} was also significantly influenced by the session ($F(1, 21) = 20.855$, $p = 0.0002$, $\eta_G^2 = 0.261$). Analysis showed that the required time reduced for the last test week compared to the first baseline week. Again, the training mode did not have an effect on

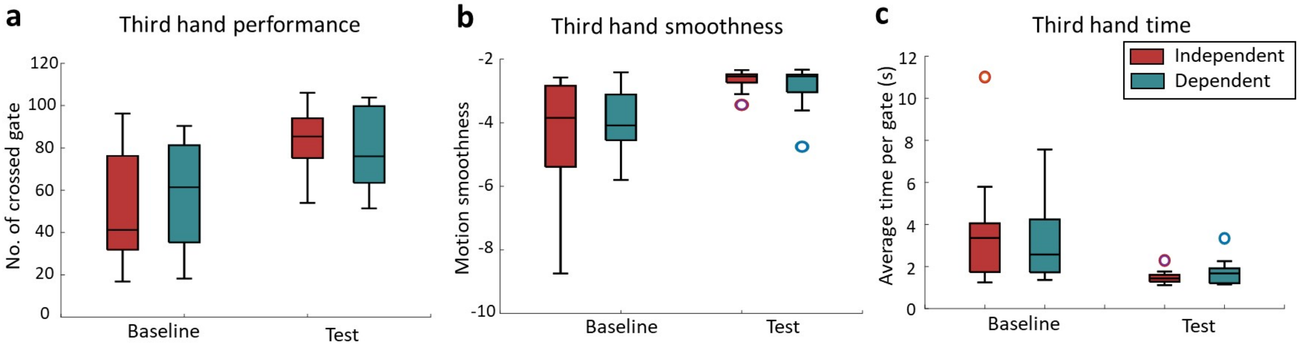

Fig. 5. Performance of the third hand for the hybrid trimanual task in the baseline and test phases with independent and dependent groups. (a) Number of successfully crossed gates. (b) Motion smoothness. (c) Average completion time passing per gate successfully.

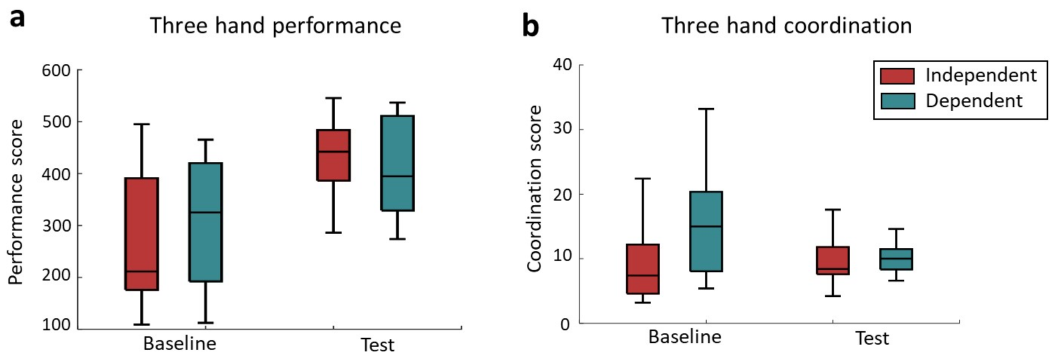

Fig. 6. Performance of the three hands in the baseline and test phases for both training groups. (a) Performance score. (b) Coordination score.

the completion time in the test task ($F(1,21) = 0.003$, $p = 0.9555$, $\eta_G^2 < 0.0001$).

B. Three hand performance

The performance (P_{score}) and coordination (C_{score}) for all three hands are shown in Fig. 6. The overall score for all three hands improved from week one to week five ($F(1,21) = 67.460$, $p < 0.0001$, $\eta_G^2 = 0.318$) and this improvement was similar for both trimanual training modes ($F(1,21) = 0.0572$, $p = 0.8134$, $\eta_G^2 = 0.002$). However, the coordination score which evaluates the natural hands' performance when the third hand successfully passes the gate remained the same for both sessions ($F(1,21) = 2.861$, $p = 0.1055$, $\eta_G^2 = 0.045$) and for both trimanual tasks ($F(1,21) = 2.389$, $p = 0.1371$, $\eta_G^2 = 0.070$). This result suggests that the improvement of the three hand performance came mainly from the third hand and the natural two hands remain performed similarly before and after training.

V. DISCUSSION

In this paper, we studied human three-DoF spatial trimanual operation using a VR training platform. We conducted an experimental evaluation of 24 subjects to examine if practicing with all hands being dependent or independent altered the learning performance of subjects in a hybrid task requiring both dependence and independence of multiple limbs. The results show that both trimanual training modes significantly improved the performance of the three virtual 'hands', and that the improvement was primarily observed in the foot-controlled 'third' hand, independently of which training task was used.

Trimanual operation is a new skill since normally only our two natural hands perform everyday activities. Polydactyly individuals with a second thumb for each hand (and foot), have extra muscles and nerves to control their supernumerary finger with a distinct cortical representation [28]. While this means that the human brain can control supernumerary limbs, learning to control artificial supernumerary limb may need long-term practice in order to be possible. Our results show that subjects do learn new skills and validated existing results conducted using shorter training duration [15], where subjects showed performance improvement from practice.

The final hybrid task did not show any difference in the subjects' performance based on whether they conducted independent or dependent training. The three-hand performance and coordination were improved from based-line session to test session, the improvements are mainly from foot-controlled hand. In addition, the subjects' performance was gradually improved from week to week, but with different learning patterns for two trimanual training tasks, which was investigated in a separated study [29].

VI. CONCLUSION

Participants training for five weeks with the VR platform showed similar improvement regardless of the training that they received. Most of the trimanual improvement was solely due to improvement in the third hand's performance. These results may be limited by the small number of training tasks and the design of the test task.

Future work will address the limitations of the current study. First, the current testing task requires not only fast and accurate navigation of the third hand but also dynamic accurate motion of the natural hands, as well as to coordinated the dependent motion between natural hands and third hand. This is highly challenging for a novice operator. The chosen weightings for the experiment score may not have motivated subjects to perform true trimanual coordination, and instead they focused on sequential unimanual performance. Therefore, we will need to include trimanual testing tasks with multiple levels of difficulties. Second, the current study only considers a subset of possible fundamental trimanual actions. More trimanual training tasks with a longer learning time will therefore need to be explored.

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